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INTERNATIONAL ASSOCIATION OF GEODESY - TRAVAUX

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Foreword

Every four year the International Association of Geodesy (IAG) publishes its reports for the past four year period, called the ”Travaux de l’Association Internationale de Geodesie”.

The “Travaux “ is published shortly after the General Assembly of the International association of Geodesy held as a part of the General Assembly of the International Union of Geodesy and Geophysics (IUGG) which took place in Birmingham, United Kingdom between the 19th and the 30th of July, 1999.

The Travaux is the complete collection of all the reports of all the bodies constituting the Association. This version of the Travaux contains a total of 25 reports. Each of the 5 sections within the IAG reports on their commissions, services, special commissions, special study groups and working groups. Finally a number out of sections reports are found.

It is an instantaneous picture of the work performed the last four years by a large number of individuals and groups through international corporation under the auspices of the International Association of Geodesy. The ”Travaux” is published in a short timetable after the General Assembly, so that scientific information can be disseminated rapidly throughout the geodetic community.

I would like to thank all the contributors who did their best to provide their report at the Birmingham IUGG General Assembly (or shortly after).

During the last four year period the IAG has established a homepage on the Internet (www.gfy.ku.dk/~iag) as an open up-to-date forum for communication. Through this electronic address, all members of the IAG are now able to have almost real time access to all information related to the IAG. An electronic version of the ”Travaux” can also be found here.

Ole B. Andersen

Report of International Association of Geodesy Section I

POSITIONING

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1. Preamble

The Handbook of Geodesy (1996) describes the tasks of Section I as:

> Section I is concerned with the scientific aspects of the measurement and analysis of regional and global geodetic networks as well as satellite, inertial, kinematic and marine positioning. The practical results of this research work should be made available through recommendations to National Survey Organisations. Applications of geodesy in engineering is a recent new task of Section I.
>
> Tremendous advances of GPS surveying have occurred, especially in precision and applicability. However, there are some remaining issues of accuracy and reliability of GPS surveying (hardware and software) which need to be addressed carefully. Recently, GPS measurements have shown the potential to be used as remote sensing tool of atmospheric parameters.

Two main driving forces of the developments by Section I can be recognised: GPS technology is changing the methods and practical tasks of positioning, and the engineering applications of geodesy are a growing field with an important geodetic kernel.

2. Structure of Section I

In order to achieve the above described tasks, Section I consists of the Commission X "Global and Regional Geodetic Networks" (President: C. Boucher, France) and of the Special Commission 4 "Application of Geodesy to Engineering" (President: H. Kahmen, Austria). Both commissions have established several working groups and address the longer term interests of positioning on an international basis. For the period 1995 - 1999, Section I set up several Special Study Groups (SSG) to investigate rather limited but highly relevant research topics with the goal to solve the underlying problems. One of the main activity of a SSG is the international coordination of the ongoing research in its field.

In 1995 the following special study groups were established:

SSG 1.153:	Precise Marine Positioning: Surface and Seafloor (D. Egge, Germany)
SSG 1.154:	Quality Issues in Real Time GPS Positioning (C. Rizos, Australia)
SSG 1.155:	Active GPS Networks (H. Tsuji, Japan)
SSG 1.156:	Advanced GPS Analysis for Precise Positioning (G. Blewitt, UK)
SSG 1.157:	GPS Ambiguity Resolution and Validation (P.J. de Jonge, Netherlands)
SSG 1.158:	GPS Antenna and Site Effects (J. Johansson, Sweden)
SSG 1.159:	Use of GPS Positioning for Atmospheric Monitoring (M. Bevis, USA)

In 1997, the SSG 1.153 was discontinued by the IAG Executive due to lack of communication.

Most SSG worked extremely well which can be seen from their reports.

The Steering Committee of Section I comprises of the Section President (F.K. Brunner, Austria), the Section Secretary (Y. Bock, USA) and the President of Commission X (C. Boucher, France). Meetings of the Steering Committee were held at IAG Executive Committee Meetings and at major international symposia.

The reports by Commission X, SC4 and SSGs groups are given in the following section. The complete report of SC4 is available from the web-side-version of the Travaux.

3. Meetings and Highlights

There were many international meetings held on topics of positioning for which IAG functioned as a sponsor. However, in my opinion three meetings had a special mission:

a) Section I organised the symposium on “Advances in Positioning and Reference Frames” as a part of the Scientific Meeting of IAG in Rio de Janeiro
b) SC4 organised a Symposium on “Geodesy for Geotechnical and Structural Engineering” in Eisenstadt
c) Section I organised the Symposium G1 ”Positioning” at the General Assembly of IUGG in Birmingham.

The Proceedings “Advances in Positioning and Reference Frames`”(Brunner, 1998) reflect the exciting and steadily growing developments of fundamental GPS work as well as novel applications of static and kinematic GPS surveying techniques. The maintenance and the densification of reference frames are treated for the purpose of establishing global and regional GPS networks. The scientific achievements of the South American Geocentric Reference System project (SIRGAS) are discussed. Several contributions review the state of the art of GPS analysis techniques, ambiguity resolution methods, as well as GPS antenna and site problems. New applications of kinematic GPS positioning and the quality control issues of real-time GPS positioning are presented.

At the Eisenstadt meeting (Kahmen, 1998) a first attempt was made to connect geotechnical problems with geodetic measurement and analysis capabilities.

Highlights of “Positioning” of the Birmingham meeting will be contained in the forthcoming IAG Proceedings. The presentations of nearly 110 posters show the tremendous impact GPS currently has on the development of positioning through achievements in:

- global reference frame definition
- subsequent definitions and maintenance of national networks
- nearly instantaneous ambiguity resolution
- much better understanding of site environmental effects
- and quality control issues of GPS.

The development of continuously operating GPS networks especially as regional active GPS networks is changing the face of positioning. Instantaneous positioning of high precision at distances up to 100 km is just rising above the horizon.

4. Achievements, trends and research opportunities in positioning

It has been a tradition of Section I Presidents to give a brief outline of their thoughts on the future of Section I. The following notes are my attempt to keep this tradition alive.

It is interesting to realise that the origins of IAG have been in the early arc measurements. At that time small parts of the Earth were measured and estimates about the whole Earth were made. Satellite geodesy reversed the situation and its outstanding success story is well known by such acronyms as IGS, IERS and ITRF. We now have available station coordinates, station velocities and precise orbits and other parameters in order to compute very accurate geodetic networks on a deforming Earth. The traditional backbone of Section I has been national networks and their combinations, like EUREF, taken care of by Commission X. Currently Commission X is involved in the maintenance of geodetic networks and the provision of the necessary terrestrial reference systems. Using IGS and ITRF we can achieve the densification of the global network for national survey purposes.

In this field we notice several recent success stories, like EUREF. My personal favourite is SIRGAS, where a whole continent started to participate in all aspects of modern geodesy, see the papers in Brunner (1998). This project had the right people, the right spirit and the outstanding and sensitive partnership with DGFI and its head, Hermann Drewes.

However, there are still opportunities for other SIRG-- stories. I think that Commission X could provide leadership though workshops etc. by actively approaching the potential users rather then waiting for them to tell what they have achieved and sometimes even what they have not achieved. I am confident that Claude Boucher will address this opportunity to provide a further service by Commission X.

The other development which is still continuing and will show more exciting results in future is the field of continuous monitoring networks at all scales. The use of these networks are twofold:

a) deformation studies, and
b) remote sensing of atmospheric parameters.

Let me start with the global network. A recent example of the determination of plate tectonic motions using GPS as a subset of IGS was presented by Reigber and Gendt (1996). A phantastic agreement was shown between the displacement vectors derived by GPS and from the NUVEL model. The NUVEL model results are based on geological and geophysical data covering time scales of millions of years. The excellent agreement of these model results with the short period GPS results is quite amazing. It means that the large scale convection processes in the Earth´s mantle are driving the tectonic plates of the Earth´s crust at a steady rate. GPS results show that these rates agree with very high accuracy even at annual periods if the individual plates are considered as rigid bodies.

On a regional scale, we have seen the establishment of several networks to monitor tectonic deformations, such as a GPS array in Japan comprising of about 1000 GPS stations, or the PGGA in California. Results from these networks have already proven to provide vital information on the tectonic deformations around fault and subduction zones.

Let me mention to you an exciting example of the combination of the results of a GPS permanent array at discrete points with INSAR results, which of course have a continuous surface distribution, Bock and Williams (1997). I believe that both techniques but especially their combination, where applicable, will be a growing and exciting research field with many significant results.

On a local scale, we can observe the establishment of continuous GPS networks to monitor deformation of volcanoes, landslide areas, and built structures such as bridges, towers and dams. The first two applications of GPS positioning have already been recognised as important geodetic contributions to IDNDR. Furthermore, there are other geophysical phenomena which so far are lacking objective information by geodetic measurements, such as “mountain spreading”. What are the real limitations of the applicability of GPS/GLONASS/etc for the study of natural disasters and the possible detection of precursors of these hazards? Definitely an exciting field also for the future.

Now, let us look at the “other face” of GPS continuous arrays, i.e. the remote sensing capability. It did not take very long for the geodetic community to realise the potential of GPS to be used as a remote sensing tool of the Earth´s atmosphere: ionosphere and water vapour. The ionospheric total electron content (TEC) can be measured using the two GPS frequencies due to the dispersive propagation effect. Ionospheric TEC computations are now routine operations using the IGS data, see Beutler et al. (1998).

Since the wet delay of the troposphere is a significant error source in precise positioning it can in-turn be considered a signal in the position results and thus estimated. As a result, the value of the vertical column of water vapour, called precipitable water vapour, can be determined. Water vapour is a highly variable greenhouse gas and a vital parameter driving the weather patterns. An impressive example of remote sensing of the water vapour distribution was shown recently (Naito et al., 1998). The temporal variation of the precipitable water vapour was nearly 6 cm during two days of a weather front moving across Japan.

Propagation effects in occultation situations can be used as a remote sensing tool of ionospheric and tropospheric parameters. This will be a very exciting field for future contributions of geodetic instrumentation and analysis to the research areas of other IUGG Associations.

During the past four years we have experienced tremendous progress or at least an improved understanding in issues such as

- reference frame definitions and their maintenance
- ambiguity resolution
- site effects
- orbit predictions
- GPS/GLONASS combination
- active GPS networks.

However, the potential precision of GPS is still masked by propagation effects, mainly multipathing and diffraction effects as is easily seen by a comparison of zero baseline versus very short baseline GPS results. This problem needs to be solved before we can achieve another improvement in precision of short site occupation results.

I believe that we will continue to see many new applications of satellite positioning. This field will expand mainly through the combination of different sensors into new measurement systems. Sensor fusion will lead to new exciting fields of positioning especially in application of geodesy to engineering, for example the guidance of construction vehicles.

Hopefully, I was able to show, is that we are also seeing a change in our research pattern in Section I. Traditionally, we investigated the market driven needs, mainly specified by national survey organisations. The work concentrated on horizontal and vertical control with all the necessary classical geodesy. Now we move to a new situation where our instrumentation and analysis capabilities open up new opportunities not seen by the “almighty market”. It is our creativity which finds new areas of novel applications of positioning.

Let me close my remarks as outgoing President of Section I by quoting an Austrian saying:

"Not even the future is any more like it used to be."

Acknowledgements:

I would like to thank all geodesists especially, of course, the IAG members for their significant contributions to the discipline of positioning during the past four years. Many thanks!

References:

Brunner F.K. (Ed.) Advances in Positioning and Reference Frames, IAG Scientific Meeting, Rio de Janeiro, Brazil, Springer Verlag (1998), Vol. 118.

Kahmen H., Brückl E. and Wunderlich T. (Eds.) Geodesy for Geotechnical and Structural Engineering, Int. Assoc. of Geodesy, Special Commission 4 (1998).

Reigber C. and Gendt G. Geodätische Messungen der Plattentektonik, Spektrum der Wissenschaften (1996): 115-117.

Bock Y. and Williams S. Integrated Satellite Interferometry in Southern California, EOS, AGU 78 (1997): 293, 299-300.

Beutler G., Rothacher M., Springer T., Kouba J. and Neilan R.E. The International GPS Service (IGS): An interdisciplinary service in support of earth sciences, 32nd COSPAR Scientific Assembly, Nagoya, Japan (1998).

Naito I., Hatanaka Y., Mannoji N., Ichikawa R., Shimada S, Yabuki T., Tsuji H. and Tanaka T. Global Positioning System Project to Improve Japanese Weather, Earthquake Predictions, EOS, AGU 79 (1998): 301, 308, 311.

COMMISSION X

GLOBAL AND REGIONAL GEODETIC NETWORKS (GRGN)

Report for 1995-1999

by **C. Boucher**

The purpose of the IAG Commission X on Global and Regional Geodetic Networks (GRGN) is to focus on the variety of existing control networks (horizontal or vertical, national or continental, global from space techniques) as well as their connections and evolutions.

The Commission X has two types of subdivisions:

(1) Subcommissions for large geographical areas:

Such subcommissions will deal with all types of networks (horizontal, vertical and threedimensional) and all related projects which belong to the geographical area.

(2) Working Groups for specific technical topics

During the 1995-1999 period, three Working groups has been established:

Working Group 1 on Datums and Coordinate Systems

Working Group 2 on the Use of GPS and IGS for ITRF densification

Working Group 3 on the Worldwide Unification of Vertical Datums

Several countries has appointed national representatives:
Belgium C. BRUYNINX
Canada M.R. CRAYMER
China Y. ZHANG
Czech Republic J. KOSTELECKY
Denmark F. MADSEN
Egypt A. SHAKER
France M. LE PAPE
Germany E. REINHART
Hungary J. ADAM
Japan H. TSUJI
New Zealand D. GRANT
Russia O.M. OSTACH
South Africa R.T. WONNACOTT
Spain J.L. CATURLA
Switzerland W. GURTNER
USA W. STRANGE

At the GRGN level a web site was developped and a GRGN mail was established. Most of the activities was done in the frame of the subcommissions and some in the Working groups. The activities are presented hereafter following this structure. A more detailed report with extensive references (bibliography or web pages) is available at: http://lareg.ensg.ign.fr/GRGN/

Report on regional activities

Africa
This area is definitively a priority for GRGN to establish and stimulate related activity. There are already some permanent sites (SLR, VLBI, GPS, DORIS or GLONASS) but a basic frame is deeply needed at centimetric level, replacing the ADOS frame established more than 10 years ago at the meter level. Some discussions already occured about a AFREF network but is is a task for the next period to actually implement it.

Antarctica
A sub commission for Antarctica was established as a formal link of the SCAR activities to the GRGN. This subcommission is co-chaired by John Manning (Australia) and Reinhard Dietrich (Germany). The following summary is extracted from their detailed report available in the GRGN web pages.

International cooperation in Antarctic Geodesy is principally coordinated by the Scientific Committee on Antarctic Research (SCAR) through its Working group on Geodesy and Geographic Information (WG-GGI). Membership consists of representatives of all SCAR Antarctic nations and the WG-GGI has two programs :

Geographic Information

Geodesy

Geodesy is implemented through the Geodetic Infrastructure of Antarctica (GIANT) program. Details of the GIANT work program are available on the WG-GGI web site http://www.scar-ggi.org.au/geodesy/giant.htm. The main geodetic activities in Antarctic in the four-year period 1995-99 were :

Increase in number of permanent GPS sites transmitting data back by satellite and submitting this data to the IGS.

Adoption of ITRF and GRS80 as reference standards

Continued epoch campaigns for geodynamics and to densify the ITRF

Establishment of Absolute gravity stations

Re activation of VLVBI facilities at Syowa

Installation of several new tide gauges

Technological developments in support of continuous GPS tracking at remote sites

In 1995 Germany took over coordination responsibility from Australia for the summer epoch campaigns beginning with the GAP95 survey. Germany has continued to coordinate the ongoing summer epoch campaigns since that time.

Europe

The sub-Commission for Europe was established as a continuation of the former EUREF and UELN/REUN subcommissions of the previous period. The name of EUREF was kept for this new structure which was chaired by Erich Gubler (Switzerland) and Helmut Hornik (Germany) as permanent secretary. The subcommission has annual meetings and a Technical Working Group meets three times per year to run the current activities. EUREF is very active and efficient.

Summary of EUREF activities:

More than ten years ago, the advantages of the GPS technology were recognised and a first GPS campaign covering the western part of Europe was organised in order to establish a uniform European Reference Frame (EUREF). Through successive GPS campaigns, the network has been extended towards eastern parts of Europe and various countries have undertaken densification campaigns. The international co-operation within Europe has resulted in the establishment of a high accuracy, three dimensional geodetic network with links to global and national reference systems.

Strategies and guidelines have been developed for network densification, observation procedures, data flow and data analysis. This has resulted in today's permanent GPS network comprising in excess of more than 75 stations, a data handling service and supported by 12 analysis centers. The results show an accurate and consistent network(+/-3mm in the horizontal component, +/-6mm in the height component).

Since 1995, emphasis has been placed on the height component, resulting in an extended and improved adjustment of the United European Levelling Network (UELN) and the establishment of the European Vertical GPS Reference Network (EUVN). Today, the EUREF Network contributes towards multi-disciplinary activities such as the estimation of meteorological parameters and links to tide gauges.

North America

Discusstions took place mainly between Canada and USA to reactivate a North american subcommission . A main objective is to improve the NAD83 realization and its link to ITRF.

South America

South America was very well covered by the SIRGAS project, for which Hermann Drewes (Germany) acted as liaison to GRGN. See references for further informations.

It is anticipated that future SIRGAS activities will be formally reported as subcommission activities.

South East Asia and Pacific

This is a report to Commission X on Geodetic activities in the Asia Pacific from the Sub Commission on SE Asia which was reformed in 1998 with John Manning (Australia) and Junyong Chen (China) as co-chairs.

International cooperation in Geodesy at the national level is coordinated through the Regional Geodetic Networks Working Group of the Permanent Committee for GIS Infrastructure in the Asia Pacific (PCGIAP)

As the objectives of Commission X are close to the aims of the Regional Geodetic Networks Working Group it was sensible to reform the sub commission from Working Group representatives.

Background

The Permanent Committee on GIS Infrastructure for Asia and the Pacific (PCGIAP) was established by the United Nations Regional Cartographic Conference for Asia and the Pacific (UNRCC-AP) at its triennial meeting in Beijing, May 1994. PCGIAP operates under, and reports to, the UNRCC-AP.

There are 55 member nations of the PCGIAP as defined by the United Nations. The countries span a wide part of the globe from Iran and Armenia in the west to French Polynesia in the east; from the Russian Federation and Japan in the north to New Zealand and Australia in the south.

Membership of PCGIAP comprises directorates of national survey and mapping organisations and equivalent national agencies of the nations from Asia and the Pacific. Each nation nominates a single representative but may invite experts as advisers.

The aims of the PCGIAP are to:

Maximise the economic, social and environmental benefits of geographic information in accordance with Agenda 21 by providing a forum for the 55 members nations from the Asia and the Pacific region to cooperate in the development of the Asia-Pacific Spatial Data Infrastructure (APSDI) and contribute to the development of the global infrastructure.

Two of the key PCGIAP objectives are to :

Design a strategy for the development of a regional geodetic framework and topographic data bases as the basis for regional GIS activity.

Determine the need for research, training and technology exchange in relation to the beneficial impact of geographic information on the social, economic and environmental objectives of member nations of Asia and the Pacific region.

The Role of the Regional Geodetic Network Working Group

The primary role of the PCGIAP working group is to facilitate a single regional datum through a linkage of compatible geodetic datums. This is fundamental to the development of an Asia Pacific Spatial Data Infrastructure (APSDI) which requires that:

A reference regional datum be established, and

Transformation values be determined between the regional datum and the local geodetic datums of the individual countries.

These then permit a homogeneous spatial data set to be readily assembled from national spatial data sets based on local datums.

Working Group activities 96-99

At the inaugural meeting of the Working Group in 1996 in Sydney a number of project responsibilities were identified and a program of regional geodetic activities endorsed. The initial activity of the Geodesy Working Group was to establish a precise regional geodetic network as a high-level reference framework.

Another area of activity identified was the investigation of techniques, which can be used to transform national spatial data into a single spatial data set in the region.

An additional role for the Working Group has been to gather information on geodetic datums used within the region. Australia has listed best known information on existing geodetic datums for all countries in the UN Asia Pacific Cartographic region on the PCGIAP Web site. http://www.percom.apgis.gov.au www.percom.apgis.gov.au a feedback mechanism has been established on the Web page to amend any incorrect, or out of date, entries.

Asia Pacific Regional Geodetic Network (APRGP 97).

One of the core projects in the region has been the establishment of a Regional Geodetic Network with a geographical spread covering the Asia and the Pacific Region, from Central Asia to the Western Pacific.

In October 1997 an Asia Pacific Regional Geodetic Project (APRGP97) campaign observed to establish an overarching geodetic frame work for the integration of national geodetic datums in the region. In the ARGP97campaign both the Radio Techniques (GPS, DORIS,), and space techniques (SLR, VLBI) were employed. The data acquired by participating countries during this campaign was assembled in Australia, which distributed the data for immediate use by Asia Pacific member countries.

A results workshop was subsequently hosted by AUSLIG in Canberra 2-4 July1998. Representatives from ten member countries of the PCGIAP attended the workshop, presenting and analysing results from the 1997 campaign, thus concluding the core component of the project. leading to the finalisation of a set of results. (AUSLIG 1998 ,papers available through PCGIAP web site) The observational data set was then made available to regional scientific researchers.

GPS Results from APRGP97

Four members presented independent results from processing the APRGP97 GPS data set:
Indonesia, Japan; China, Australia

The first three countries used GAMIT to process the data set utilising the final IGS orbit product. Solutions were then generated using GLOBK producing SINEX files as outputs. Australia computed precise global orbits in the Regional GPS solution process using MicroCosm and generated a campaign solution using the SOLVE program. The results presented showed good agreement and demonstrated a significant achievement in technology for those involved. It was noted that Malaysia and Iran are also close to also establishing high precision GPS processing capability in their analysis centres whilst smaller countries such as Vietnam and PNG were working with receiver manufacturers proprietary software such as PRISM.

The workshop examined the options for definition of a regional geodetic datum in a global setting and recommended an interim ITRF product based on a combined GPS solution, pending further work on an integrated solution of all techniques utilising ground ties at collocated sites.The APRGP97 campaign produced significant results, but also has achieved a degree of technology transfer for participating members in the development of a regional capability for high level processing of GPS data.

Further the workshop considered the need for a strategy to link individual vertical datums, such as
Land locked countries
isolated island
chart datums,
as well as scientific sea level determinations.

It recommended the concept of a unified vertical datum using data stored in earth centred Cartesian coordinates or related to the GRS80 ellipsoid in the ITRF system.

Plans were developed for the implementation of an expanded observational campaign in November 1998 (APRGP98). cooperative strategy was developed with the GEODYSSEA project for a common observational campaign and sharing of data from key sites.

A second APRGP field campaign was subsequently held in November 1998 (ARGP98) at the same time as the Geodyssea98 campaign. There was greater participation in this campaign compared to APRG97 but there are still significant areas to be infilled when countries gain access to GPS resources. Seventeen nations were able to participate and GPS observations from some 87 sites in addition to the existing IGS sites were achieved. The GPS data (except from four sites in India) was collated by AUSLIG and distributed on CD ROMs to all countries for processing, analysis and presentation of results. A VLBI campaign was again arranged by China (Shanghai Observatory) through APSG cooperation and SLR (through WPLTN) with DORIS observations also made at that time.

The ARGP98 results computed by individual countries will be analysed with view to a combined solution at the Regional Geodetic at a results Workshop hosted by Vietnam in 12-14th July 1999.

Future Activities.

For the Regional Geodetic Network to best contribute to the Regional Spatial Data Infrastructure and furthermore to the Global Spatial Data Infrastructure through a regional densification of , a lot of work still needs to be done. By taking into account the existence of various international scientific effort in establishing a Global Geodetic Network, such as those by IAG, IGS/ITRF, DORIS, PRARE, GEODYSSEA and Asia Pacific Space Geodynamic Program (APSG),

The aim for the establishment of a Regional Geodetic Network is to provide a common datum for all nations in the Asia Pacific region and to densify ITRF. To be able to provide data to a homogeneous spatial data base individual countries whose datum is not in ITRF and on GRS80 need to be able to transform from their individual datum. To develop these transformations the individual datums need to be well defined and have sufficient common stations in both individual and regional systems to determine datum transformations.

A new cooperation strategy will be required to promote a strong cooperation in setting camapign linkages and data sharing across the region. In addition the issue of regional sea level connections to a universal vertical datum and a related regional geoid must also be addressed. Enhanced linkags need to be formed between national Geodetic bodies represented by the PCGIAP and scientific bodies such as represented By APSG together with individual scientific researchers funded from outside the region.

Since the individual datums within the Asia and Pacific Region differ from country to country, some country might need assistance to perform the datum transformation. This assistance ranges from GPS equipment, survey expertise, datum definition to the definition of datum transformation parameters.

Report of Commission X Working groups

Working Group 1 on Datums and Coordinate Systems

The purpose of this group is to:

- establish standards and terminology about datums and coordinate systems (a preliminary work has been done in Europe and circulated in the EUREF subcommission)
- participate to the ISO TC 211 group on geographical information
- establish a catalogue of datum and coordinate systems existing over the World

There was no significant activities in this group besides the work done in the frame of standardization of geographical information in Europe (CEN TC273) and internationally (ISO TC211). See the GRGN web report for more details.

Working Group 2 on the Use of GPS and IGS for ITRF densification

This group should establish specifications to process properly GPS campaigns using IGS products and to be if wished included rigourously into the densification of the ITRF/IGS network as a so called IGS regional network. Unfortunately no activity was explicitely done in this structure. It is therefore needed to reconsider this issue with a new charter.

Working Group 3 on the Worldwide Unification of Vertical Datums

Chairman: H. W. KEARSLEY (Australia)

The Goal:

To investigate the possible actions to be undertaken to realize a global vertical datum, and to determine its connection to various existing vertical datums.

Significance:

To bring the many height-related data sets around the globe onto the one common reference surface - the global geoid;

To enable the scientific study of departures of the regional vertical datums (both inter-regional and intra-regional) from the global geoid;

To ensure all height-related data, and results derived therefrom, relate to the global geoid. For example, to ensure that gravity reductions or terrain effects for global geopotential models based upon national height datums relate to the common global geoid.

To assist the study of distortions in the National Height Datums, and the study of oceanographic phenomena (SST) at tide gauges.

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Meetings

1 IAG, Rio (Sept, 1997)

After an informal meeting of the Working Group in IAG, Rio, the following email was circulated:

ìThose of you who I originally circulated will remember my proposal to adopt a system for this purpose (for those not on the original circulation list, I have included this original proposal at the end of this email.) I was told that it was NOT possible to propose any resolution such as the one below at the IAG meeting in Rio. In any case, at the informal meeting of some members of the working group, it was felt to do this would be premature. Instead, it was proposed that

(i) (say) four study groups be set up to carry out research into the operational and theoretical aspects of vertical datum connections,

(ii) using selected regions for pilot studies. Such regions would include those which already had extensive experience in datum unification,

eg EUVN for Europe, NAVD for Nth America; and those areas where there were or are to be extensive regional high-precision GPS campaigns (eg SIRGAS - Sth America, and the Asia-Pacific Space Geodynamics Project (APSG - Pacific and SE Asia; or its subset GEODYSSEA)),

(iii) that the results be presented in 2 years at the IUGG in the Birmingham, UK meeting, commenting on such matters as

(a) preferred height systems

(b) preferred geometric reference

(c) preferred tide model, and

(d) preferred geopotential model.

This can be used as the basis for a resolution at IUGG which proposes the method to be used in the unification of the vertical datums.

Comments:

(i) A meeting of the Regional Geodetic Network Working Group was held between the dates of 2-4 July 1998 in Canberra Australia, hosted by AUSLIG. A this meeting a number of important objectives and strategies directly related to the vertical datum unification were devised; see

http://www.gmat.unsw.edu.au/final_year_thesis/p_epstein/campag.htm

(ii) Unfortunately there is no special session specifically set aside at IUGG 1999 for the discussion of the matters above.. However, a number of papers touching on these matters are being presented at session G6.

2. IERS Workshop, Paris, 14 ñ18 October, 1996
A meeting entitled ìVertical Referencesî, and chaired by C. Boucher and W. E. Carter, produced a very useful report canvassing various theoretical and practical impediments to the realization of a unified vertical datum. It also made four recommendations specifically dealing with this problem, addressing both housekeeping and operational matters to overcome these difficulties (IERS 1997, Technical Note No 22).

World Wide Web Page
A summary of recent developments, the problems of unification, recent papers, and links to other relevant scientific groups and campaigns (eg EUVN, NAVD) is now available at

http://www.gmat.unsw.edu.au/final_year_thesis/p_epstein/main.htm .

Conclusions and recommendations
We can conclude that the topic of the GRGN commission has shown during the last quadriennium a tremendous development of activities, in particular on the generalized use of GPS and the rapid unification of reference systems through the use of ITRF. We should hope a vivid continuation of this trend.
Therefore GRGN should play mainly a role of stimulation and coordination by helping the dissemination of information, standardization, cooperation and education.
To be some more specific for the next quadriennium, we can give the following goals:

1) to expand the present GRGN web site in order to give a proper source of information of relevant activities, including subcommissions and working groups, but also related activities at national or international level, such as survey agencies, international programs or projects, services such as IGS, IERS or others. This site should also provide informations on standards and terminology, catalogue of datums and cartographic coordinate systems

2) to expand the list of national representatives and involve them more in the Commission activities (for instance updates of the web system)

3) to stimulate new subcommissions (South America or North America seem good candidates)

4) to update the list and charters of the Working Groups

5) to stimulate the development of a modern frame for Africa (AFREF)

6) to stimulate the organization of training school related to the GRGN field (modern networks, ITRF, GPS,..)

7) to promote ITRF as international frame and realize its densification for all type of uses, help to remove misunderstandings wrt WGS84, and promote ITRF for the new global navigation satellite systems., such as the european Galileo program

Special Commission IV

APPLICATIONS OF GEODESY TO ENGINEERING

Report for the period 1995 - 1999

by Heribert Kahmen
University of Technology, Vienna

Contents

1. Objectives of SC4

Rapid developments in engineering, microelectronics and computersciences have greatly changed both instrumentation and methodology in engineering geodesy. The objectives of Special Commission 4 are on the one hand, to document the body of knowledge in this field and on the other hand, to encourage new developments and present them in a consistent framework. To accomplish the first objective, an International Symposium and a series of Workshops were organized to document the current state of development in engineering applications of geodesy. The second objective was accomplished by five Working Groups which were established in areas of current research interest.

2. Activities in 1995 - 1999

To promote the activities of the Working Groups and to provide a platform for international scientific discussions, IAG founded SC4 organized an International Symposium "Geodesy for Geotechnical and Structural Engineering" in Eisenstadt (Austria) 1998. This Symposium was one in a row of the activities of SC4. The topic of the Congress truly reflects the broadening concern of the engineering geodesy community for matters that go partly beyond the technical demands of the profession. An extraction of the contributions of the Plenary and Special Sessions proves that:

- Geotechnical Exploration Strategies
- Machine Guidance
- Mobile Multi-Sensor Systems
- Local Geodynamic Processes
- Building Structures as Kinematic Systems
- Traffic Guidance Control
- Geometrical Investigation of Spatial Geodetic Problems
- Technical Networks of Large Construction Sites

The programme included Sessions with topics that were of current interest for practitioners and scientists. The Symposium was co-sponsered by IAG Section I, FIG-Commission 5 & 6, the Federal Board of Architects and Engineers, and the Austrian Society of Surveying and Geoinformation. More than 160 participants from 22 different countries attended the meetings.

The proceedings of the Symposium have been published by the Institute for Geodesy and Geophysics, Gusshausstrasse 27 - 29, A-1040 Vienna.

In addition a row of Workshops was organized by the Working Groups. Informations about those meetings are given in the reports of the Working Groups.

3. The Working Groups

Five Working Groups were regarded to be challenging and rewarding:

WG1: Mobile Multi-Sensor Systems
WG2: Building Structures as Kinematic Systems
WG3: Geodetic Reference Systems for Traffic Guidance Control
WG4: Geometrical Investigations of Spatial Geodetic Problems
WG5: Geotechnical Exploration Strategy

The Working Groups met during the Symposium in Eisenstadt and during especially organized workshops. The Working Groups WG1, WG2, WG3 and WG5 should continue their work during the period 1999 - 2003, as there will be many interesting new developments in their fields of acitivity. On the other hand a new Working Group "Geodesy on large Construction Sites" should be established.

The full reports of the Working Groups can be found on the IAG webpage.

4. Acknowledgement

A great part of the reported research work was performed by the chairman and the member of the Working Groups. I would like to thank them for their contributions and cooperation.

SC4 was strongly related to other international Commissions in related fields:

- FIG Commission 5
- FIG Commission 6.

Thanks to the Commission Presidents Jean-Marie Becker (Sweden) and Michael Mayoud (France).

INTERNATIONAL ASSOCIATION OF GEODESY SSG 1.154

QUALITY ISSUES IN REAL-TIME GPS POSITIONING

by
Chairman: Chris Rizos

IUGG Congress, Birmingham U.K.
18-29 July 1999

1. INTRODUCTION

At the 1995 IUGG congress in Boulder, Colorado, USA, the IAG established several Special Study Groups (SSG). One was to deal with what was perceived as the critical issue with regards to precise static and kinematic positioning, that is, the "quality" of the observations and, by extension, that of the coordinate results as well. In order to narrow down such a broad topic area it was decided to focus on "real-time GPS positioning". In the course of the life of SSG 1.154, several other decisions were made in order to set a more realistic research and scholarship agenda. In this report the basic issues are discussed, and the outcomes and achievements of the SSG are noted. Finally, the quality control *technical* issues for kinematic GPS positioning are again raised within the context of an overall scheme that includes the rover (user) GPS receiver and base station (reference) receiver, the data link between the two, as well as the data processing for high precision carrier phase-based positioning.

1.1 Terms of Reference

Concerns about GPS positioning quality are shared by all users, from those engaged in the most precise geodetic applications through to the casual navigator. The quality of GPS positioning, however, is dependent on a number of factors. Experience with precise geodetic applications of GPS has shown that sophisticated mathematical modelling, careful field procedures and top-of-the-line GPS hardware are all necessary prerequisites. Nevertheless great care still has to be applied to ensure that data quality is uniformly high. The procedure of data screening, position computations, result evaluation and quality assurance has generally been an off-line (as well as iterative) process. With the development of precise "on-the-fly" (OTF) GPS positioning techniques it is no longer possible to process (and re-process) GPS data in post-mission mode until the positioning quality is assured. The challenge therefore is to develop quality control and quality assurance procedures that can be applied in "real-time" (or "near-real-time") GPS positioning.

The work of the SSG 1.154 on "Quality Issues in Real-Time GPS Positioning" will focus on identifying practical procedures, as well as mathematical techniques, that can be applied to assure the quality of positioning results obtained from this distinct class of GPS applications. The objectives of the SSG therefore were identified as being:

(a) IDENTIFY the main issues impacting on the "quality" of real-time GPS positioning -- *including those due to instrumental effects, environmental sources, site-dependent effects, communcations-dependent, etc.*

(b) COMPILE a set of procedures, algorithms and guidelines that can be implemented within real-time GPS positioning software -- *this is the practical outcome*.

(c) DEFINE areas for further research and development -- *as derived from both practical experience, and a study of the literature and research trends in the development of mathematical and/or empirical tools for "quality control"*.

In hindsight it would appear that this was a very ambitious set of objectives for the SSG. In this report, in subsequent sections, this theme of noble and wide-ranging objectives not being matched by outcomes will be raised again and again.

1.2 Tasks to be Undertaken

The abovementioned objectives were translated into a series of tasks:

1) Compile and document the QC procedures and algorithms as implemented in scientific GPS geodesy software.
2) Investigate which of these procedures are adaptable for "real-time" operation -- *for example, for the detection of faulty navigation messages, data spikes, etc.*

3) Compile a bibliography of D-I-A literature specifically applicable to precise real-time kinematic GPS positioning.
4) Research fault detection algorithms for real-time GPS applications.
5) Encourage discussion and critical evaluation of such algorithms.
6) Monitor the activity taking place in the development of quality control (QC) and quality assurance (QA) for standard pseudo-range based DGPS.
7) Determine the appropriate "mix" of QC/QA procedures that can be recommended for real-time precise GPS positioning -- *as it is was felt that a "cocktail" of procedures will be necessary to give greatest assurance on quality*.
8) Prepare a report on the SSG's activities and recommendations.

1.3 SSG Membership

As of June 1999, the SSG membership was (see §A.1):

C. Rizos	(Australia) President
H. Abidin	(Indonesia)
J. Behr	(USA)
E. Cannon	(Canada)
P. Collins	(Canada)
R. Galas	(Germany)
S. Han	(Australia)
Y. Hatanaka	(Japan)
X. Jin	(Switzerland)
H. Kutterer	(Germany)
Y. Li	(Canada)
S. Mertikas	(Greece)
P. Morgan	(Australia)
S. Oszczak	(Poland)
W. Roberts	(United Kingdom)
G. Seeber	(Germany)
M. Stewart	(Australia)
L. Wanninger	(Germany)

Was the composition of the membership ideal to undertake this task? It could be argued that voluntary membership of an IAG SSG will never bring together the most appropriate expertise and interests. It is one of the roles of the Chairman of the SSG to select (or recruit) the membership according to criteria that ensure the "best" people are coopted. If the focus of the SSG were narrower, then the membership could "select itself", by simply inviting the handful of "experts" and "active researchers" to the SSG. It would then be expected that this mix of theoreticians and experimeters (or "number crunchers") would generate the environment in which active discourse and detailed studies could be promoted. (With email contact, certainly the geographic separation of the SSG members could no longer be held to be a constraint on scholarly activity.) In reality, the selection of members was not a careful and scientific process.

The membership list contains mostly academics, graduate students and government employees. Yet the only real-time, carrier phase-based GPS positioning systems are commercial products. The small number (just two) of members drawn from private industry could be construed as a glaring shortcoming. However, it is debatable whether scientists employed by GPS manufacturers would be able to freely contribute their expertise and knowledge to the SSG. Another group that, in hindsight, is underrepresented (again by just two members) are staff from the geodetic departments that deal, on an everyday basis, with the processing of data from permanent GPS networks such as SCIGN (USA) and GEONET (Japan). Although they would not be dealing with "real-time" processing, the issue of "quality control" would certainly be addressed on an institutional basis.

1.4 Comments to the SSG Research Agenda

Before dealing with explicit outcomes, it is appropriate to make some comments on the rationale behind the SSG's original research agenda, and to comment on its shortcomings:

1) At the time of the establishment of the SSG the Chairman had suggested the following characteristics that distinguish those real-time positioning techniques that would be the focus of study from those that would not:

- the communication of data from GPS receivers to a computing site where it is processed with no, or minimum, delay[1],
- make use of carrier phase data[2],
- rely on data processing on an epoch-by-epoch basis, or at the very least small "batches" of GPS data[3],
- do not permit extensive data "pre-processing" or the review of data and results in iterative procedures[4], and
- may involve kinematic or static[5] positioning.

2) One of the first tasks of the SSG (§1.2) was to **compile and document the QC procedures and algorithms as implemented in scientific GPS geodesy software**. It was reasoned that because this type of data processing is at the most sophisticated level, it would be expected that they would be the most highly developed. The comment was made that it was likely that these procedures were largely "empirical" and based on extensive experience gained working with GPS data, and that they were unlikely to be documented in the available literature. Members of the SSG did have experience with a range of scientific GPS geodesy softwre packages. After several prompts, some members did come forth and volunteered their knowledge of QC procedures, and it was clear that these were indeed in the category of empirical "rules-of-thumb" and were not founded on a well developed mathematical basis. *What correspondence the Chairman did receive was compiled into email SSG memos for the benefit of the other SSG members, and can be inspected by all through a visit to the SSG's website (§2.2). Given that several IGS Processing Centres now have many years of experience in the automatic processing of large volumes of GPS data on a daily basis, it is disappointing that the QC procedures are not well defined or documented*.

3) The next step was intended to be the **investigation into which of these procedures are adaptable for "real-time" operation.** This would "bridge" the pragmatic procedures based on such criteria as size and distribution of "data gaps", signal-to-noise ratio values, faulty navigation messages, data spans for which both L1 and L2 data were available, ionospheric activity (as indicated by L1/L2 combinations), etc., with the highly developed "fault detection" algorithms associated with digital signal processing in general, and the D-I-A procedures implemented in navigation software. This would be at the "heart" of the SSG's activities. Unfortunately very few members had the requisite background in signal processing, reliability theory, D-I-A algorithms and statistical testing to make contributions. Several members did indeed make significant contributions, and the Chairman acknowledges their contribution (§2.1). One of the important outcomes of the SSG was to be the **compilation of a bibliography of D-I-A[6] literature specifically applicable to kinematic GPS applications**. One member of the SSG did compile a list of general references to fundamental literature on "fault detection", statistical testing, and the like (see §2.3 and §A.2). *However, the Chairman was remiss in not updating this list with literature that specifically dealt with its application to kinematic GPS positioning*.

4) It was recognised from the start by the Chairman that the current "best practice" was that applicable to pseudo-range-based differential GPS (DGPS). The first real-time applications addressed by GPS were those for differential positioning using transmitted pseudo-range corrections (generated by a stationary reference receiver located on a known site)[7]. The SSG was fortunate that one member was closely involved in the development of QC practices for DGPS for the offshore industry. It was reasonable to

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[1] For some applications, communication of data is from "rover" receiver to "reference" receiver (the tracking applications) , yet other applications imply transmission of data from "reference" receiver to "rover" receiver (autonomous positioning applications). It is assumed that communication is by electronic means, and that the computing site is located adjacent to one of the GPS receivers.

[2] Does not preclude the use of pseudo-range or Doppler data, but must be supplemental to the processing of carrier phase data.

[3] For some applications communication of data is on a continuous basis, and data processing can proceed on an epoch-by-epoch basis. Other applications are addressed by processing a data series that have been transmitted to the computer site on an episodic basis.

[4] This constraint is necessary in order to preclude the use of techniques that rely on extensive screening of long series of residuals, "backward-forward" type processing, or the use of superior post-processed orbits, ionosphere and clock models obtained from external sources; as it is felt that these cannot be applied in real-time.

[5] Real-time static applications? By this is meant the increasing interest in permanent GPS arrays deployed to monitor the stability of volcanoes or engineering structures such as dams. The receivers in the array are assumed to transmit the data (on a continuous or episodic basis) to a computing site where it is processed with minimum delay.

[6] Detect an error, Identify its source, and Adapt the system to overcome the bias effect.

[7] These will be referred to by the shorthand acronym "DGPS".

conclude that the SSG could learn from that experience, and in many respects to emulate the process, but in relation to carrier phase-based positioning. Emails were exchanged between SSG members, and the relevant correspondence was summarised and place on the SSG's website (§2.2). The following comments were made at the time (and are still valid today):

- While not within the direct interest of this SSG, "quality control" for real-time DGPS is a useful starting point because of the extensive activity in this area over the last few years[8].
- A recent study of "quality measures" for DGPS has identified many factors impacting on quality that cannot be overcome by mere recourse to new mathematical algorithms. "Quality" is something that must be viewed as being somehow a holistic concept that requires "quality management" to be at its core. Hence attention must also be paid to many other non-mathematical issues such as equipment quality (certification? cabling and antenna quality), communications reliability and integrity, site-specific disturbing effects, hardware/software calibration procedures and maintenance schedules, and even operator training.
- A *holistic* study of GPS quality is likely to be well beyond the expertise of this SSG. However, the partitioning of error sources into distinct categories, permitting a "targetted" effort to address each error sources using appropriate tools, should be attempted. Hence recommendations on improving real-time GPS positioning quality are likely to include the definition of a "cocktail" of tools, some with the rigorous mathematical basis (e.g. "data-snooping" techniques), while others may be essentially derived from empirical analysis.

5) From the very beginning the SSG Chairman held the view that **a "mix" of Quality Control and Quality Assurance procedures would be needed for real-time precise GPS positioning.** However, unfortunately one of the outcomes of the SSG's work is a rather incomplete list of QC issues that need to be addressed if fast, reliable, real-time, centimetre accuracy GPS positioning results are to be assured close to 100% of the time (§3). It became obvious with time that the expertise of most SSG members was in improving the efficiency and reliability of "on-the-fly" (OTF) ambiguity resolution (AR), a critical step in making high precision kinematic GPS positioning. *Hence the technical issues associated with OTF-AR became the focus as these were "quality control" issues in the classic mathematical/statistical sense.* However, the *holistic* QC approach had to be shelved.

1.5 Administrative Issues

At the time the SSG was established the Chairman had some thoughts on how the SSG could function. It is worth mentioning them here, and to indicate how some of the reasons for the SSG not fulfilling its ambitious agenda can be traced to a failure to provide the appropriate leadership at crucial times.

In an ideal world a SSG consists of a small group of dedicated researchers, drawn together by their interest in, expertise of and everyday involvement with the topic under study. Once the Chairman defines the scope of the topic and deals with the procedural matters concerning membership, etc., the SSG would then provide a forum for the exchange of ideas and the reporting of the results of new investigations. The members would be able to collectively push forward the frontier of knowledge, and the Chairman's role would be to report progress to the wider IAG community.

In reality the members of the SSG come from different backgrounds, and have varying levels of interest, experise and involvement in the topic area. A small core may be identified as being particularly active, but the others may only contribute occasionally, if at all. The core participants may communicate regularly (particularly by email), and often without involving the Chairman. Although it could be reported that "progress was made", it would be difficult to disprove the claim that such progress would have been made even without the formation of the SSG. **So what can an SSG realistically accomplish?**

- The appointment of an SSG in an area sends a "signal" that the IAG recognises the importance of this area of work.
- The SSG can focus light on the disparate activities that may be taking place and organise specialised session at conferences where the work of investigators can be presented to the wider geodetic community.

[8] Significant work has been done in this respect under the auspices of the UK Offshore Operators Association (UKOOA). An introduction to the basic statistical techniques for defining and monitoring "quality measures" can be found in the article "Quality Measures for Differential GPS Positioning", by P.A. Cross, D.J. Hawksbee & R. Nicolai, The Hydrographic Journal, 72, 17-21. A comprehensive report prepared under contract to the UKOOA is also available. These recommendations are likely to be adopted by agencies and organisations outside the UK as well.

- The SSG may initially introduce an investigator in one country to colleagues in other countries who are undertaking similar activities (less likely these days given the volume of published literature and the ubiquitous use of the Internet).
- The SSG report can be a valuable resource for system developers who wish to implement the recommendations concerning algorithms and procedures, or for investigators to continue the research work.
- For those within the SSG, there is the possibility of obtaining direct access to up-to-date reports and results (only if the SSG contains active researchers in the area of interest).

Clearly how well the SSG functions (the SSG could be deemed satisfactory if at least some of these functions are fulfilled) is very much dependent on the efforts and talents of the Chairman and individual members of the SSG.
So what can an SSG NOT do?

- It cannot commission studies in the conventional, prescriptive sense (afterall, the members are volunteers).
- It cannot function as an "advisory board", dispensing advice and "remedies" to individuals or organisations.
- It cannot force the SSG members to collaborate when they chose not to, or for various reasons are unable to.
- It cannot insist that SSG members divulge sensitive information and data to other members before the normal processes of publication or patent submission.
- It cannot force SSG members to attend conferences and meetings.

The Chairman's task is in many ways a thankless one. For many SSGs, no matter how well meaning and idealistic everyone is in the first months after the formation of an SSG, enthusiasm often wanes alarmingly. If this is not checked, then by the end of the four year life of the SSG the only person contributing is the Chairman, and his contribution is an insipid report to the IAG. He (or she) may have grown disillusioned as his/her repeated exhortions to SSG members to contribute literature, recommendations or even opinions for inclusion in the final report are largely ignored. How does one guard against this? One suggestion is to keep the work of the SSG "focussed" on a single well-defined issue. How does one define a "focussed" topic for the SSG? Already, even a cursory study of the "quality issues in real-time GPS positioning" would raise an alarm. A suggestion may be to:

- Pepare a report that reflects the diversity of the topic "quality issues in real-time GPS positioning".
- Report on specific algorithms or procedural developments that are practical and immediately useful.

The first requires that the Chairman take a lead, and that members of the SSG contribute: (a) ideas and advice on the structure and content of the report, and (b) bibliographical lists. At this level the report can be viewed as a well researched "plan-of-action". In the context of this SSG, even if it just contains a clear definition of terminologies, a comprehensive catalogue of error sources, a summary of mathematical techniques (with their assumptions clearly stated), quality guidelines of a "non-mathematical" nature, supported by a comprehensive bibliography, then one would be satisfied that the SSG had succeeded in fulfilling one of its objectives.

The second is the more traditional function of an SSG, i.e. the reporting of work of the members of the SSG as well as of others known to the members. This is done through conference presentations, SSG internal discussion channels, and remaining alert to developments appearing in the literature. However, preference must be given to practical developments, i.e. those that can be tested, implemented and used unambiguously by others beyond the SSG.

The members of the SSG are drawn from many backgrounds, and from as wide a geographic spread as possible. What this SSG does not have in significant numbers are members from the GPS industry who are responsible for the development current real-time kinematic systems. It could be argued that our SSG (in fact the IAG) suffers by not having such members. While the SSG Chairman can picture himself/herself as an orchestra"conductor", the SSG members cannot be considered to be at his/her "beck and call". The SSG members could be expected to contribute in the following manner:

- Thoughts, suggestions and advice (both solicited and unsolicited) on the topic of QC and QA.
- Submitting to the Chairman, and other SSG members, copies of relevant reports and publications that they have prepared.
- Drawing attention to the SSG relevant articles or research activity that they may have become aware of.
- Participating in sessions at conferences that this SSG may chose to organise.
- Respond to specific requests by the Chairman.

Even a cursory glance at the above comments, and a study of the outcomes and achievements in the next section, would indicate that this SSG has failed to achieve the (admittedly unrealistic) objectives that it set itself. *It could* *be argued that this failure is partly due to the SSG Chairman not completing the tasks that he set himself, as well as a membership that does not have sufficient experience in developing real-time positioning systems.*

2. OUTCOMES AND ACHIEVEMENTS

2.1 Communications

Communications is what makes possible the SSG's activities. The Chairman has periodically written memos that have been sent to members by email. These have also been placed on the SSG's web site (§2.2). While this communication is necessary the more "productive" communications is between SSG members (to which the Chairman cannot comment on) and feedback from individual SSG members to the Chairman. There are members who have corresponded with the Chairman, and who have contributed to discussions, and there are members who have played almost no part in the SSG communications. Only 6 memos were written by the Chairman, however many more emails were sent to individual members asking for their comments and advice. Some correspondence was also had with non-members. *The last Chairman's memo was written in early 1998.*

The following is a summary of the correspondences:

- M. Stewart & J. Wang -- papers and draft documents on "empirical" QC procedures, mathematical techniques for GPS+Glonass AR and validation procedures, modification of stochastic models, system modelling in Kalman filters.
- W. Roberts -- definition of "quality", UKOOA QC guidelines, shortcomings of DGPS QC, stochastic modelling, statistical testing, ideas for carrier phase-based procedures.
- Y. Hatanaka -- orbit issues, broadcast vs IGS precise ephemerides, scientific softwre data screening procedures.
- L. Wanninger -- ionospheric disturbances, mitigation of biases using multiple reference station techniques.
- S. Mertikas -- definition of "quality", development of fault detection algorithms, quality "measures", co-authored several papers with Chairman.
- H. Kutterer -- terms of reference of the SSG, QC procedures within the Bernese scientific GPS software, experiences with RTK with the Trimble receiver, GPS signals through forest foliage.
- S. Han, L.S. Lin -- ambiguity resolution and QC & validation procedures, strategies for mitigating residual biases for short, medium and long-range GPS positioning, multipath, ionospheric studies, data communication latency issues.
- F.K. Brunner -- literature related to data quality and modelling.

2.2 Web Site

One of the most important outcomes was the establishment of a web site by the Chairman. The URL is: www.gmat.unsw.edu.au/ssg_RTQC. The site contains the terms of reference, the text of the Chairman's memos, membership details, as well as email messages received from members that might be of interest to the general community. The SSG bibliography is a HTML document on the web site. This report can be downloaded as a PDF file from the web site.

2.3 Bibliography

Development of a bibliography of relevant literature was identified as an important objective of the SSG. One member, S. Metikas, compiled a bibliography of general references to statistical testing, quality control, fault detection, etc., that forms a valuable resource. However, the compilation of a similarly detailed bibliography focussing on the literature dealing with the techniques of carrier phase-based, kinematic GPS positioning has not been carried out. This remains, in the Chairman's opinion, one of the greatest failings of the SSG.

2.4 Miscellaneous

As stated elsewhere, the objectives of the SSG were ambitious. By attempting to go for the all-encompassing approach of "quality control", more achievable (though perhaps minor) objectives could not be systematically addressed. Yet it is conceded by most investigators that "quality control" is an ever more important issue as high precision GPS kinematic strives to do "more with less". That is, less data to achieve similar levels of performance (measured in terms of accuracy and reliability). Hence the traditional fields of investigation of on-the-fly (OTF) ambiguity resolution (AR) have in fact contributed more to QC studies than would have been expected. The literature on "QC issues for real-time kinematic positioning" is dominated by papers dealing with OTF-AR techniques, and in particular the validation procedures that must guard against wrong AR. These validation procedures have forced a closer study of "data quality" in general. Hence, QC not only deals with the results, but also identifying the conditions at the data capture stage that assure "good quality data". Unfortunately no objectives "quality measures" have been defined for "data quality", although some, such as signal-to-noise ratios, have been proposed.

Site specific influences on data quality are important, particularly the multipath disturbance. However, other SSGs in fact deal with topics that overlap the terms of reference of this SSG (e.g. SSG 1.156 Advanced GPS Analysis for Precise Positioning, SSG 1.157 GPS Ambiguity Resolution and Validation, SSG 1.1.58 GPS Antenna and Site Effects). In the opinion of the Chairman, the "blueprint" for a quality "audit" is the UKOOA study on QC guidelines for DGPS in the offshore industry.

Finally, although big strides have been made in improving AR and validation, there is little experience of real-time implementation of QC procedures. In the Chairman's opinion this is a serious failing of the SSG. No member had intimate knowledge of how to establish, "from the ground up", a real-time, kinematic GPS positioning system. Hence the work that can be acknowledged is piecemeal and generally relates to QC for OTF-AR at the data processing level. What is ignored are the various components and algorithms for signal tracking (including signal processing within the GPS receiver), site location and its influence on data quality, data link issues, base (or static reference) receiver issues. In order to go someway towards redressing this failing, the Chairman has described the issues that had to be addressed in the development of two real-time or "near"-real-time systems capable of supporting carrier phase-based, kinematic GPS positioning.

3. QC ISSUES IDENTIFIED AS BEING CRUCIAL FOR FURTHER STUDY

Real-time, carrier phase-based GPS positioning techniques are now increasingly used for many surveying and precise navigation applications on land, at sea and in the air. Quality control (QC) issues have to be addressed at different stages of the GPS positioning process, for example, data collection, data processing and data display. In this section, the quality control procedures or methodologies for the following critical operations are discussed:

- Measurement quality control for single receiver data, concerned with issues such as failured satellites, ionospheric scintillation, multipath and cycle slips.
- Quality assurance for data communication and data transmission delay.
- Quality control of the position modelling procedure, related to systematic error mitigation and stochastic modelling.
- Ambiguity resolution and validation procedures

As examples, the proposed quality control procedures to be implemented in: (a) the Singaporean multi-base station network, and (b) the GPS-based volcano deformation monitoring system in Indonesia are described, and future or unresolved considerations are outlined. The aim of this is to indicate the range of issues that would need to be considered by the SSG, by using specific examples of systems under development at the Chairman's institution, the University of New South Wales, Sydney, Australia. *The Chairman acknowledges the valuable work done in this area by his colleague, and SSG member, Dr. Shaowei Han.*

3.1 Quality Control for Data Logging

Quality Control Issues at a Single Receiver Site

The following are some of the QC issues that impact on data logging from a single receiver:
- Detection of failed satellites
- Ionospheric activity
- Multipath disturbances
- Cycle slip detection and repair using one-way data

Although GPS satellites are quite reliable, the failure of satellites is not an uncommon occurrence. The GLONASS satellites fail more regularly. Satellite failure could be indicated by the broadcast navigation message, signal being missing, measurement signal-to-noise ratio too small, or measurement “quality” (an admittedly vague term). However, the pseudo-range measurement quality could be judged by a point positioning procedure if more than four satellites are available. A procedure for scanning the raw observation data based on using a Kalman filter to model the behaviour of phase and phase-rate measurements (and their changes) in discrete time is described in, for example, Mertikas & Rizos (1997). This procedure can be applied to each of the data types separately. The information from different receivers provides the external check for the satellite failure.

Ionospheric delay could be estimated by pseudo-range and carrier phase data. If a single-frequency receiver is used, the difference between pseudo-range and carrier phase could be used to estimate the ionosphere delay (Qiu, et al, 1995). However, the dual-frequency data offers especially rich opportunities to construct combinations of observables (phase-only, pseudo-range-only, as well as phase *and* pseudo-range) (e.g., Rizos, 1997) which may be screened using a number of procedures based on Kalman filters of various types, trend-following polynomials, digital filters, and so on. Ionospheric disturbances, which can occur suddenly and can be very severe, affect the amplitude and phase of GPS signals (Wanninger, 1993; Knight & Finn, 1996). One of the phenomena responsible for these are "travelling ionospheric disturbances", another is due to irregularities in the ionosphere causing "scintillations" (especially in the tropical and auroral zones). Under such conditions the ionosphere is so perturbed that single-frequency operations may become impossible because the GPS receiver loses lock on the satellite signals. Where tracking is possible, the likelihood of cycle slips and interrupted tracking is increased, both of which, for example, make ambiguity resolution a more difficult and unreliable task. Knight & Finn (1996) describe an algorithm for determining the so-called S_4 "scintillation index". Empirical filtering techniques will need to be developed to cope with such effects in real-time, particularly when the next solar cycle maximum occurs at the turn of the century.

Multipath is a signal *disturbance* arising from the fact that the signal entering the GPS antenna, in addition to containing the direct satellite-receiver component, also includes reflections from buildings, water surfaces and the ground. Multipath and diffraction effects cannot be easily accounted for during data processing. Fortunately the multipath error on carrier phase observations is significantly less than that experienced on pseudo-range data (of the order of several centimetres, compared with metre level disturbance on pseudo-ranges). Furthermore, its effect tends to average out for static baseline determinations with observation sessions of the order of an hour or more. Nevertheless, for the highest precision static and kinematic applications the effect of multipath disturbance must be addressed. The multipath component in the L1 and L2 pseudo-range data can be estimated (Rizos, 1997). The multipath error in carrier phase cannot be estimated from the raw measurements on a single receiver basis, but may be estimable on a baseline basis from the double-differenced residuals *after* baseline processing. In the case of a reference receiver, the geometry of the satellites, relative to the receiver and surrounding reflective objects, is almost exactly the same after one sidereal day. Hence the multipath disturbance tends to exhibit a daily signature, both in the raw measurements and in the baseline residuals. So-called "multipath-templates" can be constructed to correct pseudo-range measurements, from an analysis of the past one or more day's data, or to correct the double-differenced carrier phase measurement (Lin & Rizos, 1997; Han & Rizos, 1997a). The SIGMA-model was suggested by Brunner et al. (1999) and Hartinger & Brunner (1999), which using the measured signal-to-noise ratio (S/N) data and a template technique to derive a proper variance for all phase data in order to improve the positioning results. However, apart from mathematical procedures there are several strategies for overcoming the problem of multipath in the observations at permanent GPS receivers:

- Careful selection of site in order to minimise the multipath environment.
- Use of multipath resistant antennas.
- Use special receivers that contain "multipath elimination tracking technology".
- If it is possible, multipath should be corrected at each receiver.

Cycle slips are discontinuities of an integer number of cycles in the measured (integrated) carrier phase resulting from a temporary loss-of-lock in the carrier tracking loop of a GPS receiver. This corrupts the carrier phase measurement, causing the unknown ambiguity value to be different after the cycle slip compared with its value before the slip. It must be "repaired" before the phase data is processed as double-differenced observables for GPS surveying techniques. GPS manufacturers have used different techniques to repair cycle slips before the carrier phase measurements are processed. A procedure for scanning the raw observation data based on using a Kalman filter to model the behaviour of phase and phase-rate measurements (and their changes) in discrete time developed by Mertikas & Rizos (1997) could be used for this purpose. Ambiguity recovery techniques used for long-range GPS kinematic positioning by Han (1997a) could also be used for cycle slip detection and repair using one-way data.

Implementation of QC Procedures at a Single Site

Different software packages to implement QC procedure and to indicate the quality of data were developed by GPS manufactures and others, e.g. TEQC by UNAVCO, EVALUATE by Ashtech. The University of New

South Wales, in conjunction with Australian Defence Science and Technology Organisation, is developing a QC system which could be used for data logging and indicating data quality. The cycle slip detection and repair procedures based on the algorithms of Mertikas & Rizos (1997) and Han (1997a) are implemented. The multipath-template for multipath is also generated. Another feature is that the system is able to detect, track and indicate ionospheric scintillation in real-time. A fuzzy expression for scintillation intensity has been used to overcome the ambiguity existing in the numerical and linguistic definition and to provide an indication of scintillation intensity.

The data flowchart is illustrated in Figure 1. The input can be from GPS receivers directly, referred to as the "Real-Time Mode" or from the RINEX files, referred to as the "Post-Processing Mode". The raw data are then scanned to detect all jump outliers, such as cycle slips in carrier phase measurements. Two algorithms proposed by Mertikas & Rizos (1997) and Han (1997a) are used. In order to give the measurement standard deviations, multipath significance, and ionospheric scintillation status, three components, which are called data quality assessment, multipath monitoring and ionospheric scintillation, are then introduced. For continuous GPS reference stations, the computer facility, e.g. harddisk, power, etc. should be also considered for quality assessment and QC.

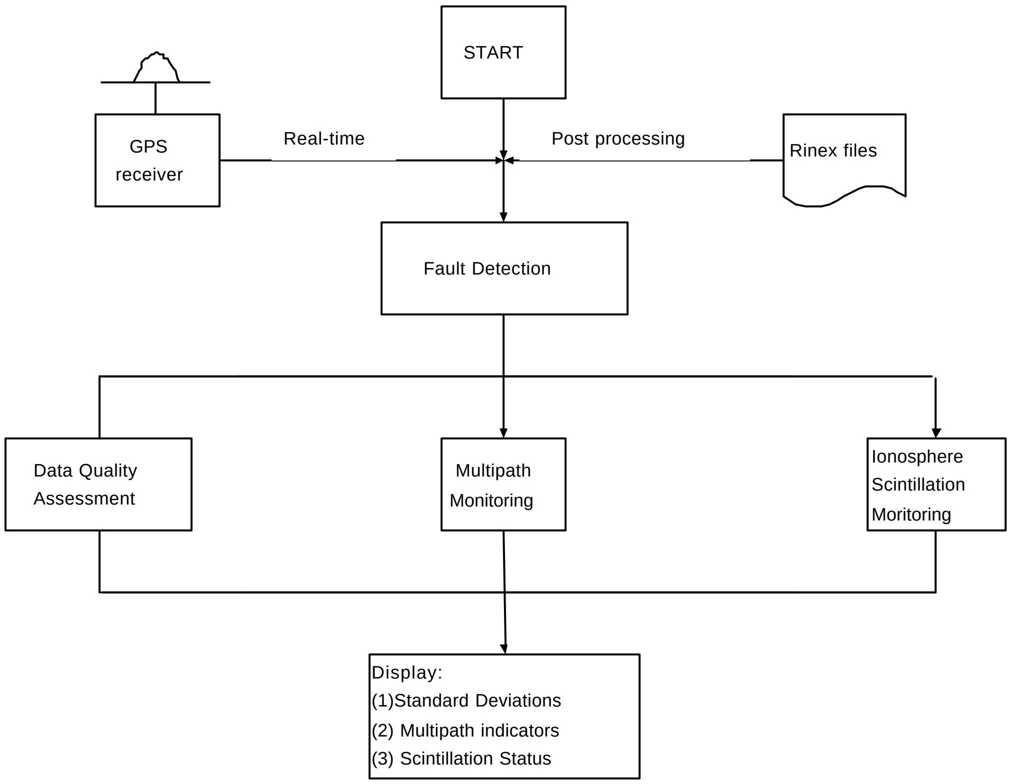

Figure 1. Implementation of QC Procedure on a Single Site

3.2 Quality Assurance for Data Communication

Communication Format, Data Rate, and Latency

The United States body, the Radio Technical Commission for Maritime (RTCM) Services, is a group concerned with the communication issues as they pertain to the maritime industry. Special Committee 104 was formed to draft a standard format for the correction messages necessary to ensure an open real-time DGPS system (Langley, 1994). The format has become known as *RTCM 104*, and has recently been updated to version 2.2.

The RTCM SC-104 message types 18 to 21 provide for RTK service, however the awkwardness of the format and their message frame "overhead" make them relatively inefficient for RTK. For example, to satisfy once per second data transmission for RTK, a baud rate of 4800-9600 would be required (the higher baud rate would be required if DGPS correction messages are also sent), quite a technical challenge, and even more so if radio repeaters have to be used (for each repeater employed, the data rate must be doubled).

As a consequence, GPS-RTK manufacturers have designed their own proprietary data transmission standards to overcome the RTCM problems. One which had been used by the Trimble RTK systems for several years, has been proposed as an "industry standard" (Talbot, 1996). This format is referred to as the Compact Measurement Record format. It uses an efficient compression/decompression algorithm which makes it suitable for communications links that run at 2400 baud, and still deliver once per second GPS solutions. The latest version of RTCM-104 may make redundant such a need for an “industry standard” that is based on a single manufacturer’s format.

Different countries have different regulations governing the use of radios, their frequency and power, hence there is considerable opportunity for confusion. In Australia, the Spectrum Management Agency is responsible for issuing permission on the use of selected radio frequency bands for data communication. In general, the UHF and VHF bands are favoured for RTK applications, in particular the "land mobile" band, 450-470 MHz. The maximum power is dependent upon the type of licence issued to the user, and may range from about 5 W for roving users, to 50 W for fixed local sites. There is a complex relation between: height of transmitting antenna, the type of antenna used (Yagi or omnidirectional), transmitting power, cable length, tree cover and other intermediate objects; and the range of the radio. For test/demonstration purposes up to a few kilometres, a 1 W transmitter operating within the UHF "land mobile" band, should be adequate if the site conditions are ideal.

Data latency problems for RTK can be resolved in either of the following two ways: (a) synchronise reference receiver data and mobile receiver data (which gives the maximum precision but a substantial delay), or (b) use the latest reference receiver data and extrapolate them to the time of the mobile receiver data (which will cause some additional error). The former is better for the carrier phase ambiguity resolution process, as all errors have to be minimised for maximum reliability and performance. However, the kinematic position will suffer due to a time delay of up to 1-2 seconds (which may be crucial for some real-time applications). The latter solution will introduce additional errors due to observation extrapolation. Experimental results show that the linear extrapolation model will introduce an additional double-differenced error of about 2cm for a 1 second delay and about 8cm for a 2 second delay. A quadratic extrapolation model will introduce an additional double-differenced error of about 4cm for a 2 second delay (Landau, et al., 1995; Lapucha, et al., 1995).

Communication Link Considerations

The following considerations must be addressed by DGPS/RTK communication links:

- **Coverage:** This is generally dependent on the frequency of the radio transmission that is used, the distribution and spacing of transmitters, the transmission power, susceptibility to fade, interference, etc.
- **Type of Service:** For example, whether the real-time DGPS/RTK service is a "closed" one available only to selected users, whether it is a subscriber service, or an open broadcast service.
- **Functionality:** This includes such link characteristics as whether it is a one-way or two-way communications link, the duty period, whether it is continuous or intermittent, whether other data is also transmitted, etc.
- **Reliability:** Does the communications link provide a "reasonable" service? For example, what are the temporal coverage characteristics? Is there gradual degradation of the link? What about short term interruptions?
- **Integrity:** This is an important consideration for critical applications, hence any errors in transmitted messages need to be detected with a high probability, and users alerted accordingly.
- **Cost:** This includes the capital as well as ongoing expenses, for both the DGPS/RTK service provider as well as users.
- **Data rate:** In general the faster the data rate, the higher the update rate for range corrections, and hence better positioning accuracy. Typically a set of correction messages every few seconds is acceptable.
- **Latency:** Refers to the time lag between computation of correction messages and the reception of message at the rover receiver. Obviously this should be kept as short as possible, and typically a latency of less than 5 seconds is suggested.
- Quality assurance for data communication and data transmission delay.

3.3 Refinements of Functional Model & Stochastic Model

The double-differenced observable is normally used in GPS positioning because of the elimination or reduction of many error sources through differencing. The notion of “short-range” is generally accepted as the distance that distance-dependent errors (or “residual biases”) could be ignored in the functional model and the coordinate and integer ambiguity parameters can be estimated. The maximum distance is dependent on the tropospheric delay, ionosphere activity and orbit bias level, and a typical value is 10-15km. However, with the increase in distance between two receivers, the “residual biases” become larger and the fidelity of the functional model will be reduced. If the distance between two GPS receivers is beyond this distance, the distance-dependent errors must be considered in someway if the integer ambiguity needs to be determined. The different modelling methodologies have been developed using multiple reference receivers, e.g. Han & Rizos (1997b), Wanninger (1995), Webster & Kleusberg (1992), Wu (1994), Wübbena et al. (1996). The notion of “medium-range” is then defined for carrier phase-based GPS positioning. The limit of medium-range is between the minimum distance at which the functional model cannot ignore the distance-dependent biases and the maximum distance at which the distance-dependent errors could be modelled accurately enough to fix integer ambiguities. The range is highly environment-related and typically would be between 10km and 100km. If the distance is beyond this medium-range, the integer ambiguity must be fixed using a special procedure, e.g. initialisation at the beginning and then maintain GPS signal tracking during the campaign (Colombo & Rizos, 1996; Han, 1997a; Blewitt, 1989; Dong & Bock, 1989).

The stochastic model is used to describe the error of the measurement apart from its functional model. Although the accuracy of the GPS carrier phase measurement is better than 1% of the cycle and almost independent between epochs and different satellites, the stochastic model cannot be determined based on the measurement noise alone. The stochastic model must consider the misclosure of the functional model and it then becomes environmentally dependent. The importance of the stochastic model can be experimentally demonstrated. For a set of data on a static baseline, the stochastic model could be determined using the residuals after data reduction. The single epoch solution using the estimated stochastic model is much better than the solution using a simple (or conventional) stochastic model (Cross, 1999). However, the stochastic model could only be obtained after intensive data analysis in post-mission mode. For real-time applications, GPS data may be separated into different segments, and the previous data segment can be used to estimate the stochastic model for the current segment (Han, 1997b). The segment length may be assumed to be just a few minutes in length. Real-time stochastic modelling is therefore still a challenging research topic.

The data quality could be judged using the classic data snooping theory (e.g. Baarda, 1977; Förstner, 1983). However, the statistic testing and reliability analysis can only be efficient if the stochastic models are correctly known or well approximated.

3.4 Ambiguity Resolution & Validation Procedures

Ambiguity Resolution Techniques

Ambiguity resolution (AR) strategy is dependent on the distance between GPS receivers. For short-range applications a number of instantaneous AR techniques have been reported (Han, 1997b; Al-Haifi, et al, 1997). Developments in fast ambiguity resolution algorithms and validation criteria procedures, together with improvements in stochastic modelling and the application of careful quality control procedures, have generally been responsible for this increased level of performance. Ambiguity searching procedures have been developed to significantly reduce the computation load, for example, LSAST (Hatch, 1990); FARA (Frei & Beutler, 1990), Cholesky decomposition method (Euler & Landau, 1992) and LAMBDA (Teunissen, 1994).

Carrier phase-based medium-range GPS kinematic positioning has been reported for baselines several tens of kilometres in length (Wanninger, 1995; Wübbena et al., 1996). The instantaneous AR has also been reported for medium-range GPS kinematic positioning (Han & Rizos, 1997b). Such *medium-range* performance requires the use of multiple reference stations in order to mitigate the orbit bias, as well as the ionospheric and tropospheric biases. These are exciting developments that will require testing and implementation in operational positioning systems. A joint project between UNSW and the Nanyang Technological University (Singapore) is concerned with establishing a multiple reference system in support of various real-time applications (Rizos et al., 1998). It has been demonstrated that the multiple reference technique could be used to improve the medium-range GPS kinematic positioning and also improve the accuracy of short-range GPS kinematic positioning.

In the case of long-range kinematic positioning several innovative concepts have been reported. Colombo & Rizos (1996) report results of decimetre accuracy navigation over baselines up to a thousand kilometres in length. Although it is not yet possible to resolve ambiguities OTF for baselines of several hundreds of kilometres in length, ambiguity re-initialisation or *ambiguity recovery* is achievable (Han, 1997a; Han & Rizos, 1995). In other words, if loss-of-lock occurs, the AR algorithm can recover the ambiguities as long as any data "gap" is less than a minute or so. Initial AR must be carried out using traditional techniques, including static initialisation. The sea surface determination using long-range airborne GPS kinematic positioning and Laser Airborne Depth Sounder (LADS) system is discussed by Han et al. (1998).

Validation Criteria and Adaptive Procedure

Using the above mentioned model, the real-valued ambiguities can be estimated and the integer ambiguity search procedure then used to determine the correct integer ambiguity set (that which generates the minimum quadratic form of the residuals). The ratio test of the second minimum and the minimum quadratic form of the residuals is normally used to validate the correct integer ambiguity set (Frei & Beutler, 1990). Euler & Schaffrin (1990) have derived another ratio test, but the critical value is still too conservative and is often experimentally specified as being the value 2 (Wei & Schwarz, 1995), or 1.5 (Han & Rizos, 1996). The testing of the difference between the minimum and second minimum quadratic form of the residuals has been suggested (Tiberius & de Jonge, 1995; Wang, et al., 1998). The other validation criteria based on reliability theory were derived by Han (1997b).

The UNSW strategy uses a series of test to assure the results. This procedure using validation criteria suggested by (ibid, 1997b) assumes that the integer ambiguity set generating the minimum quadratic form of the residuals is correct but detects the outlier of the integer set generating the second minimum quadratic form of the residuals. If this outlier can be detected, the integer set generating the minimum quadratic form of the residuals is considered to be the correct one. On the other hand, the sequence generated by differencing the double-differenced ionospheric delay on L1 and L2 carrier phase can also be used as a validation criteria. If this sequence has a slip (or "jump") at the current epoch, the wrong ambiguity resolution can be confirmed at this epoch. If ambiguity resolution fails and six or more satellites are observed at the current epoch, an adaptive procedure can be applied using a satellite elimination procedure, starting with the one with the lowest elevation, repeating the process until ambiguity resolution is successful. If all possible sets of five or more satellites are combined and the ambiguity test still fails, the ambiguity resolution step is considered to have failed.

3.5 Concluding Remarks

The above discussion is intended as a demonstration of the multi-dimensional approach to QC if the total positioning system is taken into account. It tries to mimic the UKOOA guidelines suggested for real-time, pseudo-range-based DGPS, by dismissing the notion that there is one “magic QC test” that can be implemented. Instead, the different sources of “bad data” and “questionable or unreliable results” are identified and QC/QA tests are suggested (some mathematical in nature, others empirical). The attention to OTF-AR (and in particular to single epoch implementations) is to acknowledge that OTF-AR is the most challenging of GPS data processing problems and that advances in this area will make significant contributions to carrier phase QC. However, unlike the UKOOA guidelines the Chairman does not propose that the tests outlined above should be the “officially” sanctioned ones. The standardisation of QC procedures for carrier phase-based kinematic GPS positioning is still some way off.

The focus on OTF-AR to be implemented in real-time is critical. As no SSG members are actively involved in the development of operational systems, the contribution that can be made in this regard is problematic. Nevertheless, the Chairman has attempted to provide some ideas on how such a system could be implemented. It may take a few more years to thoroughly test and evaluate the appropriate “mix” of QC/QA procedures that would be needed. The Chairman hopes that this report has made a humble contribution to this area of study.

3.6 References

Al-Haifi, Y.M., S.J. Corbett and P.A. Cross (1997). Performance Evaluation of GPS Single-Epoch On-The-Fly Ambiguity Resolution. *Navigation*, Journal of The Institute of Navigation, 44(4):479-487.

Baarda, W. (1977). Measures for the Accuracy of Geodetic Networks. In: *"Optimization of Design and Computation of Control Networks"*, lectures from the symposium held in Sopron, Budapest, Hungary, 4-10 July, 419-426.

Blewitt, G. (1989). Carrier Phase Ambiguity Resolution for the Global Positioning System Applied to Geodetic Baseline up to 2000km. *Journal of Geophysical Research*, 94(B8), 10187-10203.

Brunner, F.K., H. Hartinger and L. Troyer (1999). GPS Signal Diffraction Modelling: the SIGMA-D Model. Submit to *Journal of Geodesy*.

Colombo, O.L., C. Rizos and B. Hirsch (1995). Decimetre-Level DGPS Navigation Over Distances of More Than 1000km: Results of the Sydney Harbour Experiment. 4th Int. Conf. on Differential Satellite Navigation Systems, Bergen, Norway, 24-28 April.

Cross, P.A. (1999). Progress In Precise Kinematic GPS Positioning, “ GPS Directions 1999” workshop, School of Geomatic Engineering, The University of New South Wales, 8-9 April.

Dong, D.N. And Y. Bock (1989). Global Positioning System Network Analysis with Phase Ambiguity Resolution Applied to Crustal Deformation Studies in California. *Journal of Geophysical Research*, 94(B4), 3949-3966.

Euler, H.-J. and H. Landau (1992). Fast GPS Ambiguity Resolution On-The-Fly for Real-Time Applications. 6th Int. Geodetic Symp. on Satellite Positioning, Columbus, Ohio, 17-20 March, 650-659.

Euler, H.-J. and B. Schaffrin (1990). On a Measure of the Discernibility between Different Ambiguity Solutions in the Static-Kinematic GPS-Mode. Banff, Canada, 10-13 September. In: K.-P. Schwarz and G. Lachapelle (ed.), *Kinematic Systems in Geodesy, Surveying, and Remote Sensing*, IAG Symposium No. 107, Springer-Verlag, 285-295.

Förstner, W. (1983). Reliability and Discernability of Extended Gauss-Markov Models. In: F.E. Ackermann (ed.), Photogrammetric Models of Geodetic/Photogrammetric Point Determination With Regard to Outliers and Systematic Errors, Deutsche Geodtische Kommission, Reihe A, Helft Nr. 98, Munich, Germany, 79-103.

Frei, E. and G. Beutler (1990). Rapid Static Positioning Based on the Fast Ambiguity Resolution Approach FARA: Theory and First Results. *Manuscripta Geodaetica*, 15, 325-356.

Han, S. (1997a). Ambiguity Recovery for GPS Long Range Kinematic Positioning. *Navigation*, Journal of The Institute of Navigation, USA, Vol 44, No. 2, 257-266.

Han, S. (1997b). Quality Control Issues Relating to Ambiguity Resolution for Real-Time GPS Kinematic Positioning. *Journal of Geodesy*, 71(6):351-361.

Han, S. and C. Rizos (1995). On-The-Fly Ambiguity Resolution for Long Range GPS Kinematic Positioning. IUGG XXI General Assembly, Colorado, 2-14 July, In: G. Beutler, G.W. Hein, W.G. Melbourne and G. Seeber (ed.*): GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, IAG Symposium No. 115, Springer-Verlag, 1996, 290-294.

Han, S. and C. Rizos (1996). Integrated Method for Instantaneous Ambiguity Resolution Using New Generation GPS Receivers. IEEE Position Location & Navigation Symp. PLANS'96, Atlanta, Georgia, 22-26 April, 254-261.

Han S. and C. Rizos (1997a). Multipath Effects on GPS in Mine Environments. Xth International Congress on the International Society for Mine Surveying, Fremantle, Australia, 2-6 November, 447-457.

Han, S. and C. Rizos, (1997b). An Instantaneous Ambiguity Resolution Technique for Medium-Range GPS Kinematic Positioning. 10th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Kansas City, Missouri, 16-19 September.

Han, S., C. Rizos and R. Abbot (1998). Flight Testing and Data Analysis of Airborne GPS LADS Survey. . 11th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Nashville, Tennessee, 15-18 September, 1211-1221.

Hatch, R.R. (1990). Instantaneous Ambiguity Resolution. In: K.-P. Schwarz and G. Lachapelle (ed.): *Kinematic Systems in Geodesy, Surveying and Remote Sensing*, IAG Symposium 107, Springer-Verlag, 299-308.

Hartinger, H. and F.K. Brunner (1999). Variance of GPS Phase Observations: The SIGMA-e Model. *GPS Solutions*, Vol 2, No. 4, 35-43.

Knight, M. and A. Finn (1996). The Impact of Ionospheric Scintillations on GPS Performance. 9th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Kansas City, Missouri, 17-20 September, 555-564.

Mertikas, S.P. and C. Rizos (1997). Real-Time Failure Detection in the Carrier Phase Measurements of GPS by Robust and Conventional Kalman Filtering. *Journal of Marine Geodesy*, 21(1), 41-65.

Landau, H. and H.J. Euler (1992). On-The-Fly Ambiguity Resolution for Precision Differential Positioning. 5th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Albuquerque, New Mexico, 22-24 September, 607-613.

Landau, H., C. Pagels and U. Vollath (1995). Development and Implementation of a Centimeter-Accurate Real-Time-Kinematic Positioning System. 8th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Palm Springs, California, 12-15 September, 1485-1491.

Langley, R.B. (1994). RTCM SC-104 DGPS standards. *GPS World*, 5(5), 48-53.

Lapucha, D., R. Barker and Z. Liu (1995). High-Rate Precise Real-Time Positioning Using Differential Carrier Phase. 8th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Palm Springs, California, 12-15 September, 1443-1449.

Lin, L.S. and C. Rizos (1997). Use of Multipath Template Technique for Mitigating GPS Pseudo-Range Multipath: Methodology and Test Results. First Trans Tasman Surveyors Conference, Newcastle, Australia, 12-18 April, paper 22, 1-9.

Qiu, W., G. Lachapelle and M.E. Cannon (1995). Ionospheric Effect Modeling for Single Frequency GPS Users. *Manuscripta Geodaetica*, 20, 96-109.

Rizos, C. (1997). Principles and Practice of GPS Surveying. Monograph 17, School of Geomatic Engineering, The University of New South Wales, ISBN 0-85839--071-X, approx. 560pp.
Rizos C., S. Han, H-Y. Chen and P.C. Goh (1998). Continuously Operating GPS Reference Station Networks: New Algorithms and Applications of Carrier Phase-Based, Medium-Range, Static and Kinematic Positioning. 3rd International Symposium on GPS Technology, Tainan, Taiwan, 10-11 November, 2-4.
Talbot, N.C. (1996). Compact Data Transmission Standard for High-Precision GPS.9th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Kansas City, Missouri, 17-20 September, 861-871.
Teunissen, P.J.G. (1994). A New Method for Fast Carrier Phase Ambiguity Estimation. IEEE Position Location & Navigation Symp. PLANS'94, Las Vegas, Nevada, 11-15 April, 562-573.
Tiberius, C.C.J.M. and P.J. de Jonge (1995). Fast Positioning Using the LAMBDA-Method. 4th Int. Conf. on Differential Satellite Navigation Systems, Bergen, Norway, 24-28 April, paper no.30, 8pp.
Wanninger, L. (1993). Effects of the Equatorial Ionosphere on GPS. *GPS World*, 4(7), 48-54.
Wanninger, L. (1995). Improved Ambiguity Resolution by Regional Differential Modelling of the Ionosphere. 8th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Palm Springs, California, 12-15 September, 55-62.
Wang, J., M. Stewart and M. Taskiri (1998). A Discrimination Test Procedure for Ambiguity Resolution On-The-Fly. *Journal of Geodesy*, 72(11):644-653.
Webster, I. and A. Kleusberg (1992). Regional Modeling of the Ionosphere for Single Frequency Users of the Global Positioning System. Sixth Int. Geodetic Symposium on Satellite Positioning, Columbus, Ohio, 17-20 March, 230-239.
Wei, M. and K.-P. Schwarz (1995). Fast Ambiguity Resolution Using an Integer Nonlinear Programming Method. 8th Int. Tech. Meeting of The Satellite Division of The U.S. Institute of Navigation, Palm Springs, California, 12-15 September, 1101-1110.
Wu, J.T. (1994). Weighted Differential GPS Method for Reducing Ephemeris Error. *Manuscripta Geodaetica*, 20, 1-7.
Wübbena, G., A. Bagge, G. Seeber, V. Böder and P. Hankemeier (1996). Reducing Distance Dependent Errors for Real-Time Precise DGPS Applications by Establishing Reference Station Networks. 9th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation, Kansas City, Missouri, 17-20 September, 1845-1852.

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Abraham, B. and N. Yatawara (1988). A Score Test for Detection of Time Series Outliers, *Journal of Time Series Analysis*, 9(2), 109-119.

Abraham, B. and A. Chuang (1989). Outlier Detection and Time Series Modeling, *Technometrics*, 31(2), 241-247.

Anderson, T.W. (1984). An Introduction to Multivariate Statistical Analysis, John Wiley, New York, second edition.

Baarda, W. (1968). A Testing Procedure for Use in Geodetic Networks, The Netherlands Geodetic Commission, New Series, 2(5), Delft.

Bansal, R.K. and P. Papantoni-Kazakos (1989). Outlier-Resistant Algorithms for Detecting a Change in a Stochastic Process, *IEEE Transactions on Information Theory*, 35(3), 521-535.

Barnett, V. and T. Lewis (1994). Outliers in Statistical Data, John Wiley and Sons, New York, third edition.

Bassevile, M. (1981). Edge Detection Using Sequential Methods for Change in Level-Part II: Sequential Detection of Change, *IEEE Transactions on Acoustics, Speech and Signal Processing*, Vol. ASSP-29, No. 1, 32-50.

Bassevile, M. and A. Benveniste, eds (1986). Detection of Abrupt Changes in Signals and Dynamical Systems, Lecture Notes in Control and Information Sciences, LNCIS No. 77, Springer-Verlag, New York.

Basseville, M. and I.V. Nikiforov (1993). Detection of Abrupt Changes: Theory and Applications, P T R Prentice Hall, Englewood Cliffs, New Jersey.

Basseville, M., A. Benveniste, G. Moustakides and A. Rougee (1987). Detection and Diagnosis of Changes in the Eigenstructure of Nonstationary Multivariate Systems, *Automatica*, 23(3), 479-489.

Basilevsky, A. (1983). Applied Matrix Algebra in the Statistical Sciences, North Holland, New York.

Bastos, L. and H. Landau (1988). Fixing Cycle Slips in Dual-Frequency Kinematic GPS-Applications Using Kalman Filtering, *Manuscripta Geodeatica*, 13, 249-256.

Bernardo, J.M. and A.F. Smith (1994). Bayesian Theory, John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore.

Biacs, Z.W., E.J. Krakiwsky, and D. Lapucha (1990). Reliability Analysis of Phase Observation in GPS Baseline Estimation, *Journal of Surveying Engineering*, American Society of Civil Engineers, 116(4), 204-224 .

Boos, D.D. (1980). A New Method for Constructing Approximate Confidence Intervals from M Estimates, *Journal of the American Statistical Association*, 75(369), 142-145.

Brown, R.G. (1983). Introduction to Random Signal Analysis and Kalman Filtering, John Wiley and Sons, New York.

Brown, R.G. (1992). A baseline GPS RAIM Scheme and a Note on the Equivalent of Three RAIM Methods, *NAVIGATION*, Journal of The Institute of Navigation, 39(3).

Brown, R.G. and P.Y.C. Hwang (1992). Introduction to Random Signals and Applied Kalman Filtering, John Wiley and Sons, second edition, New York.

Brumback, B.D. and M.D. Srinath (1987). A Chi-Square Test for Fault-Detection in Kalman Filters, *IEEE Transactions on Automatic Control*, AC-32(6), 552-554, June.

Bryson, A.E. and L.J. Henrikson (1968). Estimation Using Sampled Data Containing Sequentially Correlated Noise, *Journal of Rocket and Spacecraft*, 5(6), 662-665.

Cannon, M.E., K.P. Schwarz, M. Wei, and D. Delikaraoglou (1992). A Consistency Test of Airborne GPS Using Multiple Monitor Stations, *Bulletin Geodesique*, 66, 2-11.

Chan, T.F., G.H. Goloub and R.J. Le Veque (1983). Algorithms for Computing the Sample Variance: Analysis and Recommendations, *The American Statistician*, 37, 242-247.
Chang, C.B. and K.P. Dunn (1979). On GLR Detection and Estimation of Unexpected Inputs in Linear Discrete Systems, *IEEE Transactions on Automatic Control*, AC-24(3), 499-501.
Chernick, M.R., D.J. Downing and D.H. Pike (1982). Detecting Outliers in Time Series Data, *Journal of the American Statistical Association*, 77(380), 743-747.
Chien, T.T. and M.B. Adams (1976). A Sequential Failure Detection Technique and its Application, *IEEE Transactions on Automatic Control*, Short Papers, 750-757, October.
Chu, K.A.C. (1973). Estimation and Decision for Linear Systems with Elliptical Random Processes, *IEEE Transactions on Automatic Control*, Short Papers, 499-505, October.
Cipra, T. and R. Romera (1991). Robust Kalman Filter and its Application in Time Series Analysis, *Kybernetika*, 27(6), 481-494.
Chang, T.C. and F.F. Gan (1995). A Cumulative Sum Control Chart for Monitoring Process Variance, *Journal of Quality Technology*, 27(2), 109-119 .
Chow, E.Y and A.S. Willsky (1984). Analytical Redundancy and the Design of Robust Failure Detection Systems, *IEEE Transactions on Automatic Control*, AC-29(7), 603-613.
Crowder, S.V. (1989). Design of Exponentially Weighted Moving Average Schemes, *Journal of Quality Technology*, 21(3), 155-162.
Csorgo, H. and L. Horvath (1988). Nonparametric Methods for Change Point Problems, In Handbook of Statistics (P.R. Krishnaiah, C.R. Rao, eds), Vol.7, Elsevier, New York, 403-425.
Da, R. (1995). A New Failure Detection Approach and Its Applications to GPS Autonomous Integrity Monitoring, *IEEE Transactions on Aerospace and Electronic Systems*, 31(1), 499-506.
Deckert, J.C., M.N. Desai, J.J. Deyst, and A.S. Willsky (1977). F-8 DFBW Sensor Failure Identification Using Analytic Redundancy, *IEEE Transactions on Automatic Control*, AC-22(5), 795-803.
Duncan, A.J. (1986). Quality Control and Industrial Statistics, Irwin, Homewood, Illinois, fifth edition.
Embrechts, P., A.M. Herzberg and A.C.K. Ng (1986). An Investigation on Andrews' Plots to Detect Period and Outliers in Time Series Data, *Communications in Statistics, Simulation*, 15(4), 1027-1051.
Ershov, A.A. and S.Sh. Liptser (1978). Robust Kalman Filter in Discrete Time, Translated from *Avtomatika i Telemekhanika*, 3, 60-69, 359-367.
Fitzgerald, R.J. (1971). Divergence of the Kalman filter, *IEEE Transactions on Automatic Control*, AC-16, 736.
Frank, P.M. (1990). Fault Diagnosis in Dynamic Systems Using Analytical and Knowledge-Based Redundancy - A Survey and Some New Results, *Automatica*, 26, 459-474.
Gan, F.F. (1991). An Optimal Design of CUSUM Quality Control Charts, *Journal of Quality Technology*, 23(4), 279-286.
Gan, F.F. (1993). The Run Length Distribution of a Cumulative Sum Control Chart, *Journal of Quality Technology*, 25(3), 205-207.
Gan, F.F. (1994). Design of Optimal Exponential CUSUM Control Charts, *Journal of Quality Technology*, 26(2), 109-124.
Gan, F.F. (1995). Joint Monitoring of Process Mean and Variance Using Exponentially Weighted Moving Average Control Charts, *Technometrics*, 37(4), 446-453.

Gan, F.F. and K.P. Choi (1994). Computing Average Run Lengths for Exponential CUSUM Schemes, *Journal of Quality Technology*, 26(2), 134-143.
Gao, Y. (1992). A Robust Quality Control System for GPS Navigation and Kinematic Positioning, Ph.D. Dissertation, Department of Geomatics Engineering, The University of Calgary, Canada.
Gelb, A. (ed, 1974). Applied Optimal Estimation, The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, Massachusetts.
Hampel, F.R., E.M. Ronchetti, P.J. Rousseeuw and W.A. Stahel (1986). Robust Statistics: The Approach Based on Influence Functions, John Wiley and Sons, New York.
Hawkins, D.M. (1980). Identification of Outliers, Monographs on Applied Probability & Statistics, Chapman & Hall, London.
Hawkins, D.M. (1981). A Cusum for a Scale Parameter, *Journal of Quality Technology*, 13(4), 228-231.
Hawkins, D.M. (1987). Self-Starting Cusum Charts for Location and Scale, *The Statistician*, 36, 299-315.
Hawkins, D.M. (1992). A Fast Accurate Approximation for Average Run Lengths of CUSUM Control Charts, *Journal of Quality Technology*, 24(1), 37-43.
Hawkins, D.M. (1993). Robustification of Cumulative Sum Charts by Winsorization, *Journal of Quality Technology*, 25(4), 248-261, October.
Hinkley, D.V. (1970). Inference About the Change Point in a Sequence of Random Variables, *Biometrika*, 57(1), 1-17.
Hinkley, D.V.(1971). Inference About the Change-Point From Cumulative Sum-Tests, *Biometrika*, 58(3), 509-523.
Hunter, J.S. (1986). The Exponentially Weighted Moving Average, *Journal of Quality Technology*, 18(4), 203-210.
Isermann, R. (1984). Process Fault Detection Based on Modelling and Estimation Methods, *Automatica*,20, 387-404.
Jazwinski, A.H. (1968). Limited Memory Optimal Filtering, *IEEE Transactions on Automatic Control*, Short Papers, 558-563, October.
Jia, M. and X. Ding (1996). On the Selection of Deformation Models and Its Impact on Deformation Analysis, Proceedings of the FIG 8th International Symposium on Deformation Measurements, Hong Kong, 25-28 June.
Johnson, R.A. and D.W. Wichern (1988). Applied Multivariate Statistical Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, second Edition.
Kemp, K.W. (1961). The Average Run Length of the Cumulative Sum Chart When a V-Mask is Used, *Journal of the Royal Statistical Society*, B-23, 149-153.
Kerr, T.H. (1977). Real-Time Failure Detection: A Nonlinear Optimization Problem That Yields a Two-Ellipsoid Overlap Test, *Journal of Optimization Theory and Applications*, 22(4), 509-536, August.
Kerr, T.H. (1980). Statistical Analysis of a Two-Ellipsoid Overlap Test for Real-Time Failure Detection, *IEEE Transactions on Automatic Control*, AC-25(4), 762-773, August.
Kerr, T.H. (1982). False Alarm and Correct Detection Probabilities over a Time Interval for Restricted Classes of Failure Detection Algorithms, *IEEE Transactions on Information Theory*, IT-28(4), 619-631.
Kerr, T.H. (1987). Decentralized Filtering and Redundancy Management for Multisensor Navigation, *IEEE Transactions on Aerospace and Electronic Systems*, AES-23(1), 83-118, corrections in AES-23(3), 412, May 1987.

Kersen, P. and L. Kurz (1976). Robustized Vector Robbins-Monro Algorithm with Applications to M-Interval Detection, *Information Sciences*, 11, 121-140.
Ketel, M. and L. Kurt (1994). Robust Sequential MIPA Array Processor With Dependent Sampling, *Journal of the Acoustical Society of America*, 95(6), 3409-3418.
Kinnaert, M., R. Hanus and Ph. Arte (1995). Fault Detection and Isolation for Unstable Linear Systems, *IEEE Transactions on Automatic Control*, 40(4), 740-742.
Kligene, N. and L. Telksnis (1984). Methods of Detecting Instants of Random Process Properties, Translated from *Avtomatika i Telemekhanika*, 10, 5-56.
Krishnaiah, P.R. and C.R. Rao (eds.) (1988). Handbook of Statistics 7: Quality Control and Reliability, North-Holland, Amsterdam, New York, Oxford.Kullback, S. (1959). Information Theory and Statistics, Wiley, New York.
Lorden, G. (1971). Procedures for Reading a Change in Distribution, *Annals of Mathematical Statistics*, 42(6), 1897-1908.
Lu, G. (1991). Quality Control for Differential Kinematic GPS Positioning, University of Calgary Surveying Engineering Report, Number 20042, August.
Lucas, J.M. (1985). Cumulative Sum (CUSUM) Control Schemes, *Communications in Statistics: Theory and Methods*, 14(11), 2689-2704.
Lucas, J.M. and R.B. Crosier (1982). Robust Cusum: A Robustness Study for Cusum Quality Control Schemes, *Communications in Statistics: Theory and Methods*, 11(23), 2669-2787.
Lucas, J.M. and R.B. Crosier (1982). Fast Initial Response for CUSUM Quality-Control Schemes: Give your CUSUM a Head Start, *Technometrics*, 24(3), 199-205.
MacGregor, J.F. and T.J. Harris (1993). The Exponentially Weighted Moving Variance, *Journal of Quality Technology*, 25(2), 106-118.
Martin, R.D. (1972). Robust Estimation of Signal Amplitude, *IEEE Transactions on Information Theory*, IT-18(5), 596-606, September.
Martin, R.D. and C.J. Masreliez (1975). Robust Estimation via Stochastic Approximation, *IEEE Transactions on Information Theory*, IT-21(3), 263-271, May.
Masreliez, C.J. and R.D. Martin (1977). Robust Bayesian Estimation for the Linear Model and Robustifying the Kalman Filter, *IEEE Transactions on Automatic Control*, AC-22(3), 361-371.
Masreliez, C.J. (1975). Approximate Non-Gaussian Filtering with Linear State and Observation Relations, *IEEE Transactions on Automatic Control*, Short Papers, 107-110, February.
Mehra, R.K. and J. Peschon (1971). An Innovations Approach to Fault Detection and Diagnosis in Dynamic Systems, *Automatica*, 7, 637-640.
Meinhold, R.J. and N.D. Singpurwalla (1989). Robustification of Kalman Filter Models, *Journal of the American Statistical Association*, 84(406), Theory and Methods, 479-486.
Mertikas, S.P. (1994). The Description of Accuracy Using Conventional and Robust Estimates of Scale, *Marine Geodesy*, 42, 251-269.
Minkler, G. and J. Minkler (1993). Theory and Application of Kalman Filtering, Magellan Book Company, Palm Bay, Florida, USA.
Mironovski, L.A. (1980). Functional Diagnosis of Dynamic Systems: A Survey, *Automation and Remote Control*, 41, 1122-1143.
Mond, C.E.D. and R.V. Lenth (1987). A Robust Confidence Interval for Location, *Technometrics*, 29(2), 211-219.
Muirhead, C.R. (1986). Distinguishing Outlier Types in Time Series, *Journal of The Royal Statistical Society*, 48(1), 39-47.

Quesenburry, C.P. (1986). Screening Outliers in Normal Process Control Data with Uniform Outliers, *Journal of Quality Technology*, 18(4), October.
Quesenburry, C.P. (1991). SPC Q Charts for Start-Up Processes and Short or Long Runs, *Journal of Quality Technology*, 23(3), 213-224.
Quesenburry, C.P. (1995). On Properties of Q Charts for Variables, *Journal of Quality Technology*, 27(3), 184-203.
Page, E.S. (1954a). Continuous Inspection Schemes, *Biometrika*, 41, 100-115.
Page, E.S. (1954b). Control Charts for the Mean of a Normal Population, *Journal Royal Statistical Society*, B-16(1), 131-135.
Page, E.S. (1955). A Test for a Change in Parameter Occurring at an Unknown Point, *Biometrika*, 43, 523-527.
Papoulis, A. (1984). Probability, Random Variables and Stochastic Processes, McGraw-Hill company, New York, second edition.
Patton, R.J. and J. Chen (1991). A Review of Parity Space Approaches to Fault Diagnosis, Proceedings of SAFEPROCESS'91, Baden-Baden, Germany, pp. 239-256.
Pau, L.F. (1981). Failure Diagnosis and Performance Monitoring, Control and Systems Theory Series Monographs and Textbooks, Dekker, New York.
Pena, D. and I. Guttman (1989). Optimal Collapsing of Mixture Distributions in Robust Recursive Estimation, *Communications in Statistics, Theory and Methods*, 18(3), 817-833.
Pervan, B.S., C. Cohen and B. Parkinson (1994). Integrity Monitoring for Precision Approach Using Kinematic GPS and Ground-Based Pseudolite, *NAVIGATION*, Journal of The Institute of Navigation, 41(2).
Piercy, N.P. (1992). Sensor Failure Estimators for Detection Filters, *IEEE Transactions on Automatic Control*, 37(10), 1553-1557.
Poljak, B.T. and J.Z. Tsypkin (1980). Robust Identification, Automatica, Vol. 16, pp. 53-63.
Rao, C.R. (1973). Linear Statistical Inference and its Applications, John Wiley and Sons, New York, second edition.
Reynolds, R.D. (1990). Robust Estimation of Covariance Matrices, *IEEE Transactions on Automatic Control*, 35(9), 1047-1051, September.
Rollins, D.K. and J.F. Davis (1993). Gross-Error Detection When Variance-Covariance Matrices are Unknown, *AI Chemical Engineering Journal*, 39(8), 1335-1341.
Rousseeuw, P.J. and A.M. Leroy (1987). Robust Regression and Outlier Detection, John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore.
Ryan, T.P. (1989). Statistical Methods for Quality Improvement, John Wiley and Sons, New York.
Roes, K.C.B. , R.J.M.M. Does and Y. Schurink (1993). Shewart-Type Control Charts for Individual Observations, *Journal of Quality Technology*, 25(3), 188-198.
Sacks, J. and D. Ylvisaker (1972). A Note on Huber's Robust Estimation of a Location Parameter, *The Annals of Mathematical Statistics*, 43(4), 1068-1075.
Saif, M. and Y. Guan (1993). A New Approach to Robust Fault Detection and Identification, *IEEE Transactions on Aerospace and Electronic Systems*, 29(3), 685-695.
Salzmann, M. (1993). Least Squares Filtering and Testing for Geodetic Navigation Applications, Ph.D. Dissertation, Technical University of Delft, Delft Geodetic Computing Centre.

Salzmann, M. and P.J.G. Teunissen (1989). Quality Control in Kinematic Data, Processing, In Deutsche Gesellschaft fuer Ortung and Navigation, Land Vehicle Navigation, Verlang TUV Rheinland, Kln, pp. 355-366.

Salzmann, M. and P.J.G. Teunissen (1990). Detection and Modelling of Coloured Noise for Kalman Filter Applications, Proceedings of the IAG International Symposium 107 on Kinematic Systems in Geodesy, Surveying and Remote Sensing, Springer-Verlag, N.Y., pp. 201-217.

Schwarz, K.P., M.E. Cannon and R.V.C. Wong (1989). A Comparison of GPS Kinematic Models for the Determination of Position and Velocity Along a Trajectory, *Manuscripta Geodetica*, 14, 345-353.

Selin, I. (1968). Detection Theory, Princenton University Press, Princenton, New Jersey.

Siegmund, D. (1975). Error Probabilities and Average Sample Number of the Sequential Probability Ratio Test, *Journal Royal Statistical Society*, B-37, 394-401.

Stoodley, K.D.C. and M. Mirnia (1978). The Automatic Detection of Transients, Step Changes and Slope Changes in the Monitoring of Medical Time Series, *The Statistician*, 28(3), 163-171.

Stahel, W. and S. Weisberg (eds,1991). Directions in Robust Statistics and Diagnostics, Springer-Verlag, New York.

Strang, G. (1980). Linear Algebra and its Application, Academic Press, New York, second edition.

Stratton, D.A. and R.F. Stengel (1993). Robust Kalman Filter Design for Predictive Wind Shear Detection, *IEEE Transactions on Aerospace and Electronic Systems*, 29(4), 1185-1193.

Tanaka, M. and T. Katayama (1987). Robust Kalman Filter for Linear Discrete Time System with Gaussian Sum Noises, *International Journal of Systems Science*, 18(9), 1721-1731.

Tanaka, M. and T.Katayama (1988). Robust Fixed-Lag Smoother for Linear Systems Including Outliers in the System and Observation Noises, *International Journal of Systems Science*, 19(11), 2243-2259.

Teunissen, P.J.G. (1990). Some Aspects of Real-time Model Validation Techniques for Use in Integrated Systems, Proceedings of the IAG International Symposium 107 on Kinematic Systems in Geodesy, Surveying and Remote Sensing, Springer-Verlag, N.Y., pp. 191-200.

Teunissen, P.J.G. (1990). Quality Control in Integrated Navigation Systems, Proceedings of the IEEE PLANS, Las Vegas, 20-23 March, pp. 158-165.

Teunissen, P.J.G. and M. Salzmann (1989). A Recursive Slippage Test for Use in State-Space Filtering, *Manuscripta Geodaetica*, 14(6), 383-390.

Tiku, M.L., W.Y. Tan and N. Balakrishnan (1986). Robust Inference, Marcel Dekker, Inc., New York, Textbooks & Monographs on Statistics, Vol. 71.

Tsui, C.C. (1994). A General Failure Detection, Isolation and Accommodation System with Model Uncertainty and Measurement Noise, *IEEE Transactions on Automatic Control*, 39(11), 2318-2321.

Turkey, A.A. (1989). Fault Detection and Diagnosis in Dynamic Systems- A Survey, No. 14 Report, Computer and Automation Institute, Hungarian Academy of Sciences.

Tsai, C. and L. Kurz (1983). An Adaptive Robustizing Approach to Kalman Filtering, *Automatica*, 19, 279-288.

Tsay, R.S. (1988). Outliers, Level Shifts and Variance Changes in Time Series, *Journal of Forecasting*, 7, 1-10.

Tukey, J.W. (1960). A Survey of Sampling From Contaminated Distributions, In Contributions to Probability and Statistics, I. Olkin (ed), Stanford University Press, Stanford, California, pp. 448-485.
Vance, L.C. (1986). Average Run Lengths of Cumulative Sum Control Charts for Controlling Normal Means, *Journal of Quality Technology*, 18(3), 189-193.
Van Dyke, K.L. (1995). Fault Detection and Exclusion Performance Using GPS and CLONASS, *NAVIGATION*, Journal of The Institute Of Navigation, 42(4).
Van Trees, H.L. (1968). Detection, Estimation and Modulation Theory, Part I, John Wiley and Sons, New York.
Wallace, D.L. (1959). Bounds on Normal Approximations to Student's and the Chi-Square Distributions, *Annals of Mathematical Statistics*, 30, 1121-1130.
Wang, Y.J. and K.K. Kubik (1993). Robust Kalman Filter and its Geodetic Applications, *Manuscripta Geodaetica*, 18, 349-354.
Warren, D.J. and J.B. Thomas (1991). Asymptotically Robust Detection and Estimation for Very Heavy-Tailed Noise, IEEE Transactions on Information Theory, Vol. 37, No. 3, pp. 475-481.
Wei, M., D. Lapucha and H. Martell (1990). Fault Detection and Estimation in Dynamic Systems, Proceedings of the IAG International Symposium 107 on Kinematic Systems in Geodesy, Surveying and Remote Sensing, Springer-Verlag, New York.
Willsky, A.S. (1976). A Survey of Design Methods for Failure Detection in Dynamic Systems, *Automatica*, 12, 601-611.
Willsky, A.S. (1986). Detection of Abrupt Changes in Dynamic Systems, Charter 2 in Detection of Abrupt Changes in Signals and Dynamic Systems, edited by M. Basseville and A. Benveniste, Control and Information Sciences No. 77, Springer-Verlag, Berlin.
Willsky, A.S., E.Y. Chow, S.B. Gershwin, C.S. Greene, P.K. Houpt and A.L. Kurkjian (1980). Dynamic Model-Based Techniques for the Detection of Incidents on Freeways, *IEEE Transactions on Automatic Control*, AC-25(3), 347-360, June.
Willsky, A.S. (1980). Failure Detection in Dynamic Systems, AGARD Lecture Series No 109 Fault Tolerance Design and Redundancy Management Techniques, Chapter 2.
Willsky, A.S., J.J. Deyst and B.S. Crawford (1975). Two Self-Test Methods Applied to an Inertial System Problem, *Journal of Spacecraft*, 12, 434-437, July.
Willsky, A.S. and H.L. Jones (1976). A Generalized Likelihood Ratio Approach to the Detection and Estimation of Jumps in Linear Systems, *IEEE Transactions on Automatic Control*, Short Papers, 108-112, February.
Wu, N.E. and Y.Y. Wang (1995). Robust Failure Detection with Parity Check on Filtered Measurements, *IEEE Transactions on Aerospace and Electronic Systems*, 31(1), 489-491.
Zhang, X.J. (1989). Auxiliary Signal Detection in Fault Detection and Diagnosis, Lecture Notes in Control and Information Sciences, No. 134, Springer-Verlag, Berlin.

SPECIAL STUDY GROUP OF THE IAG 1.157

AMBIGUITY RESOLUTION AND VALIDATION

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Since the founding of the special study group at the IUGG meeting in Boulder in 1995, GPS ambiguity resolution and validation continued to be an important research topic. Of the 325 papers collected in the on-line bibliography on ambiguity resolution and validation (http://www.geo.tudelft.nl/mgp/people/paul/amb.html) 177 are from the years 1995-1999:

										total
1981	1	1982	0	1983	0	1984	0			1
1985	4	1986	1	1987	3	1988	6	1989	10	24
1990	13	1991	14	1992	30	1993	27	1994	39	123
1995	34	1996	35	1997	59	1998	38	1999	11	177
										325

This large interest for ambiguity resolution is partly driven by the interesting scientific aspects, and partly by the large commercial interests in the area.

Traditionally, algorithms for resolving the GPS ambiguities have been developed for two different applications. On the one hand methods have been devised for applications where a multiple of stations are occupied for several hours until several days, and maximum inter-station distance can be of the order of thousands of kilometers.

At the moment (June 1999), four of the seven IGS processing centers are, in their global networks, resolving a varying percentage of the ambiguities for baselines up to several thousands of kilometer.

On the other hand methods have been developed for rapid-static and navigation applications, where usually only two stations are involved, the maximum distance is some tens of kilometers, and time of occupation is of the order of seconds to minutes, or the receiver is moving.

Successful instantaneous ambiguity resolution (using only one epoch of dual frequency carrier phase and pseudorange data) has been reported for baselines of tens of kilometers. It is not always clear however, if these are isolated cases, or that the results can be reproduced at any place on the Earth at any moment during the day. In this respect, considerably more is known about the long baseline, long time span application, since the IGS processing centers operate on a daily basis.

It can not be stressed enough that conceptually there are no differences between the two applications, and that research directed to one application can benefit from research conducted for the other application.

This SSG was founded with the idea to make the field of ambiguity resolution more transparent. Citing form the terms of reference:

"Despite the large effort spent by many groups from all over the world in devising various schemes, knowledge about their theoretical foundation, and how the schemes are related to each other, is still lacking. Different terminology is used and comparisons between methods are rare. Due to a lack of knowledge about the various methods, the implementations used in the comparisons (if made at all) are not always complete, thereby making the test results unreliable. Moreover, results reported of one particular method, are often difficult to relate to the results of another method, due to lacking knowledge of the characteristics of the data and the type of computer that was used."

After four years, many aspects of the problems mentioned above are still present. Although progress has been made, and even more methods for ambiguity resolution and validation were proposed, detailed descriptions remain rare. To be able to reproduce results and compare methods, either the data set and the model for the float solution has to be completely specified, or a low-level (preferably some sort of source code) of the method used for the ambiguity resolution should be available. At this moment there is only one method (LAMBDA) for which the source code and a detailed description is freely available (http://www.geo.tudelft.nl/mgp/lambda/).

Validation methods are usually described in more detail and comparisons can be found in the literature. There is however still no general agreement on its theoretical foundations.

An new interesting approach has been the proposal for a new diagnostic quantity for assessing the probability of correct ambiguity resolution (ADOP, or Ambiguity Dilution of Precision). It is, as the existing DOPs, based solely on the model at hand and the expected satellite configuration (so it can be computed before any measurements are made, i.e. in the design stage).

We are currently entering a period with, due to the rise of the solar sunspot number to its next maximum (expected to take place somewhere between June 1999 and January 2001), an highly active ionosphere. It will be the first time we are experiencing this since the GPS became operational, and it will likely provide us with some interesting problems with respect to ambiguity resolution.

References:

At the site http://www.geo.tudelft.nl/mgp/people/paul/amb.html a bibliography on ambiguity resolution and validation can be found. It is intended to keep this bibliography up-to-date.

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SPECIAL STUDY GROUP 1.158:

GPS ANTENNA AND SITE EFFECTS

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1 Introduction

During the last few years, an increasing number of permanent GPS sites have been established. The demonstrated repeatability of horizontal position estimates for regional networks is currently of the order of 2 mm and typically a factor of 3-5 greater for the vertical component. There are many advantages to continuously operating GPS networks. Stable pillars with fixed antennas eliminate errors associated with variations in the measurement of the local vector from the reference marker to the phase reference point of the antenna. For fixed pillars in a continuously operating network, the reference marker is usually a fixed, well-defined point on the antenna. In addition, denser position estimates (spatially and temporally) decrease the statistical uncertainty of the results. Continuously operating networks may also serve as a global or regional reference frame for different types of regional and local surveys. Another essential advantage is the increased ability to study and eliminate unmodeled systematic effects on daily estimates of site positions, both short- and long-term effects.

To be able to constrain the common mode of motion, sometimes in the sub-millimeter range, in a regional or local network a strong reference network is needed. The origin of the reference frame must be maintained with a high degree of robustness. In addition, orbits must be compatible with the reference frame. Site-specific errors at permanent stations may introduce errors in the determination of satellite orbit parameters and in the estimate of site positions. In the following we address the problem of site-specific errors and present some recommendations on how to handle these errors.

2 Objectives

The objectives of SSG 1.158 were to:

1. investigate the characteristics of different GPS antennas (mainly those used in high-precision applications) based on measurements in anechoic chambers, field experiments, and numerical evaluation; study the effects of ”antenna mixing”; design and evaluate new GPS antennas;
2. study the influence of electromagnetic scattering (including multipath) and provide information on how to minimize these effects;
3. investigate and formulate recommendations regarding establishment of new GPS sites, including the design and construction of pillars (monuments) and the monitoring of their long-term stability; evaluate radomes used to protect permanently installed antennas;
4. study and minimize the influence of snow, rain, and local atmospheric conditions on the final estimates; provide information and recommendations on how to eliminate (or minimize) the effects of radio interference.

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5 Meetings

Discussions and special sessions have been organized at meetings such as of the American Geophysical Unions (AGU), The European Geophysical Society (EGS), International GPS Service (IGS), and IAG.

6 Work

Site Specific Errors

We have chosen to divide the site specific error sources into three subgroups. The first group consists of problems associated with the receiver, antenna, radome, and the signal. These are effects that will not, in general, change on a day-to-day basis. However, they might introduce biases in the solution. As long as nothing changes the effect stays the same. If something changes, such as the satellite constellation or the elevation cut-off angle, the results will be affected.

The influence is especially obvious looking at the estimates of the vertical components and precipitable water vapor where bias terms can be introduced (*Elòsegui et al.* 1995; *Niell et al*., 1994; *Niell*, 1995). Such a bias could seriously affect the interpretation of the GPS data. The second group represents areas of site effects that will vary, but will only periodically affect the measurements. Precipitation, multipath, atmospheric pressure loading, and atmospheric gradients are probably the most important of these, but others may be discovered.

Finally, the third group consists of errors that might affect the long-term stability of a site such as the location of the site, ground, and the monument. Most of the material related to this specific group of site errors are rather new. These errors may seriously affect the reference frame and the geodynamical projects.

GPS Antennas

It has been found that antenna-to-antenna phase differences can introduce range biases at the several centimeter level, which may limit the precision of the measurements *Rocken* (1992). Differential phase errors due to GPS antennas will not only affect the precision in GPS networks with different types of antennas, but also in networks using identical antennas if the network covers a large spatial area (baseline lengths ~1000 km) (*Schupler and Clark* 1991; *Schupler et al*. 1994). Differential phase errors in regional networks (baseline lengths ~1000 km) using identical antennas are dependent on the electromagnetic environment around each individual antenna.

The problem of antenna mixing was addressed at the IGS Analysis Center Workshop in Silver Spring, 1996. Two sets of phase calibration corrections (PCC) tables have been put together based on material presented *by Mader and MacKay* (1996), *Rothacher and Schär* (1996), and *Meertens et al.* (1996a) to be used by the IGS Analysis Centers and others in the GPS community: (1) a set of ''mean'' phase center offsets and (2) a set of elevation-dependent PCC and offsets relative to the Dorne Margolin T antenna.

Since the PCC values are all relative to the Dorne Margolin T antenna some effects of antenna mixing still remain. Even with the same type of antenna the variation in the apparent phase center as a function of elevation angle will influence the results on longer baselines. Therefore the task of getting absolute calibration of the antennas through, e.g., chamber measurements or simulation software may be essential for some applications even though these calibration values most likely will change when the antenna is deployed in the field. Effects like these can of course be reduced by utilizing antennas less sensitive to scattering from external structures. One way to achieve this is to reduce the side- and back-lobe levels of the amplitude patterns by means of well designed ground-planes. For this purpose new antenna designs have been proposed (see e.g., *Alber*, 1996; *Ware et al.,* 1997; *Jaldehag et al.* 1995; and *Clark et al.* 1996). Furthermore, several groups are currently developing methods to perform absolute field calibration of antennas (*Wubbena* et al., 1996; *Elòsegui et al*., 1999) and in-situ calibration of antenna/pillar systems.

Antenna-Pillar System and the Signal

Here we concentrate on the site-dependent error associated with the electromagnetic coupling between the antenna and its nearby environment (*Tranquilla*, 1986; *Tranquilla and Colpitts*, 1988). The total electromagnetic field of an antenna which radiates a signal in the presence of conducting structures may be expressed as a superposition of the transmitted field and the fields scattered (i.e., reflected and diffracted) by the structures. By reciprocity, the same is true for a receiving antenna. The significance of the scattered field depends on the degree of electromagnetic coupling between the antenna and the scatterer, that is, the distance to the scatterer and the size and reflectivity of the scatterer. Signal scattering affects both the amplitude and phase of the received GPS signal, presumably independently at each site in a network. This independence creates differential phase errors. Scattering from structures in the vicinity of the antenna effectively changes the antenna phase pattern, and, thus, affects the precision of the carrier phase measurements of the GPS signal. In studies by *Elòsegui et al.* (1995) *and Jaldehag et al.* (1996a) it was shown that estimates of the vertical component of baselines formed between sites using identical antennas were dependent on the minimum elevation angle of the data processed. Both studies found that the elevation-angle-dependent systematic effect was associated with non-identical pillar arrangements, causing differential phase errors due to scattering from structures associated with the mounting of the antenna to the pillar, and with the pillar itself. Even the most perfectly calibrated antenna the antenna phase pattern will change when attached to a pillar.

Jaldehag et al. (1996a) demonstrate that estimates of the vertical component of many baselines strongly depend on the minimum elevation angle (elevation cutoff angle) of the data analyzed. A significant part was found to be due to differential phase errors caused by scattering from structures associated with the mounting of the antenna to the pillar and with the pillar itself. As the precision and accuracy of GPS measurements improve in general, antenna phase pattern variations due to different pillars and antenna mounts could be the major error source in just a few years, if not now. Modeling of the scattering effect, or rather the complete phase response of the antenna system, including the pillar, is an important issue for future improvements of the GPS technique.

Radomes - Protective Covers

At several permanent GPS sites located in areas with periodically severe environmental conditions (snow, rain) radomes have been employed. Until recently, most radomes in use have had a conical shape. All materials have some effect on a electromagnetic wave. Radomes appear to delay and refract the GPS-signal in a similar way as snow *Jaldehag et al*. (1996b). Several groups have recently been investigating effects due to the excess signal path delay through the radome. Different radomes have been tested in anechoic chambers *Clark et al*. (1996); *Meertens et al*. (1996b) as well as in field tests *Meertens et al*. (1996b); *Jaldehag et al*. (1996c). All tests show that a conical cover may cause cm-level vertical errors when the tropospheric delay parameter is estimated. The recently employed hemispheric radomes seems to show much less elevation dependence. The influence on the tropospheric wet delay estimates and subsequently, the vertical component will only be on the 1-2 mm level. We can conclude that all radomes effect the GPS signal at some level and in form of an excess signal path delay which will map into other parameters in the GPS software. The effect of the protective covers can most likely be misinterpreted as a tropospheric effect in a similar way as snow. The effect is more or less constant and may be calibrated or modeled.

Precipitation

Signal propagation delay during snow storms has been investigated by, e.g., *Tranquilla and Al-Rizzo* (1993) and *Tranquilla et al*. (1994) who demonstrated that due to the localized nature of many snow storms differential effects may cause systematic variations at the centimeter level in estimates of the vertical coordinate of site position. Systematic variations introduced by snow storms may, however, if short-lived (minutes to hours), be reduced to a high degree by data averaging. A potentially more serious effect of heavy snow precipitation is the accumulation of snow on the top of the GPS antenna and on its surroundings, such as on the top of the GPS pillar or, when present, on the radome covering the antenna. This accumulation may last for days, weeks, or months. *Webb et al*. (1995) reported variations on the order of 0.4 m in estimates of the vertical coordinate of site position. The variations were correlated with the accumulation of snow over the antenna. Variations at the several centimeter level in estimates of the vertical coordinate of site position strongly correlated with changes in the accumulation of snow on top of GPS antennas have also been observed by others *Jaldehag et al.* (1996b); *BIFROST project members* (1996); *Meertens et al.* (1996a). The results indicate that the variations in the vertical coordinate of site position can be fully explained by reasonable accumulations of snow which retard the GPS signals and enhance signal scattering effects.

Horizontal Atmospheric Gradients and Air Pressure Loading Effects

In the data processing the atmosphere is normally considered to be spherically stratified. We assume that one equivalent zenith wet delay value determines the wet delay in any direction, given a certain elevation angle. More advanced models, using more parameters to describe the atmosphere, have been proposed as alternatives to this very simplified model (*Davis et al*., 1993; *Macmillan*, 1995). Several groups are now implementing possibilities to estimate horizontal gradients in the software *Bar-Sever and Kroger* (1996); *Chen and Herring* (1996).

The lack of pressure data available during the GPS analysis can be the reason for different errors. During the entire GPS processing we have to model many external and internal effects on the crust of the earth. One effect currently not modeled is the pressure loading. The vertical position of the GPS receiver changes due to different atmospheric pressure loading the Earth (*vanDam and Herring*, 1994). Extreme values could affect the vertical component of the GPS estimates on the cm level. These effects are of course related more to the general pressure field in the region rather than to a specific site. To properly model this effect a grid of pressure data has to be available. Unfortunately, it is very difficult to isolate these effects from other elevation-angle-dependent effects (multipath, scattering, snow/ice etc.). Small variations in the vertical component are also caused by these other errors. We are thus not in the position of being able to correct for horizontal atmospheric gradients and loading errors optimally. At this point, theoretical studies are needed to quantify these effects, and to understand how we can best deal with these problems.

Local Stability and Monumentation

As GPS measurements have become more precise and are more frequently acquired, the issue of monumentation and site stability has become more important. The long-term contribution to the maintenance and densification of the global reference frame could be seriously affected by unstable sites. The IGS network consists of a large variety of monuments established on top of everything from solid bedrock to buildings. The long-term stability of the reference frame and products associated with it, such as the orbits, are at issue here. Much attention is currently focused towards motions of geodetic monuments. These motions have been found by some researchers to be random-walk-like (e.g. *Johnson et al*., 1995; *Johnson et al.,* 1996) while others find no evidence for random walk behavior (e.g. *Mao et al*., 1996; *Davis et al*., 1996). An ideal GPS monument would move in response only to the tectonic motion of the Earth. However, location, ground, and the environment at ground surface can have dramatic impact on the long-term stability of a site. The implication of this type of power-law noise is serious if the data are used to estimate low-frequency characteristics of a time series such as the slope (deformation rate). *Mao et all* (1996) and *Davis et al.* (1996) found no tendency of a random-walk like behavior possibly because the records where not long enough to see a random walk component above the noise in the low portion of the signal. It is also quite possible that monument motion may depend critically on the monument design and the site locations. Nevertheless these investigations will continue and are most effectively addressed using continuous GPS measurements gathering data in a large variety of local conditions and GPS satellite configurations. There are design techniques that can be employed to mitigate this unwanted influence, most of which involve anchoring the monument to several points at depth and isolating the monument from surface material. Detailed spectral analyses and examination of the long time series available for some of the global sites. Monument and local stability problems could also manifest themselves with a periodic behavior, and be correlated with atmospheric conditions and precipitation.

7 Conclusion and Recommendations

Site-specific errors cannot be separated out when data from permanent sites are being used to determine orbits and reference frame. To be able to constrain the common mode of motion, sometimes in the sub-millimeter range, in a regional or local network a strong reference network is needed. The origin of the reference frame must be maintained with a

high degree of robustness. In addition, orbits must be compatible with the reference frame. For this purpose the permanent sites need to be better examined. We especially found that the problems associated with the antenna-pillar system and the signal distortions have to be addressed. The effect of the antenna and signal related errors are constant from day-to-day but are biasing products like the orbit determination, station time series, and precipitable water vapor time series. Any changes either at a station or in the GPS-data analysis strategy might change this bias and thereby affect the daily products and the reference frame. The other important issue that needs attention is the long-term stability of the sites and the monuments. This is especially important bearing in mind that local and regional continuously operating GPS networks are now used to detect motion at the level of 1 mm/yr or less.
A list of recommendations have been compiled. Most of the items are related to permanent stations which has been the main focus of the studies. Many of the recommendation will also have implications in campaign type of measurement if high-precision results should be obtained.

- Use Calibrated and well-known antennas
- Avoid pillar-scattering and multipath
- If possible, calibrate antenna/pillar
- If radome, use hemispheric type
- For time-transfer purposes (and more??) keep hardware in a temperature controlled environment
- Long-term stability of site and monument
- Low elevation data, atmospheric gradients and atmospheric loading needs further investigations

8 Future Work

GPS/GLONASS receiver systems and site effects are important error sources. The individual members of the SSG 1.158 have contributed to the increased awareness of problems associated with GPS antennas and site effects. The work must continue to push current limits of navigation satellite systems development in hardware and software (both satellites and receivers). A new IAG SSG are being established. Similar activities are also being organized in many countries.

9 Some Web Sites

www.grdl.noaa.gov/GRD/GPS/Projects/ANTCAL/
.igscb.jpl.nasa.gov
www.oma.be/KSB-ORB/EUREF/eurefhome.html
www.unavco.ucar.edu
www.cx.unibe.ch/aiub
www.unb.ca/GGE/personnel/Langley/Langley.html

10 References

Alber, C., Millimeter Precision GPS Surveying and GPS Sensing of Slant Path Water Vapor, Ph.D.Thesis, Univ. Colorado, Dec. 1996.

BIFROST project members, GPS Measurements to Constrain Geodynamic Processes in Fennoscandia, EOS, Transactions, American Geophysical Union, 35, 1996.

Bar-Sever, Y., and P. M. Kroger, Strategies for GPS-Based Estimates of Troposphere Delay, Proc. of the 9th International Technical Meeting of the Satellite Division of the Institute of Navigation, vol. 1, 615-623, 1996.

Chen, G., and Herring, T.A., Effects of Atmospheric Azimuth Asymmetry in the Analysis of Space Geodetic Data, Eos Trans. AGU, 77(46), Fall Meet. Suppl., F453, 1996.

Clark, T.A., B. Schupler, C. Kodak, and R. Allshouse, GPS Antennas: Towards Improving Our Understanding of Factors Affecting Geodetic Performance, Eos Trans. AGU, 77, Fall Met. Suppl. 1996

Davis, J. L., G. Elgered, A. E. Niell, and C. E. Kuehn, Ground-based measurement of gradients in the ``wet'' radio refractivity of air, Radio Sci.,28, 1003-1018, 1993.

Davis, J.L., R.A. Bennet, J.M. Johansson, H.G. Scherneck, and J.X Mitrovica, Spectral Analysis of Site Position Variations from Project BIFROST, Eos Trans. AGU, 77(46), Fall Meet. Suppl. F453, 1996.

Elòsegui, P., J.L. Davis, R.T.K. Jaldehag, J.M. Johansson, and A.E. Niell, Effects of Signal Multipath on GPS Estimates of the Atmospheric Propagation Delay, Eos Trans. AGU, 75(44), p. 173, Fall Meeting Suppl., 1994.

Elòsegui, P., J. L. Davis, R. T. K. Jaldehag, J. M. Johansson, A. E. Niell, and I. I. Shapiro, Geodesy Using the Global Positioning System: The Effects of Signal Scattering on Estimates of Site Position, J. Geophys. Res., 100, 9921-9934, 1995.

Elòsegui, P;Jarlemark, P O J;Corey, B E; Davis, J L; Niell, A E; Meertens, C M GPS Calibration System for High-Accuracy Geodetic Measurements, Eos Trans. AGU AGU, 80 (49), Spring Meet. Suppl., 1999.

Jaldehag, R. T. K., Space Geodesy Techniques: An Experimental and Theoretical Study of Antenna Related Error Sources, Ph. D. Thesis, Tech.Rept. No. 276, School of Electrical and Computer Engineering, Chalmers University of Technology, Gothenburg, Sweden, 1995.

Jaldehag, R. T. K., J. M. Johansson, P. Elosegui, J. L. Davis, A. E. Niell, B. O. Rönnäng, and I. I. Shapiro, Geodesy Using the Swedish Permanent GPS Network: Effects of Signal Scattering on Estimates of Relative Site Positions, J. Geophys. Res., 101, 17814-17860, 1996a.

Jaldehag, R. T. K., J.M. Johansson, J.L. Davis, and P. Elosegui, Geodesy using the Swedish Permanent GPS Network: Effects of snow accumulation on estimates of site positions, Geophys. Res. Lett., 23, 1601-1604, 1996b.

Jaldehag, R.T.K., J.M. Johansson, and J.L. Davis, Environmental Effects on the Swedish Permanent Network, Eos Trans. AGU, 77 (46), Fall Meet. Suppl., F453, 1996c.

Johnson H.O.and D.C. Agnew, Monument Motion and Measurements Crustal Velocities, Geophys. Res. Lett., 22, 3533-3536, 1995.

Johnson H.O., F.K. Wyatt, D.C.Agnew, and J. Langbein, Evidence for Power-Law Behavior in Geodetic Time Series: Should we care, and if so, Why?, Eos Trans. AGU, 77 (46), Fall Meet. Suppl. F453, 1996.

Mao A., C.G.S. Harison, and T. Dixon, Monument Stability of the Permanent GPS stations and Tide Gauges, Eos Trans. AGU, 77(46), Fall Meet. Suppl., F453, 1996.

MacMillan, D. S., Atmospheric gradients from very long baseline interferometry observations, Geophys. Res. Letters, 22(9), 1041-1044, 1995.

Mader, G.L., and MacKay, J.R., Calibration of GPS Antennas, Proc. IGS Analysis Center Workshop, Silver Sping, MD, 1996.

Meertens C., Rocken, C., Braun, J., Exner, M., Stephens, B., and Ware, R., Field and Anechoic Chamber Tests of GPS Antennas, Proc. IGS Analysis Center Workshop, Silver Sping, MD, 1996a.

Meertens C., Braun, J., Alber C., Johnson J., Rocken C., Van Hove, T., Stephens, B., and Ware, R., Antenna and Antenna Mounting Effects in GPS Surveying and Atmospheric Sensing, EOS Trans. AGU, 77(46), Fall Meet. Suppl., F453, 1996b.

Niell, A. E., P. Elosegui, J.L. Davis, I.I. Shapiro, R.T.K. Jaldehag, and J.M. Johansson, Reduction of Signal Multipath Effects on GPS Estimates of Site Position (abstract), Eos Trans. AGU, 75 (44), p. 171 Fall Meeting Suppl., 1994.
Niell A.E., Reducing elvation-dependent errors for ground-based measurements, EOS Trans. AGU, 77 (46), Fall Meet. Suppl., F453, 1996.

Rocken, C., GPS antenna mixing problems, UNAVCO Memo, UNAVCO, Boulder, Colorado, 1992.

Rothacher, M., and Schär, S., Antenna Phase Center Offsets and Variations Estimated from GPS Data, Proc. IGS Analysis Center Workshop, Silver Sping, MD, 1996.

Schupler, B. R. and T. A. Clark, How different antennas affect the GPS observable, GPS World, 32-36, Nov./Dec., 1991.

Schupler, B. R., R. L. Allshouse, and T. A. Clark, Signal characteristics of GPS user antennas, Navigation, 41, No. 3, 277-295, 1994.

Tranquilla, J.M., Multipath and imaging problems in GPS receiver antennas, paper presented at Fourth International Symposium of Satellite Positioning, DMA, Austin, Tex., 1986.

Tranquilla, J.M., and B.G. Colpitts, GPS antenna design characteristics for high precision applications, paper presented at ASCE Specialty Conference GPS-88: Engineering Applications of GPS Satellite Surveying Technology, Am. Soc. Civ. Eng., Nashville, Tenn., May 11-14, 1988.

Tranquilla, J.M. and H.M. Al-Rizzo, Theoretical and experimental evaluation of precise relative positioning during periods of snowfall precipitation using the global positioning system, Manuscripta Geodaetica, 18, 362-379, 1993.

Tranquilla, J.M. and H.M. Al-Rizzo, Range errors in Global Positioning System during ice cloud and snowfall periods, IEEE Trans. Antennas and Propagat., 42, 157-165, 1994.

vanDam, T. M., and T. A. Herring, Detection of Atmospheric Pressure loading using Very Long Baseline Interferometry Measurements, J. Geophys. Res., 99, 4505-4517, 1994.

Ware, R., C. Alber, C. Rocken, and F. Solheim, Sensing integrated water vapor along GPS ray paths, Geophys. Res. Lett 24, pp 417-420, 1997.

Webb, F.H., M. Bursik, T. Dixon, F. Farina, G. Marshall, and R.S. Stein, Inflation of Long Valley Caldera from one year of continuous GPS observations, Geophy. Res. Lett., 22, 195-198, 1995.

Wubbena G., Menge F., Schmitz, M., Seeber, G., and Völksen, C., A New Approach for Field Calibrations of Absolute Antenna Phase Center Variations, Proc. ION GPS-96, 1996

SPECIAL STUDY GROUP 1.159

GROUND-BASED GPS METEOROLOGY

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Introduction

Ground-based GPS meteorology has both advanced and expanded quite dramatically during the last four years. When this SSG was formed in 1995 the notion of using continuous GPS (or CGPS) networks to monitor atmospheric water vapor in support of basic meteorological research, climatology and operational weather analysis and prediction was still fairly new (Bevis et al., 1992, 1994; Rocken et al., 1993; Yuan et al., 1993) and despite the success of the first large proof-of-concept experiment "GPS/STORM" (Rocken et al., 1995; Duan et al., 1996) many meteorologists familiar with the idea remained rather sceptical about the prospect of using emerging regional CGPS networks as meteorological observing systems. Now, at the time of the 1999 IUGG meeting, there are at least one hundred scientists and engineers working on ground-based GPS meteorology in more than one dozen countries, and several large national or multinational groups have been formed to engage collaborative research and development of GPS met, including meteorological impact studies. This influx of researchers has led to very rapid development on the geodetic side of the technique, and far wider interest by the meteorological community. This report provides some background on the scope of these activities, including a listing of some major R&D efforts and a bibliography (1995 – present).

While IAG SSG 1.150 focuses on ground-based GPS meteorology, SSG 2.161 focuses on the space-based or occultation approach. Christopher Rocken has reviewed this complementary class of GPS meteorology in his SSG 2.161 report. While ground- and space-based GPS meteorology have been developed largely independently in the last few years, it is likely that in the next few years considerably more effort will be focused on using them together. In the rest of this report the term 'GPS meteorology' will refer solely to the ground-based approach unless explicitly stated otherwise.

National and Regional GPS Meteorology Programs

The first continuous GPS network built specifically for meteorological measurements was the NOAA GPS PW Network led by NOAA's Forecast System Laboratory (FSL) in the USA. This project is working in a quasi-operational status and is mainly focused on measuring the impact of GPS PW data on numerical weather modeling and on improving quality control for nearly real-time solutions. Perhaps the single largest project to date is the Japanese GPS Met Project which seeks to exploit the 1,000 station CGPS network operated in Japan by GSI. This project has completed its initial proof-of-concept phase, and is now focused on R&D relevant to establishing an operational status. More than any other GPS met project established to date, the Japanese effort emphasises using meteorological products to benefit real-time geodesy as well as exploiting geodesy for meteorology. The first extensive European trials of GPS met were mounted through projects WAVEFRONT, BALTEX and MAGIC funded by the EC. More recently the EC has adopted COST Action 716 "Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Applications" which emphasises operational exploitation of GPS met. A new German project associated with this cost action, known as the 'GPS Atmosphere Sounding Project', is already performing nearly real-time GPS PW measurements in an operational setting, and hopes to add many more CGPS stations to its network in the near future. This project emphasises integration of both the ground- and space-based approaches.

Several of these projects are described in more detail in the appendices. Here is a list of the larger projects (known to our SSG) with contact information:

PROJECT NAME	**REGION**	**AGENCY/ PARTICIPANTS**	**CONTACT INFORMATION**
NOAA GPS IPW Project	USA	Forecast Systems Laboratory SOPAC,Univ Hawaii,UNAVCO	S. Gutman
Japanese GPS Meteorology Project	Japan	IGS, JMA, CRL, NRAO and several universities	I. Naito, Y. Hatanaka
WAVEFRONT *(recently concluded)*	Europe	See appendix 3	A. Dodson
BALTEX	Baltic Sea & adjacent areas		Jan Johansson jmj@oso.chalmers.se
MAGIC	Mediterranean & adjacent areas	See appendix 5	Jennifer Hase jh@acri.fr
COST Action 716	Europe	European Community See appendix 3	G. Elgered A. Dodson
GPS Atmosphere Sounding Project	Germany & Europe	GFZ and many others, see appendix 4	C. Reigber reigber@gfz-potsdam.de

References and Bibliography

Bar-Sever Y.E., P.M. Kroger, and J.A. Borjesson, Estimating horizontal gradients of tropospheric path delay with a single GPS receiver, J. Geophys. Res., 103, pp 5019-5035, 1998.

Bevis, M., Businger, S., Herring, T.A., Rocken, C., Anthes, A., and Ware, R., 1992, GPS Meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System, Journal of Geophysical Research, 97, 15,787-15,801.

Bevis, M., Businger, S., Chiswell, S., Herring, T.A., Anthes, R., Rocken, C., and Ware, R, 1994, GPS Meteorology: Mapping zenith wet delays onto precipitable water, Journal of Applied Meteorology, 33, 379-386.

Businger, S., S.R. Chiswell, M. Bevis, J. Duan, R. Anthes, C. Rocken, R. Ware, T. M. Exner, VanHove, F. Solheim, 1996, The promise of GPS in atmospheric monitoring, Bulletin of the American Meteorological Society, 77, 5-18.

Carlsson, T.R., G. Elgered, and J.M. Johansson, A Quality Assessment of the Wet Path Delay Estimated From GPS Data, Proc. of the 11th Working Meeting on European VLBI for Geodesy and Astrometry, Research Report 177, Ed. G. Elgered, Onsala Space Observatory, Chalmers University of Technology, 89-95, 1996.

Coster, A.J., A.E. Niell, F.S. Solheim, V.B. Mendes, P.C. Toor, R.B. Langley, and C.A. Upham (1998). "The Westford Water Vapor Experiment: Accuracy issues involving the use of GPS to measure total precipitable water vapor." Proceedings of the 10th Symposium on Meteorological Observations and Instrumentation, 78th Annual Meeting of the American Meteorological Society, Phoenix, AZ, 11-16 January, pp. J70-J75.

Coster, A.J., A.E. Niell, F.S. Solheim,V.B. Mendes, P.C. Toor, K.P. Buchmann, and C.A. Upham (1996). "Measurements of precipitable water vapor by GPS, radiosondes, and a microwave water vapor radiometer." Proceedings of the ION GPS-96, the 9th International Technical Meeting of the Satellite Division of the Institute of Navigation, Kansas City, MO, 17-20 September, pp. 625-634.

Coster, A.J., A.E. Niell, F.S. Solheim, V.B. Mendes, P.C. Toor, and R.B. Langley (1997). "The Effect of Gradients in the GPS Estimation of Tropospheric Water Vapor." Proceedings of The Institute of Navigation 53rd Annual Meeting, Albuquerque, NM, U.S.A., 30 June - 1 July; pp. 107-114.

Davis, J.L. and G. Elgered, The Spatio-Temporal Structure of GPS Water-Vapor Determinations, Physics and Chemistry of the Earth, 23, 91-96, 1998.

Davis, J.L., M.L. Cosmo, and G. Elgered, Using the Global Positioning System to Study the Atmosphere of the Earth: Overview and Prospects, in GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications, Eds. G. Beutler, G.W. Hein, W.G. Melbourne, G. Seeber, IAG Symposia, Vol. 115, Springer Verlag, Berlin, pp. 233-242, 1996.

Dodson A H; Baker H C (1998) ; Accuracy of Orbits for GPS Atmospheric Water Vapour Estimation, Physics and Chemistry of the Earth, Vol 23, No 1, pp 119 - 124, April 1998.

Duan, J. , M. Bevis, P. Fang, Y. Bock, S. Chiswell, S. Businger, C. Rocken, F. Solheim, T. Van Hove, R. Ware, S. Mcclusky, T.Herring, R. W. King, 1996, GPS Meteorology: Direct Estimation of the Absolute Value of Precipitable Water, Journal of Applied Meteorology, 35, 830-838.

Elgered, G., J.M. Johansson, and J.L. Davis, Using Microwave Radiometry and Space Geodetic Systems for Studies of Atmospheric Water-Vapor Variations, in Microwave Radiometry and Remote Sensing of the Environment, ed. D. Solimini, VSP Int. Sci. Publ., Zeist, Netherlands, pp. 69-78, 1995.

Elgered, G., J.M. Johansson, B.O. Ronnang, and J.L. Davis, Measuring regional atmospheric water vapor using the Swedish permanent GPS network, Geophys. Res. Let., 24, 2663-2666, 1997.

Emardson, T.R., G. Elgered, and J.M. Johansson, Three Months of Continuous Monitoring of Atmospheric Water Vapor with a Network of Global Positioning System Receivers, J. Geophys. Res., 103(D2), 1807-1820, 1998.

Emardson, T.R., J.M. Johansson, and G. Elgered, The systematic behavior of water vapor estimates using four years of GPS observations, Trans. IEEE Geoscience and Remote Sensing, accepted, 1999.

Fang, P., M. Bevis, Y. Bock, S. Gutman and D. Wolfe, 1998, GPS meteorology: Reducing systematic errors in geodetic estimates for zenith delay, Geophysical Research Letters, 25, 3583-3586.

Gendt G, G Beutler: Consistency in the Troposphere Estimations Using the IGS Network, Proceedings IGS Workshop "Special Topics and New Directions", Potsdam, May 15-18, 1995, GeoForschungsZentrum Potsdam, Germany, Eds. G Gendt and G Dick, pp.115-127

Gendt, G., Comparison of IGS Troposphere Estimations Proceedings IGS Analysis Centers Workshop, 19-21 Maerz, 1996 Silver Spring, Maryland USA , Eds. R E Neilan, P A Van Scoy, J F Zumberge. pp. 151-164

Gendt, G., IGS Combination of Tropospheric Estimates -- The Pilot Experiment. 1997 Technical Reports, Oct. 1998, Ed. I Mueler, K Gowey, R Neilan, pp. 265-269

Gendt, G., IGS Combination of torposphereic Estimates - Experience from Pilot Experiment. Proceedings IGS AC Workshop, 9-11 Febr. 1998, Darmstadt Eds. J Dow, J Kouba, T Springer, pp.205-216

Gendt, G., M. Bevis: Some remarks on new and existing tropospheric products. Proceedings IGS Network Systems Workshop, Annapolis, MD., November 2-5, 1998Eds. J Dow, J Kouba, T Springer, pp.205-216, , in press.

Gossard, E.G., S. I. Gutman, B.B. Stankov, and D.E. Wolfe,1999. Profiles of radio refractive index and humidity derived from radar wind profilers and the Global Positioning System. Radio Sci.,34, 371-383.

Gutman, S., D. Wolfe, A. Simon, 1996: Status of the GPS Precipitable Water Vapor Observing System. FSL Forum, Dec. 1996, 29-33.

Haines, B.J., and Y.E. Bar-Sever, Monitoring the TOPEX microwave radiometer with GPS: Stability of columnar water vapor measurements, Geophys. Res. Lett., Vol. 25, No. 19, pp 3563-3566, 1998.

Ichikawa, R., M. Kasahara, N. Mannoji, and I. Naito, Estimations of atmospheric excess path delay based on three-dimensional, numerical prediction model Data, J. Geod. Soc. Japan, 41, 379-408, 1995.

Ichikawa, R., M. Kasahara, N. Mannoji, and I. Naito, Positioning Error in GPS Measurements due to Atmospheric Excess Path Delay Estimated From Three-Dimensional, Numerical Prediction Model Data, J. Geod. Soc. Japan, 42, 183-204, 1996.

Johansson, J.M., T.R. Emardson, P.O.J. Jarlemark, L. Gradinarski, and G. Elgered, The Atmospheric Influence on the Results from the Swedish GPS Network, Physics and Chemistry of the Earth, 23, 107-112, 1998.

Kimata, F., N. Kato, and T. Sugiyama, GPS measurements errors for Nagoya-Atsumi baseline at the passing of cold front on November 7, 1995, J. Geod. Soc. Japan, Vol. 42, 119-122, 1996 (in Japanese).

Kruse, L.P., B. Sierk, T. Springer and M. Cocard (1999), GPS-Meteorology: Impact of Predicted Orbits on Precipitable Water Estimates, Geophys. Res. Lett., 26, No. 14, in press.

Mannoji, N., GPS meteorology, Journal of the Visualization Soc. of Japan, Vol.16, 107-111, 1996(in Japanese).
Mousa, A. and T. Tanaka, Tropospheric wet delay of microwaves at Shionomisaki, southwest Japan, and a preliminary evaluation of mapping functions, J. Geod. Soc. Japan, 43, 145-158, 1997.
Naito, I., GPS meteorology, J. Japan Soc. Hydrol. and Water Resourc. Vol. 9, 570-578, 1996(in Japanese).
Naito, I., Y. Hatanaka, N. Mannoji, R. Ichikawa, S. Shimada, T. Yabuki, H. Tsuji, and T. Tanaka, Global Positioning System Project to Improve Japanese Weather, Earthquake Predictions, EOS, Transactions, American Geophysical Union, 79, 301, 308, 311, June, 1998.
Ohtani, R., H.Tsuji, N.Mannoji, J.Segawa and I.Naito: Precipitable water vapor observed by Geographical Survey Institute's GPS network, TENKI, 44, 317-325, 1997(in Japanese).
Rocken, C., R. Ware, T. Van Hove, F. Solheim, C. Alber, J. Johnson, M. Bevis, S. Businger, 1993, Sensing atmospheric water vapor with the Global Positioning System, Geophysical Research Letters, 20, 2631-2634.
Rocken, C., T. Van Hove, J. Johnson, F. Solheim , R. Ware, M. Bevis, S. Chiswell, S. Businger, 1995, GPS/Storm - GPS Sensing of Atmospheric Water Vapor for Meteorology, Journal of Atmospheric and Oceanic Technology, 12, 468 - 478.
Ruffini, G., L.P., A. Rius, B. Burki, L. Cucurull, A. Flores, Estimation of Tropospheric Zenith Delay and Gradients over the Madrid Area Using GPS and WVR Data, Geophysical Research Letters, in press.
Sierk, B., Bürki, B., Becker-Ross, H., Florek, S., Neubert, R., Kruse, L.P., and H.-G. Kahle (1997): Tropospheric water vapor derived from solar spectrometer, radiometer and GPS measurements, Journal of Geophysical Research, 102, No. B10, pp. 22411-22424.
Sierk, B., Bürki, B., Kruse, L.P., Becker-Ross, H., Florek, S. Kahle, H.-G. and R. Neubert (1998): A new instrumental approach for water vapor determination based on Solar Spectrometry. Phys. Chem. Earth, 32, No. 1, pp. 113-117.
Steinhagen,H, S Bakan, J Boesenberg H Dier D Engelbart J Fischer G Gendt et al., Field campaign LINEX 96/1 - Possibilities of water vapor observation in the free atmosphere, Meteorol. Zeitschrift, N.F.7, 377-391.
Tsuda T., K. Heki, S. Miyazaki, K. Aonashi, K. Hirahara, H. Nakamura, M. Tobita, F. Kimura, T. Tabei, T. Matsushima, F., Kimura, M. Satomura, T. Kato, and I. Naito, GPS Meteorology Project of Japan -Exploring Frontiers of Geodesy-, Earth Planet Space, 50, i-v, October, 1998.
Yuan, L., Anthes, R., Ware, R., Rocken, C., Bonner, W., Bevis, M., and Businger, S., 1993, Sensing global climate change using the Global Positioning System, Journal of Geophysical Research, 98, 14,925-14,937.
Yang, X., B. Sass, G. Elgered, T.R. Emardson, and J.M. Johansson, A comparison of the integrated water vapor estimation by a NWP simulation and GPS observation, J. Appl. Meteorol., 38, pp. 941-956, 1999.
Westwater, E.R., Y. Han, S.I. Gutman, and D.E. Wolfe, 1998. Remote sensing of total precipitable water vapor by microwave radiometers and GPS during the 1997 Water Vapor Intensive Operating Period. 1998 IEEE International Geoscience and Remote Sensing Symposium Proceedings: Vol. IV, 2158-2161.

Wolfe, D.E. and S.I. Gutman, Developing an operational surface-based GPS water vapor observing system for NOAA: network design and results. J. Atmos. Oceanic Technol., in press.
Zuffada, C., G. Hajj and E.R. Kursinski, A novel approach to atmospheric profiling with a mountain-based or air-borne GPS receiver, to appear in JGR atmosphere.

APPENDIX 1:

THE IGS TROPOSPHERIC PRODUCT

by Gerd Gendt, GFZ (gendt@gfz-potsdam.de)

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The existing global IGS network of permanent GPS receivers installed for geodetic and geophysical applications can be used with marginal additional efforts for the determination of atmospheric water vapor.

The IGS has produced a tropospheric product on a regular basis since the beginning of 1997. After the successful performance of the Pilot Experiment the tropospheric estimates became an official IGS product in 1998. All IGS Analysis Centers submit their individual solutions to the GeoForschungsZentrum Potsdam (GFZ) where the official combined product is generated. It is a weighted least squares estimate for the zenith neutral delay (ZND) at selected IGS stations with a sampling rate of 2 hours, and is available with a delay of 3 to 4 weeks. The product meets the demands for climate studies where for the interesting long-term characteristics a resolution of 2 hours is sufficient, and a delay of a few weeks is acceptable.

Estimates for more than 80 sites are provided by 3 or more Analysis Centers. For these sites reasonable estimates of internal consistency can be obtained. The standard deviation for most of the sites is in the level of 2-5 mm ZND (corresponding to better than 1 mm in the precipitable water vapor (PWV)) and the scattering of the bias from site to site is about 3 mm ZND. For sites in the equatorial region, where partly severe problems with the higher ionospheric activities occur, the scattering is much higher but in most cases below the 2 mm level in PWV. Site solutions delivered by only one Analysis Center are also contained in the product, sampled and transformed into the troposphere format. Most of those sites are located in denser parts of the network, where all sites have nearly the same accuracy and therefore the quality can be deduced from neighboring sites.

In addition to the ZND product RINEX meteorological files are offered for conversion into PWV. Despite the fact that IGS has encouraged its members to add suitable met packages to the IGS tracking stations, very little progress has been made during the last two years. At the moment only 30 sites are equipped with met packages. Unfortunately, for some sites data quality is not good enough. The precision of the sensors is not usually the problem, however. Rather, there are too many meteorological data gaps (often days long), and in such cases no meaningful series of water vapor may be compiled. To support the decision as to where future met packages should be installed, IGS will maintain a list of high priority candidate sites. Criterions for the selection may be the quality of the tropospheric estimates and the location of the sites (e.g. equatorial regions may be especially interesting).

The number of projects and activities involving near real-time monitoring of water vapor using ground-based GPS is steadily increasing. IGS will not be involved in such near real-time activities directly. However, IGS can support regional activities of this kind by making available hourly RINEX data within the global tracking network and by generating predicted orbits. The presently available predictions based on daily data batches have to be predicted over 48 hours and are for a number of satellites often not in the quality needed. Based on the hourly downloads IGS will be able to generate predictions more frequently and the shortened prediction interval will lead to significant improvements. During 1999 within the IGS the development into this new direction will be discussed and technologies will be developed.

APPENDIX 2

PRESENT STATUS OF GPS METEOROLOGY PROJECT OF JAPAN

The GPS meteorology project of Japan is a five-year project launched April, 1997 funded by Science and Technology Agency (STA) of Japan. The project is basically motivated by the nationwide GPS array of GSI (Geographical Survey Institute of Japan), composed of nearly one thousand stations separated by 15-30 km, and has following three major goals. The first goal is to create a system to let the retrieved precipitatble water vapor (PWV) data from GSI's GPS array flow to the four dimensional data assimilation (4DDA) system for numerical weather prediction in JMA (Japan Meteorological Agency). This improve the forecast systems of meso- to local-scale phenomena that often trigger torrential rains in humid Japan. The second is to improve accuracy in crustal deformation measurements in the nationwide GPS array using a GPS meteorology, in which three dimensional meteorological data of JMA's 4DDA system enhanced by PWV data from GPS are applied to establish a system diagnosing or removing the errors in estimated site coordinates in vertical due to water vapor. The third is to construct a database of nationwide GPS PWV information for uses in interdisciplinary environmental studies, hydrology, meteorology, and geodesy (see Naito et al., 1998 and Tsuda et al., 1998, for more details). Below are the products achieved through the project so far.

PWVs routinely retrieved from GSI's GPS array agreed well with those from radiosonde observations by JMA with RMS differences of about 3mm, but showed small biases caused mainly by vertical displacements due to ocean tidal loading. The GPS array also detected dense temporal anomalies of PWVs during heavy rainfalls over the Japan Islands that can be applicable for 4DDA system, though there have been found to exist differences between PWVs obtained from GPS made on real topography and those in 4DDA system based on model topography. Estimated horizontal coordinates in the GSI's GPS array were found to strongly reflect horizontal gradients in zenith tropospheric delay (ZTD). This was confirmed by improvements in horizontal coordinates made by GPS analysis with horizontal gradient in ZTD. GSI's GPS array detected a local circulation system associated with land and sea breezes in Kanto area through GPS PWVs. GPS's PWVs were found to be a useful tool for predicting torrential rain and fog related to the local circulation system. Two dimensional tomography experiments using a dedicated dense GPS array detected vertical profiles of atmospheric refractive index due to water vapor. The tomography coupled with a model simulation was found to be a useful tool for detecting dry and wet regions in local torrential rainfalls.

Moreover, GPS measurements in Thailand under GAME (GEWEX Asian Monsoon Experiment) proved GPS's ability as water vapor sensor in comparison with radiosonde observation. GPS measurements also played a key role in detecting onsets of the monsoon in Tibetan plateau. A global distribution of potential energy due to atmospheric waves at altitudes of 20-30 km were obtained from the space-based GPS meteorology data of UCAR (University Corporation for Atmospheric Research), which provides valuable information in the tropical middle atmospheric dynamics, for such as the Quasi-Biennial Oscillation (QBO), for example.

References:

Naito, I., et al., 1997, Global Positioning System Project to Improve Japanese Weather, Earthquake Prediction, Eos, 79, 301, 308, 311.

Tsuda, T., et al., 1997, GPS meteorology project of Japan --- Exploring frontiers of geodesy ---, Earth Planet Space, 50, 1-5.

APPENDIX 3

REPORT ON PROJECT WAVEFRONT AND THE NEW EUROPEAN COST ACTION

By Helen Baker

WAVEFRONT (GPS WAter Vapour Experiment For Regional Operational Network Trials) is a three year collaborative project funded by the European Commission (EC). The project is coordinated at IESSG (University of Nottingham, UK) in collaboration with Onsala Space Observatory (Chalmers University, Sweden), Eidgenhossische Technische Hochschule (Switzerland) and Institut d'Estudis Espacials de Catalunya (Spain) in association with the UK Meteorological Office, the Astronomical Institute at the University of Berne (Switzerland) and the Danish Meteorological Institute.

WAVEFRONT started in September 1996 under the EC Environment and Climate work programme, aiming to develop the potential for using ground-based GPS to estimate the variable water vapour content of the atmosphere, ultimately for meteorological and climatological applications. More specifically WAVEFRONT aims to fulfil the following objectives:

•· Validate the accuracy and temporal resolution of GPS meteorology, by comparison with ground-based water vapour radiometers (WVR)and radiosonde profiles
•· Assess the feasibility of near real-time (less than three hour latency) estimation of GPS IWV to an accuracy of 1-2 kg/m2
•· Compute a post-processed data set of GPS IWV estimates from a European sub-set of established permanent GPS monitoring stations (part of the International GPS Service) for climate modelling studies
•· Investigate the possibility of obtaining a more detailed tomographic profile of water vapour over a smaller, denser GPS network to develop a data set to study micro-scale synoptic processes

The validation of GPS estimates against WVRs and radiosondes has been undertaken through a number of field campaigns and an extensive examination of the associated error sources within the GPS processing procedure, a-priori statistics, conversion constants applied and network processing strategies. Using findings from these analyses, a comparison of tropospheric estimates from three GPS processing software packages used within the WAVEFRONT project (BERNESE, GAS and GIPSY) has been undertaken using two climatically different three-month data sets. A feasibility study for estimating GPS water vapour on a near real-time basis has been completed in preparation for meteorological forecasting impact assessments at the UK Meteorological Office. The archiving of one-hour averages of atmospheric water vapour is also being performed at approximately forty European IGS stations, ultimately to obtain a continuous water vapour time series for climate studies. A dense network of GPS receivers has also been used over short campaign periods to assess the feasibility of tomographic analysis to examine three dimensional water vapour distribution.

Initial results from WAVEFRONT have indicated agreement between GPS, WVR and radiosonde water vapour estimates at the 1-1.5 kg/m2 level using a recommended processing strategy developed from the analysis of processing procedures and error source examinations. European algorithms have been derived to improve the accuracy of the conversion from GPS atmospheric delay estimates to IWV. In addition to the European GPS tropospheric archive collected for climate study purposes, further data sets have been used in a 'sliding window' processing approach with predicted orbit data, to demonstrate the potential for near real-time water vapour estimation at a corresponding level of accuracy (1-2 kg/m2). Preliminary results from the tomographic examination have produced vertical profiles which compare well with ECMWF profiles.

EC COST ACTION 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications

The memorandum of understanding for COST Action 716, entered into force on 16 September 1998. The Action has as its primary objective:

"Assessment of the operational potential on an international scale of the exploitation of a ground based GPS system to provide near real-time observations for Numerical Weather Prediction and Climate
Applications."

With secondary objectives of:

•· Development and demonstration of a prototype ground-based GPS System
on an international scale
•· Validation and performance verification of the prototype system
•· Development and demonstration of a data exploitation scheme for NWP and analysis of data exploitation techniques needed for climatic applications
•· Requirements for operational implementation of a ground-based GPS system on an international scale.

The 4-year Action at present involves 14 countries (Austria, Belgium, Denmark, Finland, France, Germany, Hungary, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland and the UK), and the chairman is Gunnar Elgered from Chalmers University in Gothenburg, Sweden.
Initial work has concentrated on the formulation of four 'work packages' addressing the above objectives.

APPENDIX 4

GPS ATMOSPHERE SOUNDING PROJECT : AN INNOVATIVE APPROACH FOR THE RECOVERY OF ATMOSPHERIC PARAMETERS

By C. Reigber, GFZ

Introduction

Reliable information on global climate change processes over future decades, and the perennial need for better weather forecasting on near and medium-term time scales, are only possible on the basis of global and regional data records and modeling that accurately represent atmospheric state parameters with high spatial and temporal resolution. Remote sensing satellite systems, such as multispectral passive radiometers, and interdisciplinary research programs, have already contributed significantly to a better understanding of the climate system. However, coverage for important data such as tropospheric water vapor is sparse and complementary observation systems are needed to reduce this lack of information. The Global Positioning System (GPS) is presently developing into a powerful candidate for such a system. With the rapid development and operation of permanent global and dense regional GPS ground station networks and associated data communications and information systems, and also in view of the rapidly expanding number of Low Earth Orbiting (LEO) satellites carrying GPS or GPS-related instrumentation for limb sounding measurements, there are excellent long-term prospects for very valuable contributions of GPS to operational meteorology and for a permanent, seamless, weather-independent and calibration-free (because of pure time difference measurements) monitoring of important parameters of state of the atmosphere and ionosphere. A basic requirement for this is that the necessary infrastructure components and methodologies are developed, tested, validated and are embedded into an operational environment. With this project the HGF centers GFZ, DLR, GKSS and AWI initiate the development into an expanded infrastructure and the performance of programs to effectively assimilate GPS data products into atmospheric and ionospheric modeling and analyses. This is done to ensure that existing GPS expertise of HGF centers is focused towards an innovative approach, the potential of which is considered high for climate research and applications in the science community, and to ensure that proper use is made of national investments into the forthcoming satellite missions CHAMP and GRACE.

Project goals

The main objective of the proposed project is: The development and/or improvement of largely already existing infrastructure (networks of GPS stations, orbiting GPS receivers, communication links, network and mission operation centers, data information and archival centers, analysis centers and related S/W systems, user interfaces) required for the use of ground- and space-borne GPS tracking data for atmospheric and ionospheric sciences and applications. This should be realized in such a short time and to such an extent, that already atmospheric/ionospheric data products from the forthcoming CHAMP and GRACE satellite missions and from densified regional geodetic GPS networks in Germany can be explored for their potential information content and operational availability in applications such as meteorological weather forecasting, climate variability investigations and space weather monitoring.

To achieve this main objective the project activities are combined into five major project goals:

- Acquisition of GPS data in near-real time from regional networks and from the global network of the International GPS Service IGS, development and implementation of necessary techniques and methods for quasi-operational determination of tropospheric water vapor concentrations and electron densities, as well as the development of optimal strategies with the cooperating partners for meteorological practice and research.

- Development of strategies and methods for the determination of atmospheric and ionospheric parameters in near-real time from limb sounding data of the satellites to be launched within the next three years including the forthcoming missions CHAMP and GRACE and starting with already existing GPS/MET data; systematic validations over a lengthy time period, and assessments of the efficiency of the technique for weather forecasting and for climate research.

- Development of assimilation techniques for ingesting limb sounding results and ground-data derived water vapor fields into existing global and regional models for both climate study and numerical weather prediction and systematic evaluations of the assimilation results.

- Extensive comparisons of GPS-based results for atmospheric parameters with correlative data sets from existing sensor systems (e.g., radiosondes, ground-/satellite-based radiometers) and models such as those from the European Center for Medium Weather Forecast (ECMWF), the Max Planck Institute (MPI) for Meteorology, Hamburg, the GKSS, and the German Weather Service (DWD) to evaluate the GPS method and to assess its effectiveness.

- Design of a data processing, archiving and distribution system and its partial development on component level on the basis of the experiences gained in the project for optimally serving users in future programs.

Project Work Breakdown

The work to be carried out in the proposed project is subdivided into the two subprojects:

Subproject 1 (SP1): Water Vapor Estimation from Ground GPS Networks and Assimilation into Atmospheric Models
Subproject 2 (SP2): Radio Limb Sounding with Spaceborne GPS

Subproject 1 is led by GFZ with contributions from AWI and GKSS. The total work is broken down into 13 work packages. Subproject 2 is led by DLR with contributions from GFZ and AWI. SP2 is split into 20 work packages. Through these HGF center activities primarily Level 2„ data products will be generated, such as orbit ephemerides, profiles of refractivity, temperature and pressure as well as Total Electron Content (TEC) records for the ionosphere. Level 3„ products pertain primarily to those products derived from cooperative activities involving HGF centers and external partner institutions engaged in climate research or weather analyses, such as the German Weather Service (DWD) and the MPI for Meteorology. This will include, for example, recovery of tropospheric water vapor fields and wind fields, model development and data assimilation, statistical studies of model performance, validation activities, temporal and spatial averages of refractivity, temperature and geopotential height profiles, etc.

Project Team

The project team will be composed of scientists from the cooperating HGF centers AWI, DLR, GFZ, GKSS. Scientists from the external partner institutions given in the sequel will support the project. Prof. Christoph Reigber, director of GFZ,s Division 1 and presently project lead of the small satellite mission CHAMP, Co-PI of the GRACE mission and chairman of the Governing Board of the International GPS Service, will lead the team.

The HGF center institutes and the lead scientists from these institutes contributing to the project with level 1 to level 2 products are:

• GFZ, Division 1 Kinematics and Dynamics of the Earth, Potsdam and Oberpfaffenhofen: Dr. G. Gendt (Manager SP1)

• DLR, Remote Sensing Data Center, Neustrelitz: Dr. N. Jakowski (Manager SP2)

• GKSS, Institute for Atmospheric Physics, Geesthacht: Prof. Dr. E. Raschke

• AWI, Section   Physics of the Atmosphere and Oceans I„, Bremerhaven and Potsdam: Dr. R. Neuber

• External partner institutions, the involved lead scientists and their anticipated contribution to the project are:

• Jet Propulsion Laboratory (JPL), Pasadena (Dr. W.G. Melbourne):
GPS Flight receiver S/W; Radio-occultation measurement resolution; validation/proof-of concept programs

• Institute of Radio Engineering and Electronics (IRE), Moscow (Prof. O. Yakovlev):
Improvements of inversion S/W under low S/N or enhanced multipath conditions

• Max Planck Institut (MPI):
- fuer Meteorologie, Hamburg (Dr. L. Kornblueh):
Assimilation methods, retrieval techniques - fuer Aeronomie, Lindau (Prof. K. Schlegel):
Ionospheric electrodynamics, space weather aspects

• Deutscher Wetterdienst (DWD):
- Offenbach (Dr. W. Wergen):
GPS data products in operational numerical weather forecasting - Observatory Lindenberg (Dr. H. Steinhagen):
Validation of GPS limb sounding measurements

• Freie Universitaet Berlin:
- Institut fuer Weltraumwissenschaften (Prof. J. Fischer):
Validation of ENVISAT MERIS water vapor with CHAMP/GRACE retrievals - Institut fuer Meteorologie (Prof. K. Labitzke): Validation of radio occultation data with model data, inspection of time series

• Universitaet Koeln, Institut für Meteorologie (Prof. P. Speth):
Study of Madden-Julian Oscillation with CHAMP/GRACE water vapor

Project Schedule

Project start is planned for July 1999. In the first phase of the project, which will last until the end of the CHAMP mission commissioning phase in about Spring to Summer 2000, the major activities will take place in Subproject 1 - network enhancement, water vapor recovery and data assimilation from ground GPS data. In Subproject 2 preparatory activities for the usage of radio occultation measurements from CHAMP will take place in this period. Operational activities with radio limb sounding data from CHAMP will start in Summer 2000. They will last until the end of the project, which is in July 2002. In the middle of this second phase the GRACE twin satellite mission will be launched, which will allow to test the performance of the infrastructure for a multi-satellite system being developed in the project.

APPENDIX 5

SUMMARY OF THE *MAGIC* PROJECT

by Jennifer Haase

Meteorological Applications of GPS Integrated Column Water Vapor Measurements in the Western Mediterranean

Keywords: water vapor, weather prediction, flooding, and climate Thematic areas: Flood and weather prediction, climate

Background and Rationale:
Humidity is a highly variable parameter in atmospheric processes and it plays a crucial role in atmospheric motions on a wide range of scales in space and time. Limitations in humidity observation accuracy, as well as temporal and spatial coverage, often lead to problems in numerical weather prediction, in particular that of clouds and precipitation. Due to these limitations, the verification of humidity simulations in operational weather forecasts and climate modeling are also difficult. At smaller scales, catastrophic rainfall events due to storm systems unique to the western Mediterranean are difficult to predict with the operational (larger scale) numerical weather prediction models. Such storm events are often associated with flash floods with loss of property, and in some cases, human casualties. While local models have some success in predicting precipitation, key humidity data are required to verify the derived humidity fields. The emerging ground-based Global Positioning System (GPS) networks present appealing opportunities for an improved humidity observation source that can help resolve these difficulties.

In brief:
MAGIC will examine the need for improved water vapor estimates by the Danish Meteorological Institute and the Servei Meteorologia de Catalunya and evaluate the ability of GPS ground based networks to address this need. Automated data processing for retrieval of zenith tropospheric delay data from the GPS data will be implemented. The data will be validated against integrated values from conventional data sources such as radiosondes, and against the DMI HIRLAM model forecasts. Assimilation algorithms will be developed by DMI and the IEEC in Spain to integrate this new type of data into mesoscale numerical weather prediction models to evaluate the impact of the data and evaluate improvements in prediction capabilities, especially in areas at high risk for storms

such as Catalonia. The project extends beyond the derivation of the required data from earth observation sources, to the actual development of the technology necessary for the user to fully exploit the data.

Recent results:
Compiling a data set from different processing centers for NWP model validation or assimilation tests requires validation of the consistency of the GPS processing methods and quality control of the output GPS IWV data. One objective of the MAGIC project is to demonstrate that this level of consistency can be achieved in direct response to the operational requirements of the meteorological community. The Danish Meteorological Institute (DMI) is the partner in the project charged with evaluating the impact of the GPS IWV data in the HIRLAM NWP model. DMI has given a target value of 0.5 cm in ZTD as an acceptable error level. A methodology has been adopted for processing the data from all permanent GPS stations in France, Spain, and Italy, in addition to data available from the IGS. In preliminary tests comparing the operational results of two of the MAGIC processing centers (CNRS, IEEC), the difference between the ZTD estimates satisfies these requirements.

MAGIC serves:
•Operational meteorological agencies
•Emergency services concerned with catastrophic flooding The European public which will benefit from better forecast models Climate modeling community
•International organisations studying climate change

Specific end users:

•Danish Meteorological Agency (Consortium partner) Servei Meteorologia de Catalunya
•Generalitat de Catalunya (Catalonian Regional Government) other potential customers:
•Other meteorological agencies of the HIRLAM consortium (including the Instituto Nacional de Meteorologia (Spain), the Italian Meteorological Service, and Meteofrance)
•Other regional weather prediction agencies and emergency services entities (Civil Protection of the Government of Andalucia, Spain). International organisations studying climate change

Consortium:
ACRI - Mécanique Appliquée et Sciences de l'Environnement
CNRS: Centre National de la Recherche Scientifique/ Géoscience Azur ES
ICC: Institut Cartografic de Catalunya ES
IEEC: Institut d'Estudis Espacial de Catalunya
ASI: Agenzia Spaziale Italiana, Centro di Geodesia Spaziale
OGMO: Osservatorio Geofisico dell'Universita di Modena
DMI: Danish Meteorological Institute
ROA: Real Instituto y Observatorio de la Armada en San Fernando

Coordinator: ACRI - Mécanique Appliquée et Sciences de l'Environnement 260, Route du Pin Montard, BP. 234, 06904 Sophia Antipolis Cedex, France
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APPENDIX 6

EUREF ANALYSIS CENTER FOR GPS METEOROLOGY

by Jan Dousa, Czech Technical University

GOP analys center (AC) takes advantage of hourly data uploads in the EUREF (EUropean REference Frame) permanent GPS network. In the beginning of 1999 it started to operate (for testing purposes only) as a ground-based GPS meteorology analysis center (approx. 20 sites). Although the final processing strategy is still under the development AC produces the results routinely. Research aims are focused on near-real-time (NRT) GPS data processing in accordance with the strategy for precise zenit total delay (ZTD)/precipitable water vapor (PWV) estimation. The emphasis is currently given for the main error source in NRT ZTD estimation: prediction of precise orbits.

Three main types of processing are set up for test purposes:
1. NRT 1h-proc. 24x/day (delay: 1-6 hours), predicted orbits IGP/COD_P2
2. NRT 4h-proc. 24x/day (delay: 1-6 hours), predicted orbits IGP/COD_P2
3. Post 24h-proc. 1x/day (delay: 20-48 hours), rapid orbits IGR/COD_R

- Post-processing solution should be considered as reference solution and archive solution for climatology studies. Two months of comparision (May+June 99') of routinely resulted PWV with radiosonde observations (4x/day) gives RMS 1.5mm and bias -1.0mm. The solution will be father improved and checked especially for the bias. - NRT-processing solutions are considered in future for meteorology operational forecasting.The comparision of 4h-proc (3rd hour) gives currently RMS lower 3.5mm and bias aprox. -1.0mm. (The ambiguity fixing is rather problematic in this solution !)

To achieve a good accuracy of NRT PWV results, it was already proved the selection of satellites for the final processing is necessary (the prediction of only few satellites is realy bad !). Different satellite exclusion (or de-weightening) procedures were tested while the stability of results has increased by 2-4 times in NRT mode. Currently the satellite exclusion procedure is based on checking the consistency between two following up predicted daily orbit arcs and does not take into account predicted accuracy code for each satellite from the header of SP3 file. Preliminary results of solutions with partial orbit improvements gives us hope to achieve the accuracy of 1-2mm RMS in NRT processing. This variant configuration is currently under the development.

GOP LAC - EUREF local analysis center Geodetic Observatory Pecny
established in collaboration between

- Research Institute of Geodesy, Topography and Cartography
- Dep. of Advanced Geodesy, Czech Technical University in Prague

APPENDIX 7

REPORT FROM NEW ZEALNAD: ESTIMATING ATMOSPHERIC WATER VAPOUR CONTENT USING GPS

Mark Falvey
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John Beavan
Institute of Geological and Nuclear Sciences (GNS), Gracefield Research Centre, P O Box 30368, Lower Hutt, NZ

Research in New Zealand has so far focused in two areas: using the country's nascent (5-station) continuous GPS network to provide an operational water vapour monitoring system, and targeted experiments aimed at studying extreme rainfall events across mountain belts.

At present, water vapour observations are restricted to surface humidity measurements and upper air radiosonde (weather balloon) observations. Surface observations are often not representative of the general state of the atmosphere, and radiosondes are costly and are released only once or twice a day at only five stations in the New Zealand region. Satellite based radiometer images in water vapour channels (NOAA, GMS) may also be received but these can be corrupted by the presence of clouds and are difficult to interpret quantitatively. GPS precipitable water measurements should provide valuable data to supplement these existing observational platforms. The hourly time resolution makes it a useful tool in those analysis situations where water vapour changes rapidly with time. Indeed GPS derived PW time series reveal a great deal of high frequency structure. We have also found the GPS PW to be very accurate. Measurements of PW made at radiosonde stations have compared to within 2 mm of those at nearby GPS sites.

For the PW estimates to be of most use, they must be available on a near real-time basis. In real-time processing predicted GPS satellite orbit data must be used. Such orbits are prone to large errors which can cause spurious features in the resulting PW time series. Much of our work so far has been to test and implement processing techniques capable of identifying and removing poor satellite data. We believe that this is now at a sufficiently refined state that we can soon begin to operate in an automated real-time test mode.

Along with the continuous station work, investigation has begun into applying GPS measurements to the study of terrain induced rainfall, using data collected during two meteorological field experiments. This is an application of GPS precipitable water which we believe is unique to our research group. It is well known that moist airflow over New Zealand's mountainous regions can result in considerable precipitation enhancement (orographic rainfall). However, quantitative models capable of predicting this enhancement and associated river flow levels have yet to be fully developed.

There have so far been two field campaigns during which GPS receivers were deployed to make precipitable water measurements. They were SALPEX'96 (Southern ALPs EXperiment) and TARPEX'99 (TARaruas Precipitation EXperiment). Both were collaborative projects involving several national and international research institutions including the National Institute for Water and Atmospheric Research (NIWA), Victoria and

Auckland Universities, and GNS. A variety of instruments were deployed (radar, rain gauge, radiosonde, specially equipped aircraft) along with dedicated networks of GPS receivers. During SALPEX, eight receivers were arranged in a transect stretching from Hokitika to Christchurch while in TARPEX, twelve receivers were deployed between the Kapiti coast and the Wairarapa. Both experiments lasted for roughly three weeks and between them a total of five interesting rainfall events have been observed.

The data from both experiments are being used to investigate the ability of the GPS technique to characterise water vapour variations over small horizontal scales. In particular we investigate the significant gradients in PW across the ranges observed during orographic rainfall events. We attribute much of this variation to condensation of water vapour as air is forced upwards over the mountains, and are attempting to relate this apparent condensation signal to observed precipitation patterns. The GPS measurements are also used to validate regional atmospheric model simulations of the SALPEX and TARPEX events.

As a more complete continuous GPS network is developed in New Zealand, we envisage the network being able to contribute water vapour data to real-time weather forecast models – as well as providing ground deformation data for earthquake and volcanic hazard monitoring.

REPORT OF INTERNATIONAL ASSOCIATION OF GEODESY SECTION II

ADVANCED SPACE TECHNOLOGY

for the period 1995-1999

by

R. Rummel

1. Introduction

1.1 Objectives of Section II

Section II, Advanced Space Technology, is engaged in new space techniques for geodesy and geodynamics. Its objectives are to anticipate and promote their implementation into geodetic/geodynamic work and, in general, support and coordinate the optimal use of modern space technology for the benefit of geodesy.

During the past four years the activities of the section include:

1. Promotion of the realisation of space experiments for the improvement of our knowledge of the Earth's gravity field in the medium spatial wavelengths.

2. Improvement of the coordination and combined use of the full range of geodetic space techniques, such us SLR, VLBI, GPS, DORIS, PRARE.

3. Continuation of the successful work of WEGENER with a broadened, new scope.

4. Stimulation of the geodetic use of interferometric SAR and of spaceborne sounding with global satellite navigation systems.

5. Development of concepts on how to come to an optimal world wide distribution of geodetic/geophysical fundamental stations.

6. Continuation and further improvement of the work of I.G.S.

The structure of the section was as follows:

Commissions:
Commission VIII: International Coordination of Space Techniques for Geodesy and

Geodynamics (CSTG)
President: G.Beutler (Switzerland)
Secretary: H.Drewes (Germany)

Special Commissions:

SC 6: Wegener Project
President: S. Zerbini (Italy)

SC 7: Gravity Field Determination by Satellite Gravity Gradiometry
President: K.-H. Ilk (Germany)

Special Study Groups:

SSG 2.160: SAR Interferometry Technology
Chairman: R. Klees (The Netherlands)

SSG 2.161: Spaceborne Atmospheric GNS Soundings
Chairman: C. Rocken (USA)

SSG 2.162: Precise Orbits using Multiple Space Techniques
Chairman: A. Marshall (USA)/ R.Scharroo (The Netherlands)

International Service:
International GPS Service (IGS)
Chairman of the Governing Board: G. Beutler (Switzerland)
Director of the Central Bureau: R.E. Neilan (USA)

1.1 Achievements and Prospects

Again we can look back to four very active years in space geodesy in general and section II work in particular. Finally, after many years of pushing and pressing, dedicated gravity satellite missions will come. The first one will be the German CHAMP mission that will be launched in early 2000. It will combine SST-hl and accelerometry. It will be followed by the US-German GRACE mission, to be launched in 2001, which is a low-low satellite to satellite tracking mission. The ESA gravity gradiometry mission GOCE is currently studied in parallel with three other Earth research missions. Two of them will be selected in fall 1999. It is of great advantage that the three experiments are complementary to each other in terms of determining the static and time variable gravity field . They will have an enormous impact on space geodesy and geodesy in general and they will bring geodesy even closer to all other disciplines of Earth sciences. It is equally important that with the approved missions ENVISAT and JASON the continuation of ocean altimetry is certain for the years to come. In addition, geodesy will benefit from the ice altimetry missions ICESAT and CRYOSAT. All of this will have an important impact on ocean, ice, geodynamic and sea level research. Decisions on GPS follow-on and add-on systems and on the future of GLONASS will be taken in the near future and will also affect their geodetic use. Geodetic observation techniques, such as laser ranging, VLBI, GPS, DORIS etc., and data analysis techniques are still improving with the focus being on precision, reliability, real-time capability and automation.

Geodetic space techniques serve (1) the realization of a global terrestrial reference system, (2) geodetic positioning and deformation measurement, (3) Earth rotation determination and (4) gravity field determination. The attained precision suggests to combine these four fields of application to one integrated observing and monitoring system. A precondition for this is, however, a better insight into the individual role of the various techniques as well as into their strengths and weaknesses. Progress in this direction is slow. The above idea of an integrated geodetic/geodynamic observing system has been chosen as theme for the section II symposium. It was held in Munich from 5 to 9 October 1998.

About the activities of the bodies of Section II , i.e. the special study groups, special commissions, CSTG and IGS it is referred to the respective chapters of this report. IGS has taken several new initiatives such as orbit analysis with the GLONASS satellites, real time orbit computation, GPS tracking of low orbiters and atmospheric sounding. All its work is very successful. The two questions of the future will be, whether IGS in its present form will be able to cope with its ever increasing range of services and, if in the near future atmospheric sounding will be used by weather services, i.e. commercially, whether routine real time orbit provision and data analysis would fit to IGS by-laws in their present form. In view of the success of IGS, CSTG decided to establish two new services: the International Laser Ranging Service (ILRS) and the International VLBI Service (IVS). It will be interesting to watch the development of these two services in view of the fact that their user communities are very different from that of the IGS. WEGENER continued its transition from a geodynamic laser tracking network, it once used to be, to an integrated regional geodynamic observing system. A recent special issue in Tectonophysics (294, 3-6, 173-347) provides an impressive picture of its current work.

One of the topics of the Munich symposium was the current structure of IAG and the need to modify it. It is felt that IAG should thoroughly review its current structure and take provisions for changes. Several facts have triggered this discussion: (1) Nowadays the major international research programs in Earth sciences are organized independent and outside of IAG and even IUGG. Should IAG define its own scientific programme? (2) Geodesy provides extremely valuable data for Earth sciences. However, this is more or less taken for granted by the other disciplines; it is not associated with IAG. (3) Space techniques have penetrated all geodetic fields, therefore it seems not warranted to "concentrate" them in one section. (4) The services, one of the most successful of IAG's activities, are somewhere, almost invisibly, hidden in the structure. (5) Finally, it is important to think of the young generation, how one can attract young brilliant scientists to IAG and what IAG can offer to them. Section II proposed therefore to discuss this topic in Birmingham and at a special retreat of the IAG Executive Committee.

COMMISSION VIII

INTERNATIONAL COORDINATION OF SPACE TECHNIQUES FOR GEODESY AND GEODYNAMICS (CSTG)

Report 1991-1995

Gerhard Beutler and Hermann Drewes, President and Secretary of CSTG

General Goals

The Commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) was established during the XVII-th General Assembly of the IUGG in Canberra in 1979. It is Commission VIII in Section II of the International Association of Geodesy (IAG) and Subcommission B.2 in COSPAR. The charter of the commission is the following:

Develop links between various groups engaged in the field of space geodesy and geodynamics by various techniques, coordinate work of these groups, elaborate and propose projects implying international cooperation, follow their progress, and report on their advancement and results.

CSTG Executive Committee 1995-1999

CSTG operates through an Executive Committee and a broad-based Steering Committee, as well as through the National Representatives in carrying out the Commission objectives stated in the charter. At the beginning of the period 1995-1999 the CSTG Executive Committee was composed as follows:

G. Beutler (Switzerland)	President
H. Drewes (Gemany)	Secretary
B.E. Schutz (USA)	Past President
T. Clark (USA)	Chair, VLBI Subcommission
J. Degnan (USA)	Chair, SLR and LLR Subcommission
P. Willis (France)	Chair, Subcommission on Precise Satellite Microwave Systems
J. Bosworth (USA)	Chair, Geodetic and Geodynamics Sites Subcommission
T. Herring (USA)	Chair, Project on Coordination and Combination of Space Geodetic Analysis

Later on, Claude Boucher (France) became member of the EC as the IERS representative, John Dow (Germany) joined the EC as the COSPAR-liaison, and James Campbell (Germany) replaced Tom Clark as Chair of the VLBI Subcommission. In March 1999, with the creation of the IVS (International VLBI Service), Wolfgang Schlüter (Germany) became Chairman of the IVS Directing Board, thus succeeding James Campbell as VLBI Subcommission Chairman.

3. CSTG Bulletins 1995-1999 and other Publications

The CSTG establishes dissemination of information between the various groups engaged in space geodesy and geodynamics through the publication of the CSTG Bulletin. The following four CSTG-Bulletins were issued in the time period 1995-1999:

- Bulletin 12: Status and Programme 1995-1999 (1996)
- Bulletin 13: Progress Report 1997 (1997)
- Bulletin 14: Advanced Space Technology in Geodesy, Achievements and Outlook (1997)
- Bulletin 15: Progress Report 1998 (1999)

Moreover the proceedings of the Munich Section II Symposium are published by CSTG.

4. Major Achievements in the 1995-1999 Time Period

The ILRS and the IVS

In geodesy we have seen the evolution of two extremely successful services, namely the IERS (International Earth Rotation Service) and the IGS (International GPS Service), providing information to the scientific community and serving as a basis for scientific research. It thus seemed important that the *old-established* space geodetic techniques, namely Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) get organized in a similar way as the GPS community in the International GPS Service (IGS). We consider it as a remarkable achievement that the

- SLR/LLR Subcommission of CSTG was restructured to become the International Laser Ranging Service (ILRS),
- The VLBI Subcommission of CSTG was restructured to become the International VLBI Service for Geodesy and Astrometry (IVS),

in the time period 1995-1999: The ILRS started operations in fall 1998, the IVS in spring 1999. Both services applied to become official scientific services of the IAG. The proposal will be addressed by the IAG Executive Committee at its meetings in Birmingham.
Currently the ILRS and the IVS are considered as services within CSTG. Section II considers the ILRS and the IVS as the successors of the mentioned subcommissions.
The ILRS and the IVS are working in close cooperation with the IERS. The establishment of the services was coordinated between CSTG and IERS.

IGEX-98

The Russian Global Navigation Satellite System (GLONASS) was in the focus of interest of the CSTG Subcommission on precise Satellite Microwave Systems. Together with the IGS, the ION (Institute of Navigation), and the IERS the International GLONASS Experiment 1998 (IGEX-98) was organized.
IGEX-98 was the first global GLONASS tracking and analysis experiment. The experiment started in October 1998 and was terminated in April 1999. Since that time GLONASS trracking and data analysis continue on a *best effort basis*. It is planned to continue activities in the sense of a pilot service. This pilot service shall be organized in close cooperation with the IGS. An international IGEX Workshop will be attached to the 1999 ION conference in Nashville (USA).

In the context of this experiment precise GLONASS orbits are produced and reference frame issues (geometry and time) could be resolved.

FRCN and ISGN

Combination of space techniques is a central issue within CSTG and, e.g., within the IERS for quite some time. In the 1995-1999 time frame several attempts were made to create stable multi-technique networks.

The attempt to form the *IUGG Fundamental Reference and Calibration Network* eventually failed and led to the process of creating the ISGN, the *International Space Geodetic Network*. As opposed to the FRCN, which was planned to become a small but global network of about 20 fundamental stations where all (space) geodetic techniques would be available, the ISGN in essence is a selected number of stations of the existing technique-specific networks of the ILRS, the IVS, the IGS, the DORIS, and the GLONASS networks. The ISGN consists of multi-technique stations with a long-term commitment. The creation of the FRCN Working Group is documented in CSTG Bulletin No. 12, its final report as it was presented to the IAG Executive Committee is included in CSTG Bulletin No. 13. Information concerning the creation of the ISGN is contained in CSTG Bulletin No. 15.

5. Problem Areas

Combining Space Geodetic Analysis

Combination of space geodetic techniques in the analysis is an important issue, but also a difficult one to achieve in practice. The issue was in the center of the project on the *coordination and combination of space geodetic analysis* (Chair Tom Herring). We believe that important progress was made in the time interval 1995-1999 through he creation of the services ILRS and IVS which are now in a position to build up contacts between the services concerning this topic.

Another milestone was the development of the SINEX, the software independent exchange format by the IGS. The SINEX was propagated through the CSTG pilot project and will hopefully soon be accepted as the official result exchange format in space geodesy, in particular within the services IGS, ILRS, and IVS.

Nevertheless, the issue is far from being resolved. Much more work and a close cooperation with the IERS will be required in the next four years period of CSTG. Efforts should be combined with the IERS. We believe that the restructuring process of the IERS asks for IERS leadership in this domain in future.

Let us mention that the GEMSTONE Workshop (25-28 January, 1999), organized by our Japanese colleagues from Communication Research Laboratory (CRL), gave an excellent overview of the issues related to collocation and combined analylsis in space geodesy. The workshop was well attended by the international scientific community, in particular by members of CSTG.

Space Geodetic Satellite Missions

There were many satellite missions in the past and there will be more in future in which the satellite is used as an observing platform to study aspects of the Earth relevant to geodesy and geodynamics. Let us mention in particular that altimetry missions significantly improved our knowledge of the sea surface topography, ocean currents, tidal motions of the oceans, etc.

For space geodesy the TOPEX/POSEIDON mission was a kind of *rosetta stone mission* because its orbit was determined using three independent systems, the French DORIS system, SLR tracking, and the GPS. All three systems proved their capability. The radial

component of the orbit (which is of crucial importance for altimetry missions) could be established with an accuracy of a few centimeters. TOPEX/POSEIDON was neither the first, nor will it be the last altimetry mission. We regret that the commission did not play an active role in this important mission.
For geodesy, geodynamics, and atmosphere physics the upcoming missions CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and application, German mission), GRACE (Gravity Recovery and Climate Experiment, U.S./German mission), and GOCE (Gravity field and Ocean Current Explorer, ESA mission) are milestones. It is expected that our knowledge of the gravity field (using spaceborne GPS receivers, accelerometers, or gradiometers) to measure the non-gravitational forces resp. gravity gradients will significantly increase through such missions.
Also, CHAMP, GRACE and GOCE are able to produce atmosphere profiles using the occultation method: the signal (phase and code) of a GPS satellite is monitored by a spaceborne GPS receiver on the Low Earth Orbiter (LEO) during the time period the line of sight LEO-GPS satellite scans through the Earth's atmosphere. These developments underline that interdisciplinary aspects are becoming more and more important in Space Geodesy.
We believe that CSTG should play a significant role in the development and coordination of space geodetic satellite missions in future.

COSPAR Liaison
CSTG activities are well incorporated in IAG. The link to COSPAR is more problematic. Attempts are made to get a strong CSTG participation for future COSPAR Scientific Assemblies. The next one will be held in summer 2000 in Warsaw, where a common symposium of the COSPAR pannel of precise orbit determination and CSTG is proposed. Based on the experiences of the time period 1999-2001 the CSTG Executive Committee should come up with a proposal whether or not to maintain the link of the commission with COSPAR by the time of the Warsaw meeting.

6. Section II Proposals concerning the future structure of IAG

CSTG, as a member of Section II, was heavily involved in the development of the proposals which might, eventually, lead to a reorganization of IAG. At its business meeting of February 12, 1999 in Munich, Section II decided to present a proposal concerning the reorganization of IAG at the IAG Executive Committee Meeting, March 22/23, 1999 in Paris.
The current structure and possible future modifications of the IAG were in the focus of the Section II Symposium in October 1998 in Munich. It was concluded that the IAG should invoke a thorough review process within the next *legislation period* 1999-2003. This process should include at least one special retreat of the IAG Executive Committee with a well selected list of guests. It must involve all IAG sections and other relevant entities (like IAG services). Section II is convinced that this review is necessary because

- geodesy underwent a dramatic development since the creation of the current structure,
- space geodesy became increasingly important and plays a dominant role in all sections,
- the current section structure does not reflect the present-day situation in an adequate way,

- IAG services (like IERS, IGS, etc.) play an increasingly important role also for research in geodesy and geodynamics. They are not well (if at all) integrated in the current structure.

Section II is convinced that these facts fully justify a reorganization. The process is not yet in an advanced stage. Section II is aware of four more or less concrete proposals, namely

- the structure proposed by the IAG president, K-P. Schwarz at the Munich symposium, where the strucure is centered around a central project (global observing system);
- the structure proposed by Martine Feissel also in Munich, which in essence maintains the section structure but gives much more weight to services, projects, and research;
- merge sections 1,2,3, thus yielding three new sections (measurement methods, modeling, geodynamics),
- form sections according to the key words geometry, rotation, gravity field.

These proposals are not yet formulated in a way that they could be compared in a meaningful way. This is why Section II is convinced that more time is required for the restructuring process. At the IAG Executive Committee Meeting on March 22-23 in Paris, Section II presented the following concrete proposals:

(1) The IAG by-laws shall be adapted in order to allow a reorganization of IAG in the period 1999-2003 through the mechanism described above. The procedure contains in particular

- one or two retreats of the "enlarged" IAG Executive Committee
- proposal to be adopted at the 2001 mid-term meeting
- a structure that can be put in place for the time period 2003-2007.

(2) The "old" IAG structure (with minor changes as proposed by the Cassinis Committee) shall remain in place for the period 1999-2003.

These proposals were in essence accepted by the IAG Executive Committee. First actions will take place at the Birmingham General Assembly.

SPECIAL COMMISSION 6

THE WEGENER PROJECT

REPORT TO IAG

President: Susanna Zerbini

The ”Working group of European Geoscientists for the Establishment of Networks for Earth-science Research” (WEGENER) was established in the beginning of the 1980s as an inter-disciplinary group centered on the application of space geodetic and other techniques to the study of geodynamics. A description of the evolution of WEGENER over the last one and a half decades is presented by (Wilson, 1996). In 1991, the “WEGENER Project: Geodetic Investigations Related to the Kinematics and Dynamics of the African, Arabian and Eurasian Plates” was established as Special Commission SC6 of the International Association of Geodesy (IAG). It is the responsibility of WEGENER to organize parts of the international geodetic and geophysical community in a concerted effort to produce high accuracy and coherent data and valuable results relevant to the three objectives defined below.

The present general study fields were basically worked out during meetings in 1990 and 1991 in response to NASA's “Dynamics of the Solid Earth” DOSE) Announcement of Opportunity, and as a natural development of the scientific activities carried out by the WEGENER group in the course of NASA's Crustal Dynamics Project (CDP) which began in the early eighties.

After the initial period of growth in both the number of scientists involved, or related to WEGENER activities, and the geographical areas covered by projects carried out within its frame, WEGENER has been restructured in 1995 following the election by the IAG of a new President (S. Zerbini) and the formation of a new Directing Board (see Appendix A). During the first meeting of the new board (Bologna, October 1995), the scientific objectives were reviewed and revised according to the most recent developments in the scientific areas of interest to the project. The Board met regularly two to three times a year. A WEGENER Web site has also been created (http://wegener.gdiv.statkart.no)

Achieving the WEGENER scientific objectives relies very much upon the acquisition of high-accuracy data in the experiments. Therefore, it is a major concern of the group that the most appropriate techniques continue to be available or will be developed, whenever possible. WEGENER is maintaining a close contact to the agencies and institutions responsible for the development and maintenance of the global space-geodetic networks in order to make them aware of the scientific needs and outcomes of the project which might have an influence on the general science policy trends.

WEGENER has evolved through the years both as regards science and technology. The Satellite Laser Ranging (SLR) technique using fixed and mobile systems ranging to the LAGEOS geodynamics satellite has first been adopted to realize and repeatedly observe a large-scale network in the Mediterranean and European area. This made it possible to determine reliably the rates of plate movements associated to the continental collision between the African and Eurasian plates and to understand better the overthrusting along the Hellenic Arc. The advent and development of the Global Positioning System (GPS) has led to the densification of the large-scale network in the central and eastern part of the Mediterranean Basin. New fundamental insights in the knowledge of the deformations occurring in the interiors of the plates were found, particularly as regards the eastern Mediterranean in Greece and Turkey. Additional terrestrial techniques, namely gravimetry, has been used to provide an alternative independent method to try to justify vertical movements at the fundamental reference sites as well as to improve the understanding of the geodynamic phenomena occurring in the area of interest to the project.

The present main objectives of WEGENER are

- to study the three-dimensional deformations and gravity along the African-Eurasian plate boundaries and in the adjacent deformation zones in order to contribute to a better understanding of the associated geodynamical processes;
- to monitor the three-dimensional deformations in a large region centered around Fennoscandia in order to determine the magnitude and extent of the present-day postglacial rebound in that area thereby extending our knowledge about the viscoelastic properties of the Earth;
- to investigate height and sea-level variations in order to identify and separate the processes contributing to these variations.

In parallel to these objectives, the mutual improvements of the measurement techniques, the testing of new technological means and proposals for new missions, as well as the synthesizing of observable quantities and the inversion of the observations for geodynamically relevant parameters are parts of all the WEGENER activities. In combination, the three objectives make extensive use of the most advanced space-geodetic and gravity techniques to contribute to scientific fields associated with three-dimensional surface deformations, which are not only relevant to basic science but also have potentially significant economic and social benefits.

Plate boundaries are, in general, geographical areas associated with high risks of natural disasters. A principal key to understanding the plate boundary processes, including the driving forces, is a detailed knowledge of the kinematics and of the associated gravity changes. In particular, a synthesis of the structural information derived, for example, from seismic tomography and the present-day kinematics determined with the geodetic measurements will establish more strict or even novel constraints for geodynamical models of plate boundary processes. Moreover, these data contribute to the framework required for an assessment of natural hazard risks.

The present-day deformations and changes in gravity associated with the ongoing postglacial rebound are an important augmentation of the existing data-sets related to glacially induced deformations such as the pleistocene and holocene sea-level changes, secular polar motion, and secular changes of the low-degree geopotential. The interactions of glacial loads, crustal deformations and sea-level changes over the past 100 ka constitute crucial boundary conditions for paleo-climate models. The uncertainties in our knowledge of the rheology of the Earth's mantle are a basic limitation for the quality of, for example, reconstructed paleo-topographies or geophysically determined ice models. Such knowledge is required as input for paleo-climate reconstructions, and as such it is of utmost significance for the quality of paleo-climate reconstructions.

Sea-level variations and in particular secular changes of sea level play a prominent role in the climate-change discussion. Climate variability on time scales from decades to centuries is presently coming into focus but is not very well understood (see, for example, Crowley and Kim 1993; Rind and Overpeck 1993). However, it is clear that at these time scales, the ocean is a major component of the climate system, and studying the sea-level variability will contribute to an improvement of our understanding of the relevant processes. Europe has coastal areas of considerable extent and ecological and economical value. Understanding sea-level variations on time scales of up to centuries is crucial for an integrated and sustainable management of coastal zones. The anticipated anthropogenic environmental changes are likely to induce significant changes in future sea levels, be it in the frequency of storm surges, tidal ranges or secular trends. Thus, the need to develop the capability of providing current rates and predicting future variations in sea level on local, regional and global scales is fully understood by the international scientific community, as is expressed in recently developed projects such as LOICZ (IGBP, 1993) and international activities of the IAPSO Commission on Mean Sea Level and Tides (Carter, 1994), the ILP (Fard, 1994), The SELF I and II projects (Zerbini et al., 1996 and Zerbini, 1999) and the IOC-Euro-Gloss project (Baker, 1996).

Sea-level records longer than a decade originate exclusively from coastal tide gauges. To determine secular changes from such records is problematic, because tide gauges provide sea level only related to a benchmark on land. In order to obtain absolute sea levels, crustal movements and sea-level variations have to be separated, which necessitates a monitoring of the crustal height variations. Thus, the height determination problem is closely related to the observation of coastal sea level. Moreover, in order to interpret correctly the observed height variations, crustal movements resulting from tectonic forces and postglacial rebound need to be known. This clearly demonstrates the synergistic nature of the three WEGENER objectives: the sea-level problem cannot be solved correctly without solving the two other problems attacked by the WEGENER activities.

During the past four years the WEGENER project held three general assemblies namely the seventh general assembly in Vila Nova de Gaia on June 3-7, 1996 hosted by the Astronomical Observatory of the Faculty of Science of the University of Porto, the eight general assembly held in Maratea, Italy on June 9-12, 1997 hosted by the Italian Space Agency and the ninth general assembly held in Krokkleiva, Norway, on June 29 – July 3, 1998 and hosted by the Norwegian Mapping Agency. The WEGENER Board has agreed to delay the tenth general assembly to year 2000 because of the XXII general assembly of the International Union of Geodesy and Geophysics taking place in July 1999. The next assembly of the project will take place in Cadiz, Spain, at the end of June 2000. Scientific outcomes of the general assemblies were three special issues of International Journals, namely the Journal of Geodynamics (1998), Tectonophysics (1998) and the Journal of Geodynamics (1999, in press) (see Appendix B)

REFERENCES

Baker, T.~F., Woodworth, P.~L., Blewitt, G., Boucher, C., and Woppelmann, G. (1996), A European network for sea level and coastal land level monitoring, Journal of Marine Systems.

Carter (1994). Report of the Surrey Workshop of the IAPSO Tide Gauge bench Mark Fixing Committee. Technical report, December 13-15, 1993, Deacon Laboratory, Godalming, Surrey, UK. NOAA Technical Report NOSOES0006.

Crowley, T.~J. and Kim, K.-Y. (1993), Towards development of a strategy for determinating the origin of decadal-centennial scale climate variability. Quat. Sci. Rev., 12, 375--385.

Rind, D. and Overpeck, J. (1993), Hypothesized causes of decade-to-century-scale limate variability: climate model results, Quat. Sci. Rev., 12, 357--374.

Wilson, P. (1996), An Introduction to the Working group of European Geo-scientists for the Establishment of Networks for Earth-science Research (WEGENER). J. Geodynamics, 25, N. 3-4 177-178.

Zerbini, S., Plag, H.-P., Baker, T., Becker, M., Billiris, H., Bürki, B., Kahle, H.-G., Marson, I., Pezzoli, L., Richter, B., Romangoli, C., Sztobryn, M., Tomasi, P., Tsimplis, M., Veis, G., and Verrone, G. (1996), Sea level in the {Mediterranean}: a first step towards separation of crustal movements and absolute sea-level variations. Global and Planetary Change, 14, 1--48.

Zerbini S. (coordinator) (1999), SEa Level Fluctuations in the Mediterranean: interaactions with climate processes and vertical crustal movements (SELF II), Final report, 254 pp.

APPENDIX A

WEGENER STRUCTURE
President SC6: S. Zerbini

SCIENCE ADVISORY COMMITTEE Chairperson: H.-P. Plag	EXECUTIVE COMMITTEE Chairperson: S. Zerbini	TECHNOLOGY COMMITTEE Chairperson: B. Richter
H.-G. Kahle	G. Beutler	B. Ambrosius
I. Marson	J. Bosworth	T. Baker
M. Pearlman	A. Cazenave	L. Bastos
H.-P. Plag	B. Engen	G. Bianco
R. Rummel	I. Kumkova	G. Blewitt
D. Smith	D. Wolf	T. Clark
W. Spakman	C. Wilson	J. Degnan
S. Tatevian	S. Zerbini	B. Richter
S. Zerbini		P. Tomasi

Appendix B
WEGENER SPECIAL ISSUES

Journal of Geodynamics 1998, vol. 25, n. 3-4: WEGENER: Scientific Objectives and Methodological Challenges for the Application of Space-Geodetic Techniques to Earth Sciences, p. 175-340.

Tectonophysics 1998, vol. 294, n. 3-4, WEGENER: An Interdisciplinary Contribution to Unraveling the Geodynamics of the European and Mediterranean area, p. 173-347.

Journal of Geodynamics 1999, in press.

SPECIAL COMMISSION SC7

GRAVITY FIELD DETERMINATION BY SATELLITE GRAVITY GRADIOMETRY

by
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1 Objectives

The necessity of a high-resolution satellite borne gravity field mission was defined already in 1969 in the so-called Williamstown Report by the leading geo-scientists at that time. The idea was to derive the gravity field and positions at the earth's surface and in space consistently at the same level of precision. For various technological as well as political reasons such a mission could not be realized within the last thirty years despite the intensive work of many individual scientists and scientific groups and the International Association of Geodesy (IAG) as a whole.
Occasionally the IAG General Assembly in Boulder, USA, in 1995 a Special Commission SC7 to Section II - Advanced Space Technology - had been established to create a forum that integrates all international activities related to gravity field determination by satellite gravity gradiometry and to prepare the conditions for a future mission. In detail, the Special Commission shall

- represent IAG interests in such a mission on a political level,
- support a gravity gradiometry mission by scientific studies,
- investigate scientific and commercial applications of a very precise high resolution gravity field,
- assist in coordination and definition of national and international concepts related to gravity gradiometry,
- act as advisor to national and international bodies responsible for such a misssion,
- inform the geodetic community about all these activities.

2 Activities

To make the work of the Special Commission as effective as possible and to integrate all interests to meet these ojectives a steering and advisory committee and various task groups have been created, as

- Ad hoc group “Scientific objectives”,
- CIGAR-IV Study Group,
- STEP-Geodesy Working Group,
- Working Group “Application of Boundary Value Techniques to Satellite Gradiometry”.

To inform the geodetic community about the relevant activities, a homepage has been created, accessible from the IAG homepage and via the homepage of the University Bonn „http://www.geod.uni-bonn.de“.
There were various reasons that the work of the Special Commission was not as effective than formerly expected. The main reason is that it turned out to be very difficult for a group with only advicing function to influence national organizations to support a certain satellite borne gravity mission. Around the year 1995 the common opinion was that only a dedicated satellite gravity gradiometry mission could provide a gravity field which meets the demands of the community. In the following years since 1995 the situation changed in so far as the cheaper satellite-to-satellite tracking concept was more succesful in being realized. In the next section the development during the past four years is sketched.

3 The past years

End of the eighties a mission concept, based on the French GRADIO instrument, the so-called ARISTOTELES mission, was discussed in detail. In 1995 it was decided GPS/ ARISTOTELES not to follow up further on. The next realistic chance to place a geodetic gravity field mission emerged with the definition of a proposal to test the equivalence principle, fundamental for Einstein’s Gravitational Theory. This so-called STEP mission was proposed as a candidate for the Medium Size Programme M2 as a joint ESA/NASA project. It was proposed again for M3 as a sole ESA project. The STEP geodesy experiment was designed to consist of a one-axis superconducting gravity gradiometer with an expected accuracy of 10^{-4} E Hz$^{-1/2}$. The experiment was finally planned to be combined with multi high-low SST. In spring 1996 STEP was not recommended as M3-mission - only a so-called MiniSTEP or GeoSTEP should be realized, most probably as a joint NASA/ESA project.
After the year 1992 a number of „intermediate“ mission concepts were proposed. They should „bridge“ the past and future in gravity field research - and they should be cheaper than the mission proposals before. This is the programmatic idea behind the French mini-satellite concept BRIDGE. It was a CNES project and was considered to be based on SST/GPS or DORIS. Improved technology, in the main parts already available as existing sensors and commercial spacecraft components, and therefore cheaper than expected before gave a new fresh impulse to the idea of a future satellite gravity mission. These are the main criteria of the so-called „small satellite mission“ concepts. Additional cost-reducing actions are the decision to reduce quality standards and test efforts. A further cost reducing factor is the availability of the Global Positioning System (GPS) or any other precise satellite navigation system as GLONASS. By these systems the high altitude component of a high-low SST configuration is provided - and a relatively cheap possibility to determine precise orbits.
The high-low mission concept based on GPS and a LEO (Low Earth Orbiter) were applied in the past for Topex/Poseidon, GPS/Met and the Explorer platform. Consequently, the high-low SST links are generally integrated in current mission concepts. Furthermore, it can be shown that SST and SGG are complementary techniques for detecting the gravity field: the long wavelength part can be improved by (high-low but also low-low) SST and the high-frequent part can be detected best by SGG. Therefore, current promising mission concepts consist of a combination of both, high-low SST and SGG or high-low SST and low-low SST. In the former case a low platform carries a gravity gradiometer (preferably a full tensor component gradiometer) and a system of high altitude satellites observes the low earth orbiter. In the latter case the low-low SST configuration is linked to the high altitude satellites of a precise satellite navigation system (GPS and/or GLONASS). Even if the

small satellite mission concepts are not able to provide the very high accuracies and resolutions necessary for some applications in the geo-sciences they could decisively contribute to a gravity field improvement.
During the last years, a series of concepts were proposed; some of them were considered as low cost missions, e.g., the American proposals GRACE, COLIBRI or HUMMINGBIRD, or the German project CHAMP. Typically, the gravity field sensitive spacecraft were planned to be equipped with GPS receivers and accelerometers. A recent proposal is SAGE (Satellite Accelerometry for Gravity field Exploration). It is an Italian mission concept aiming at determining the gravity field of the earth by the high-low SST mode based on very accurate acceleration and position measurements. In case of the mission concepts GRACE and TIDES the relative motion of two small free-flying spacecrafts is planned to be measured. TIDES (Tidal Interferometric Detector in Space) is based on laser doppler interferometry using ultra-stable lasers. The concept consists of two small free-flying spacecraft in tandem formation about 500km apart and in near-circular orbit. The surface forces are considered to be compensated or measured and taken into account afterwards. Other mission concepts were based on satellite gravity gradiometry for deriving the high frequency part, eventually equipped with GPS receivers to enable satellite-to-satellite tracking to improve also the long wavelength part of the gravity field, as e.g. the American mission concept GEOID or ESA’s Earth Explorer Mission candidate GOCE. GEOID (Gravity for Earth, Ocean, and Ice Dynamics) was a spaceflight mission proposed by GSFC and based on the University of Maryland’s superconducting gravity gradiometer. These concepts can be considered as dedicated gravity missions. They have the potential to improve high frequent features of the static part of the gravity field up to a degree of 200 of a spherical harmonics expansion or even more - but they are expected to be more expensive and do not fulfill the criteria of small satellite missions.

4. The present situation
After careful selection procedures two mission concepts were successful and will be realized in the coming years: CHAMP, a German multi-sensor satellite mission with international contributions and GRACE, a combined high-low/low-low SST mission as a joint American-German mission. The European SGG - mission concept GOCE has a realistic chance for realisation and is under intensive preparation.
In early 2000, the German geoscientific small satellite CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) will be brought into a nearly circular orbit with an inclination of $83°$ at an altitude of about 400km. In a five years mission the observation system will provide earth system related data with yet unattained accuracy. The following main tasks are envisaged:

- measurement of the stationary and time variable part of the global gravity field in the medium and long wavelength frequency range,
- measurement of the global magnetic field and its temporal variations,
- sounding of the atmosphere and the ionosphere.

The satellite mission will be carried out by DLR (German Space Agency) and GFZ (GeoForschungsZentrum) Potsdam. Of special importance of this mission is the fact that the first time in the history of satellite geodesy important earth related data will be collected at the same time for a time span of five years on a low altitude platform:

- precise intersatellite measurements between the low satellite CHAMP and the high GPS satellites (high-low SST with a range accuracy of $0.1\mathrm{m}/\sqrt{\mathrm{Hz}}$),

- accelerations along three axis to determine the surface and inertial forces of CHAMP (accuracy of acceleration: $1nm/s^2\sqrt{Hz}$),
- orientation measurements by star sensors and by various GPS antennas,
- radio occultation measurements between CHAMP and the GPS satellites,
- measurement of scalar and vector magnetic field strengths,
- measurement of the electrical field by ion drift meter,
- precise earth bound (two-color) laser ranging,
- altimeter measurements between CHAMP and the sea/ice surface by nadir oriented GPS antenna.

The measurement accuracy of the GPS receivers and the altitude of CHAMP between 300 to 500km enables a spatial resolution of the gravity field of approximately 500km. The expected accuracy of the corresponding spectral range is by a factor ten higher than realized in the present gravity field models. That means that the geoid can be determined with an accuracy of one centimeter for wavelengths down to 1000km.
The American-German mission GRACE (Gravity Recovery and Climate Experiment) will open the door to a further improvement of the gravity field with respect to accuracy and resolution. GRACE is a follow-on mission to CHAMP. The mission will consist of two identical CHAMP satellites without the boom where the magnetometers are placed in case of CHAMP. The intersatellite range-rates in along-track direction between the low satellites (at an altitude of about 400km) will be measured with μm -accuracy. The high-low links to the GPS satellites will have a comparable accuracy as planned for the CHAMP mission. With these measurement accuracies it will be possible to determine the medium and long wavelength part of the geoid down to 500km wavelengths with an accuracy of about $0.1mm$. These are two orders better than in case of CHAMP. The launch of GRACE is planned for the year 2001. CHAMP and GRACE will have a parallel mission period of approximately two years. The parallel missions with different orbits will enable additional experiments which will lead to a synergetic effect of both missions. The tasks of GRACE are directed to the:

- determination of the static part of the global gravity field with unattained accuracy in the medium spectral range; geoid accuracies of $0.01mm$ for a resolution of $>5000km$ and of 0.01 to $0.1mm$ for a resolution of 500 to $5000km$ can be expected,
- determination of the time variability of the gravity field in two to four weeks temporal resolution; the accuracy of the change of the geoid in the size of 0.01 to $0.001mm$ / year can be expected,
- sounding of the atmosphere and the ionosphere.

The GRACE low-low SST mission and the GPS-GRACE high-low SST test system will provide valuable earth related observables over a mission period of five years:

- precise along-track intersatellite measurements between the low satellites of GRACE (low-low SST) in the size of few μm and a mutual distance of both satellites between 200 and $500\,km$,
- precise relative measurements between the GRACE satellites and the GPS satellites,
- accelerations along three axis to determine the surface and inertial forces of CHAMP (accuracy of acceleration: $1nm/s^2\sqrt{Hz}$),
- radio occultation measurements between the low satellites of GRACE and the high GPS satellites at the setting and rising phase,

GOCE (Gravity Field and Steady-State Ocean Circulation Explorer Misson) is one of the candidates to become the first Earth Explorer core mission. It is a high resolution gravity field mission concept and will open a completely new range of spatial scales of the earth's gravitational field spectrum down to 100km wavelength. GOCE is planned to be launched in a nearly circular sun-synchronous orbit with an inclination of $\approx 97°$ at an altitude of around 250 km, carrying a

- dual frequency combined GPS and GLONASS receiver called GRAS (for its utilisation as GNSS receiver for atmospheric sounding), and a
- three-axis gravity gradiometer, either an ambient temperature instrument with a precision of about $4 \cdot 10^{-3} \mathrm{E} / \sqrt{\mathrm{Hz}}$ for the diagonal components of the gravity tensor, or a cryogenic gradiometer with a performance raughly one order of magnitude better, furthermore a
- star tracker to control the orientation of the gradiometer with an accuracy of about $3 \cdot 10^{-3} \mathrm{rad} / \sqrt{\mathrm{Hz}}$, and an
- equipment to keep the satellite motion drag-free.

The excellent evaluation of this mission concept under nine mission proposals of ESA's Earth Explorer Mission programme justifies the hope that also this mission will be realized within the coming decade.

5 The future

CHAMP, GRACE and GOCE have the potential to revolutionize the knowledge of the system earth. Not only the static part of the gravity field can be determined with unattained accuracy also an eventual time dependency can be derived. Despite the fact that all three missions have the potential to measure the gravity field by sort of relative measurements between free falling sensors, they are not redundant. Indeed, the characteristics of high-low SST, low-low SST and SGG are rather complementary than competitive SST is superior in the lower harmonics below degree and order 50 to 60. A mission like GRACE, therefore, is optimal for studying time-varying gravity effects at moderate wavelengths. The static part of the gravity field up to approximately degree 50 can be expected with high accuracy. A condition to detect temporal effects is a corresponding mission duration of several years. Satellite gradiometry is superior for obtaining high spatial resolution from a moderate mission length. A recent study by ESA showed that increase of measurement precision or decrease of altitude results in a clear gain of spatial resolution in case of SGG, while this effect is very moderate in case of SST. A SGG mission like GOCE is superior in the short wavelengths parts of the gravity field up to a spherical harmonics degree of 250. The results of a mission like GOCE start to be better than those of a low-low SST mission from degree 60 to 80 on. A high-low SST mission like CHAMP can provide an improvement in the knowledge of the gravity field of approximately one order of magnitude over present models for wavelengths between 400 to 2000km.
One should be aware of the fact that the coming years will represent an enormous challenge for the geo-sciences. First of all with respect to the measurement and the processing procedures. Typical for the future satellite missions is the fact that they are not just point masses moving free within the gravity field as in the past. Instead they are multi-purpose observation and test systems on low flying platforms. Various different observables are collected parallel over years providing valuable information of the system earth. The first time in history it is possible to investigate the interactions of the potential fields of the earth. Challenging questions are related to the

- formulation of balance equations for the various model parameters of the static and temporal parts of the gravity field,

- development of models to take into account the fact that the three-dimensional orbits are measured together with atmospheric data, atitude control data (by star sensors) and accelerations in three directions to eliminate the surface forces,
- data verfication, calibration and combination procedures based on existing terrestrial measurements and available models, and
- tackling the inverse geophysical/geodetic models based on time series of the gravity field and the ionosphere, collected over a time span of severeal years.

Satellite measurements can provide unprecedented views of the earth's gravity field and its changes with time. Together with complementary geophysical data, satellite gravity data represent a "new frontier" in studies of the system earth. It can be expected that the work of Special Commission 7 can be more successful in the coming years than in the past. Indeed, the data available in the next future will attract many groups with different analysis concepts. In that case SC7 might have the chance to support the international exchange of ideas and to draw the greatest possible benefit out of these data.

6 Selected Literature

ASI: SAGE, Phase A Final Report, International Geoid Service, Milano, Nov. 1998

Bills, B.G. and Paik, H.J.: GEOID mission: Gradiometer Views of Static and Dynamic Gravity Signals, presented at: AGU Spring Meeting, Baltimore, May 1996

Canavan, E.R. and M. Vol Moody: GEOID Mission: Instrument and Error Budget, presented at: AGU Spring Meeting, Baltimore, May 1996

Chao, B.F., Colombo, O.L. and P.L. Bender: Global Gravitational Changes and The Mission Concept of TIDES, presented at: AGU Spring Meeting, Baltimore, May 1996

Clark, T.A., Skillman, D.R., Bauer, F.H., O'Donnell, J.R., Pavlis, E.C., Liberman, D.I. and F. Bisiacci: COLIBRI: A Low-cost Spacecraft Design for Gravity Change Studies, presented at: AGU Spring Meeting, Baltimore, May 1996

Davis, E.S., Melbourne, W.G., Reigber, Ch., Tapley, B.D. and M.M. Watkins: GRACE: An SST Mission for Gravity Mapping, presented at: AGU Spring Meeting, Baltimore, May 1996

ESA: Geophysical Interpretation of High Resolution Gravity Field Information, Final report, 1991

ESA: Gravity Field and Stead-State Ocean Circulation Mission, Reports for Assessment: The Nine Candidate Earth Explorer Missions, ESA SP-1196(1), ESA Publications Division, ESTEC, Noordwijk, 1996

ESA: European Views on Dedicated Gravity Field Missions: GRACE and GOCE, European Space Agency, ESD-MAG-REP-CON-001, May 1998

GOCE: Gravity Field and Steady-State Ocean Circulation Mission. Reports for Assessment, The Nine Candidate Earth Explorer Missions, ESA SP-1196(1), 1996

Müller, J., Sneeuw, N., and R. Rummel: Problems and Prospects of the Planned Gravity Missions GOCE and CHAMP, this volume, Oct. 1996

NASA: Geophysical and Geodetic Requirements of Global Gravity Field Measurements (1987-2000). Report of a Gravity Workshop at Colorado Springs, Geodynamics Branch, 1987

NRC: NRC (National Research Council): Satellite Gravity and the Geosphere. National Academy Press, Washington D.C., 1997

Paik, H.J.: Superconducting Gravity Gradiometers on STEP, in: R. Rummel and P. Schwintzer (eds.), A Major STEP For Geodesy, Report 1994 of the STEP Geodesy Working Group, Munich, Potsdam, Nov. 1994

Pavlis, E.C., Clark, T.A. and B. Bills: Gravity Modelling With the Hummingbird Constellation, presented at: AGU Spring Meeting, Baltimore, May 1996

Pavlis, E.C., Lemoine, F.G., Olson, T.R., Rowlands, D.D. and J.C. Chan: Earth Gravity Model Improvement From GPS Tracking of Topex/Poseidon, GPS/Met and Explorer Platform, presented at: AGU Spring Meeting, Baltimore, May 1996

Reigber, Ch., Kang, Z., König, R. and P. Schwintzer: CHAMP - A Minisatellite Mission for Geopotential and Atmospheric Research, presented at: AGU Spring Meeting, Baltimore, May 1996a

Reigber, Ch., Bock, R., Förste, Ch., Grunwaldt, L., Jakowski, N., Lühr, H., Schwintzer, P. and C. Tilgner: CHAMP Phase B, Executive Summary, Scientific Technical Report STR96/13, GeoForschungsZentrum Potsdam, Potsdam, Nov. 1996b

Rim, H.J., Schutz, B.E., Abusali, P.A.M., Nam, Y.S., Poole, S.R., Ries, J.C., Shum, C.K. and B.D. Tapley: The Contribution of GPS Data to Modern Gravity Model Improvement, presented at: AGU Spring Meeting, Baltimore, May 1996

Rummel, R., Sneeuw, N. and J. Müller: Geodetic Requirements and Prospects Study of Gravity Explorer Mission Requirements (A Simulation Study), Technical Note, prepared for DASA, Dornier Satellitensysteme GmbH, München, Sept. 1995

Shirron, P., DiPirro, M., and S. Castles: GEOID Mission: Spacecraft and Dewar Design, presented at: AGU Spring Meeting, Baltimore, May 1996

Sneeuw, N.: Global Gravity Field Error Simulations for STEP-Geodesy, in: R. Rummel and P. Schwintzer (eds.), A Major STEP For Geodesy, Report 1994 of the STEP Geodesy Working Group, Munich, Potsdam, Nov. 1994

Sneeuw, N., Rummel, R., and J. Müller: The Earth's Gravity Field from the STEP Mission, Class. Quantum Grav. 13, A113-A117, 1996

Sneeuw, N. and K. H. Ilk: The Status of Spaceborne gravity field mission consepts: a comparative simulation study, in J. Segawa, etal. (eds): Gravity, Geoid and Marine Geodesy, IAG Symposia Vol. 117, Springer, Berlin, etc., 1997

Williamstown Report: The Terrestrial Environment. Solid-Earth and Ocean Physics, Application of Space and Astronomic Techniques. Report of a Study at Willliamstown, Mass, to the NASA, 1969.

SPECIAL STUDY GROUP 2.160

SAR INTERFEROMETRY TECHNOLOGY

Period 1995-1999
XXII IUGG General Assembly
Birmingham, 19-30 July, 1999

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Introduction

The technical challenges and the application of Synthetic Aperture Radar (SAR) interferometry (InSAR) for topographic mapping and deformation measurements from space have developed dramatically since the beginning of the 1990s. Whereas in the beginning of the 1990s only a few groups world-wide focussed on this new technique for remotely monitoring the Earth's surface, there are dozens of research teams currently active world-wide. Their background is completely different: among them are electrical engineers, geophysicists, geologists, space engineers, and geodesists. Correspondingly, the number of scientific publications related to InSAR technology and applications has exploded in the same period. In the meanwhile there are special symposia devoted to InSAR with hundreds of participants, e.g., the ESA FRINGE meetings and the yearly IGARSS symposia. In the same period there are special sessions on InSAR and its applications in geosciences at all large geoscientific meetings such as the General Assembly of the EGS and the yearly meetings of the AGU. For years, InSAR, was rather unknown to geodesists also geodesists have a long tradition in techniques and methods for mapping the topography and surface deformations from space. In 1995 at the XXI General Assembly of the IUGG in Boulder, Colorado, the IAG gave credit to this new technique and established the Special Study Group (SSG) 2.160 on InSAR Technology within the IAG Section II Advanced Space Technology. Appendix A contains the list of members of the SSG.

Membership:

R. Bamler, DLR/DFD, Germany
S. Coulson, ESA/ESRIN, Italy
E. van Halsema, TNO-FEL, The Netherlands
R.Hanssen, Delft University of Technology, The Netherlands
Ph. Hartl, München, Germany
R. Klees (chairman), Delft University of Technology,The Netherlands

D. Massonnet, Centre National d'Etudes Spatiales, France.
M. MurakamiGeographical Survey Institute, Japan.
Chr. Pearson, The University of Otago, New Zealand
P.A. Rosen, Jet Propulsion Laboratory, U.S.A.
M. Schmidt, DGFI, Germany
P. Vachon, CCRS, Canada,
S. Usai, Delft University of Technology, The Netherlands

Research objectives

The major objective of the SSG was to develop techniques that allow extracting unambiguously the topographic and deformation signal from spaceborne repeat-pass across-track SAR interferometry, to develop data processing strategies and algorithms that allow to process radar interferometry data accurately and efficiently, to identify and examine the main limitations to SAR interferometry, to develop strategies to overcome these limitations, and to perform a thorough validation of topographic and deformation maps for various applications and under various environmental conditions. All thematic applications of SAR and InSAR and related problems such as land cover classification, bio-mass measurements, snow and soil moisture measurements, monitoring of sea ice thickness, and characterisation of oil slicks, were out of the scope of the SSG. A secondary objective was to promote InSAR in the geo-scientific community by publishing a number of review articles in scientific journals and by organising special InSAR related sessions at (geo-) scientific symposia and workshops of the IAG, EGS, and AGU. As far as the second objective concerns three larger review papers have been published by members of the SSG, cf. (Massonnet and Feigl 1998), (Bamler and Hartl 1998), (Klees and Massonnet 1999). Moreover, several InSAR devoted sessions have been organised at scientific meetings, workshops and General Assemblies of the EGS and the AGU, and members of the SSG usually act as convenor or chairman.

The scientific objective has led to the following research items:

1. Data processing strategies and algorithms
   Filtering, phase unwrapping, coherence estimation
2. Error sources and quality description

Limitations to interferometric measurements, atmospheric disturbances, temporal decorrelation, nature of noise, and error propagation

3. Specific applications in geo-sciences
   Earthquakes, volcanoes, anthropogenic processes, glaciers and ice sheets

In the following I will summarise the major findings of the SSG. Appendix B contains the scientific output of the SSG.

Results

1.1 Data processing strategies and algorithms

The main focus of the SSG within this research item was on the problem of two-dimensional phase unwrapping. The reason is that phase unwrapping is the core technique that enables InSAR. SAR interferometry exploits the phase of two or more coherent signals. Since the phase influences the signal only through phase principal values between $\pm\pi$ radians we can actually measure only these principal values, the so-called wrapped phases. In other words, the phase measurements in SAR interferograms are ambiguous by integer multiples of 2π. This ambiguity must be resolved in order to obtain unambiguous information about the topography or the surface deformation. However, the relation between the discretely measured wrapped phase values and the geometric information is highly non-linear, and the problem of phase unwrapping is from the mathematical point of view a non-linear inverse problem. In addition, imaging geometry, noise, and aliasing can destroy our ability to unwrap the phase correctly. A variety of ideas and algorithms have been proposed so far, but to a large extent it is not clear which methods are good and which are not. A first step in order to answer this question was the definition of different test data sets by ESA's FRINGE group, which allow comparing and analysing the various algorithms under different conditions. Although the best method (if it exists at all) has not been found yet, the SSG could make some important contributions to the problem of phase unwrapping.

Phase unwrapping in SAR interferometry consists of two steps: (1) the estimation of phase gradients from the interferogram, and (2) the integration of the estimated phase gradients in order to obtain an unwrapped phase surface. The various phase unwrapping algorithms differ in the way these two steps are done. Bamler and Davidson (1996) and Bamler et al. (1996) showed that the commonly used estimator for phase gradients underestimates the slopes in the presence of noise. Hence, all linear estimators operating on these phase gradients like least squares methods tend to globally distort the reconstructed terrain or deformation field. This motivates the research on unbiased estimators for phase gradients. In a number of papers (Davidson and Bamler, 1996a, 1996b, Bamler and Davidson 1997, Bamler et al. 1998, Davidson and Bamler 1999) an estimator for phase gradients is proposed that is asymptotically unbiased. Whereas the usual approach uses small estimation windows of $2*2$ samples, leading to a high probability of aliasing, they propose to estimate local fringe frequencies over larger windows at the cost of lower spatial resolution. This estimate is then used to reduce the phase variation of the next higher resolution, i.e., of the next smaller estimation window. This is repeated until the highest resolution is obtained. The final frequency estimation at the highest resolution is obtained by summing up the frequency differences as long as aliasing errors in the frequency estimates do not occur as detected by the curl of the measured phase gradient. Although aliasing errors due to noise still occur, the error has asymptotically zero mean because of the smaller frequencies being estimated at each level, and a smooth reconstruction of the unwrapped phase is obtained. Thus, a trade-off between bias and resolution has to be made taking the coherence as indicator of the local quality of the phase values into account. Multiresolution frequency analysis, using a modification of a spectral centroid estimator as local frequency estimator given by the phase of the autocorrelation function at the lag of 1 sample, allows for such an adaptive adjustment of window sizes. Moreover, it makes the estimation computationally more efficient. The estimator is proved to provide asymptotically unbiased gradient estimates. In Davidson and Bamler (1999) the approach to 2D phase unwrapping is further improved. The idea is that phase unwrapping can be improved if a coarse resolution phase surface is available. Instead of using a DEM they estimate a coarse phase surface from the data itself using a weighted least-squares method based on coherence weighting. Then, the coarse phase is used in their slope-adaptive spectral shift filtering approach in order to improve the coherence and to reduce the phase variation in the interferogram. The resulting "flattened" interferogram can be performed more accurately with any algorithm, and the effect of phase slope on the aliasing error in phase gradient estimation is reduced.

Just et al. (1995) compared different approaches to phase unwrapping, namely the cut-and-branch approach, the classical representative of path-following methods, and two minimum-norm methods, the weighted and unweighted least-squares methods. Main emphasis has been put on how these methods behave in the presence of noise and undersampling. They concluded that the cut-and-branch approach is likely to introduce global errors in the unwrapped image. Later on Ghiglia and Pritt (1998) argued that this may be due to their special implementation of the original algorithm.

Massonnet et al. (1996) proposed a method, which sometimes avoids phase unwrapping in topographic mapping. The method requires a (rough) digital elevation model (DEM) to be available. The unwrapping procedure is replaced by forming a number of integer linear combinations of interferograms with an artificially high height of ambiguity such that unwrapping is not necessary. The method is a variant of the so-called multi-baseline technique, which uses at least three SAR images with one baseline large and the others small. The small baseline interferogram (large height of ambiguity) is used to provide a coarse estimate of the topography. Then, a more precise estimate is derived from the large baseline interferogram. Although this procedure is not general enough, it may sometimes reduce the need for phase unwrapping.

Coherence is a very important indicator of the quality of the phase values in interferograms, and is thus needed in many interferometric processing steps, e.g., in weighted least-squares techniques to phase unwrapping. Touzi et al. (1996a-b, 1998) derived the statistics of classical coherence estimators for Gaussian scenes. They showed that the classical coherence estimator is biased towards higher values for partially coherent areas. They proposed a multilook complex coherence estimator, which has been shown to be "less" biased than the classical multilook magnitude estimator. The statistics of the former is then used to remove the coherence bias. They also discussed coherence estimation for non-stationary targets and showed that the averaged sample coherence permits the calculation of an unbiased coherence estimate provided that the original signals can be assumed to be locally stationary over a sufficiently coarse resolution cell. Vachon et al. (1995) corrected for the estimation bias for low coherence levels based on a theoretical probability density function. They found that the temporal decorrelation is strongly dependent on local weather conditions and vegetation type. Zebker et al. (1996) confirmed an empirical result of Wegmueller and Werner (1995) that the number of pixels used to compute the ensemble mean biases the correlation coefficient in low coherence areas, and that a larger window size is required for those areas.

1.2 Error sources and quality description

There are numerous processes that affect the quality of the phase values and may introduce bias in the estimated topography or deformation field. Among them are satellite clock errors, residual topographic signals in differential interferograms, satellite orbit errors, atmospheric disturbances, and various types of decorrelation. In a number of studies the

SSG could prove that the most serious limitations to SAR interferometry are changes of the refractive index in the time between the image acquisitions (atmospheric disturbances), and changes of the backscatter characteristics within a pixel (temporal decorrelation). Whereas atmospheric disturbances may be interpreted as topography or deformation signal, temporal decorrelation causes loss of coherence, thus degrading the quality of the phase values or even make SAR interferometry impossible.

The main focus of the SSG was on a detailed examination of phase distortions in SAR interferograms caused by atmosphere and on the problem of temporal decorrelation. As far as atmospheric disturbances concerns the objective was to detect atmospheric effects in SAR interferograms, to assess their impact on the performance of spaceborne InSAR for topographic mapping and deformation measurements, and to understand their relation to physical characteristics of the atmosphere. The followed strategy was to select test areas and SAR images that allow studying the atmospheric distortions, to perform the interferometric data processing, to detect artefacts using methods still to be developed, to estimate the delay, e.g. from weather radar observations, radio sondes, satellite imagery or ground meteo observations, and to correlate these estimates with estimated phase variations from InSAR. Massonnet and Feigl (1995) and Massonnet et al. (1995) published first speculations on the contamination of interferograms of atmospheric origin. They developed a pair-wise logic useful in order to discriminate signal from various types of artefacts, and correspondingly applied this approach to identify artefacts in interferograms and to speculate about the origin of these effects. They argued that both ionospheric and tropospheric effects are responsible for phase distortions in interferograms. The pair-wise approach (cf. Massonnet and Feigl 1995, Tarayre and Massonnet 1996) is based on the fact that single-epoch events contaminate every interferometric pair that uses the image acquired at this epoch. By comparing several interferograms, this single-epoch event can be distinguished from the topographic or deformation signal. Consequently, the corresponding SAR image is removed from the data processing. In that way it was possible to identify phase signatures in interferograms as caused by local neutralisation of the ionosphere and water vapour and turbulence in the troposphere. However, the pair-wise logic cannot remove atmospheric signatures from interferograms, which is still the most serious and unsolved problem.

Other studies of the SSG also described various types of atmospheric effects in SAR interferograms and showed that temporal and spatial variations of the refractive index of the propagation medium lead to phase variations in the interferograms (cf. Hanssen and Feijt 1996, Rosen et al. 1996, Hanssen and Usai 1997, Zebker et al. 1997, Fujiwara et al. 1998). Tarayre and Massonnet (1996) observed up to three phase cycles localized phase shift caused by cumulus clouds, while Hanssen and Usai (1997) reported wave effects with a wavelength of about 2 km and amplitudes of 0.25 cycles, and localised phase shifts up to 5 phase cycles. In a detailed study on atmospheric effects in InSAR surface deformation and topography maps Zebker et al. (1997) analysed shuttle imaging radar-C/X-SAR C- and L-band Hawaii data. They showed that time and space variations of atmospheric water vapour are by far the dominant error source in repeat-pass spaceborne SAR interferometry in wet regions. Spatial and temporal changes of 20% in relative humidity lead to 10-cm errors in deformation products, and perhaps 100 m of error in topographic maps for unfavourable baseline lengths. For topographic mapping the errors may be mitigated by choosing interferometric pairs with relatively long baselines (within the limits of baseline decorrelation), as the error is inversely proportional to the perpendicular component of the baseline. In the case of deformation measurements the error is almost independent on the baseline length, and the only solution is averaging of independent interferograms. This requires that many SAR images are available and that the deformation is a linear function of time. Then, accuracies of 10 m for digital elevation models and 1 cm for deformation maps are possible even in wet regions.

The currently most detailed assessment of the influence of the atmosphere on SAR interferograms has been done by Hanssen (1998). He analysed the influence of atmospheric heterogeneities on the interferometric phase observations from a series of 26 ERS tandem mission interferograms, and evaluated them using additional meteo data. Main emphasis has been put on a quantitative analysis of the observed atmospheric phase artefacts in terms of spatial scale and magnitude, on a classification of the effects, and a comparison with meteo data in order to assess the atmospheric phenomena causing the artefacts. Moreover, he investigated how and which meteo data can serve as a warning flag for atmospheric contamination in the automatic processing of SAR images. Atmospheric effects have been observed in each of the 26 interferograms. The observed spatial scales reached from hundreds of meters to 100-200 km. Observed rms values reached from 0.5-4 radians. Extreme ranges of 4 phase cycles are found during thunderstorms at the two SAR acquisitions. The effects have been classified into five categories: (1) *isolated anomalies*, i.e. anomalies with a spatial extent of 20 km or less and a phase disturbance of 2 radians or more, observed in 18 interferograms. (2) *striated anomalies*, i.e. linear features over a significant portion of the interferogram, often connected with transport of moisture, observed in 10 interferograms. (3) *wave effects* such as gravity waves or cloud/moisture streets, which have been often observed in only a part of the interferogram. (4) *frontal zones* with quite different characteristics from smooth phase gradients to very distinct wave crest with a wavelength of just some 5 kilometres. Finally, (5) *overall atmospheric variation* characterised by a limited phase magnitude and varying wavelengths mostly connected with turbulent behaviour of air and its constituents. As driving mechanisms of localised temporal and spatial variations in the refractive index not only pressure, temperature, and water vapour distribution have been identified but also rain fall and cold fronts. Mostly, the spatial variation of pressure and temperature is not large enough to cause strong localised phase gradients within a full scene but rather gradients over the whole interferogram, which are difficult to separate from orbit errors. The dominant driving mechanism is the spatial and temporal variation of humidity.

Two methods to handle atmospheric signals in interferograms have been developed and successfully applied by members of the SSG: the first one is a careful selection of the SAR images using the pair-wise logic in order to eliminate suspicious images from the data processing, the second one is statistical suppression based on stacking and averaging interferograms. The latter has been successfully applied if overall atmospheric variations occurred, whereas this procedure did not work if convective processes were responsible for the atmospheric distortions since many interferograms will be necessary in order to eliminate these type of effects.

The second error source, which has been studied intensively by members of the SSG, is temporal decorrelation, i.e. time variations of the radar-scattering characteristics within each pixel, specifically the rms position of the surface scatters within a pixel. The objective is to understand the relation between temporal decorrelation and the type of vegetation, to determine the role of the radar wavelength in this context, and to develop strategies for extracting the deformation signal even in highly decorrelated interferograms.

It is well-known that temporal decorrelation precludes or makes difficult the phase comparison of the SAR images. In a number of studies done by members of the SSG temporal decorrelation has been observed on time scales of a few hours in vegetated areas experiencing windy conditions. On the other hand, results obtained for the arid Landers area in California has shown to be sufficiently high over time scales of years. Similar results have been obtained for other arid regions. Murakami et al. (1995, 1996a, 1996b) and Rosen et al. (1996) could show operationally what has been noted many times theoretically, namely that the correlation at longer wavelengths (e.g., SIR-C/X-SAR and JERS 1 SAR L-band SAR) generally exceeds that at the shorter wavelengths (e.g. ERS 1 and ERS 2 C-band SAR) since L-band radar waves penetrate the vegetation more easily. Also, it has been demonstrated by Zebker et al. (1997) that the scattering behaviour and decorrelation causative mechanisms at C- and L-band may be quite different and is not simply related by scaling of the surface roughness. For instance, they found that for L-band correlation gets steadily weaker with time, with the rate dependent on surface terrain, whereas for C-band abrupt correlation changes have been noted several times related to freezing and thawing of the ground surface. Fujiware et al. (1998) examined temporal decorrelation over de Izu Peninsula, Japan, using SAR images acquired by the Japanese Earth Resources Satellite JERS 1, the only continuously operating spaceborne L-band SAR so far. Their analysis has shown that decorrelation in mixed conifer and deciduous forest is a weak function of the time between observations, imposing a roughly constant level of additional decorrelation relative to scatter-stable areas. They also demonstrated that wet snow cover may reduce correlation significantly although scatters such as buildings and tree branches seem to remain correlated. Finally they found that elevation-dependent weather effects such as snow cover are likely to cause decorrelation above a certain altitude in high altitude areas.

Another research line followed by the SSG is to investigate whether anthropogenic features contain valuable information in otherwise completely decorrelated SAR interferograms. This would be necessary when applying InSAR for monitoring slow deformation processes. Usai and Hanssen (1997) and Usai and Klees (1998, 1999) studied information derived from highly decorrelated interferograms. In order to understand whether the correlated anthropogenic features provide valid though point-wise information over long time spans they tested man-made features for their phase stability in space and time on a pixel-by-pixel basis. For a single feature such as a building or a road they showed that they are phase stable in space and time on a level of 0.4 radians. For a city, the homogeneity in space and time is reduced since it must be considered as a collection of objects instead of a single object only, and therefore, the chance is higher that the phase information of some of them is affected differently by local processes. The proven stability properties permit to use man-made features for monitoring slow deformation processes in otherwise decorrelated interferograms.

2. Specific applications in geo-sciences

Most activities of the SSG were devoted to the development of algorithms that convert interferometric observations to quantitative geophysical parameters. The main questions the SSG wanted to answer were (1) what is the potential of spaceborne InSAR in topographic mapping and ground deformation monitoring, (2) what are the specific problems related to the application and how to solve these problems, and (3) what is the benefit of InSAR derived deformation fields in geophysical modelling? In order to answer the latter, various new co-operations with other geoscientists have been established. Main emphasis was on the application of InSAR for ground deformation monitoring connected with natural hazards, in particular earthquakes and volcanic eruptions, but also for monitoring surface deformations caused by anthropogenic processes and ice sheet and glaciers motions.

In numerous studies of displacement fields the SSG could gain more insight into the potential and limitation of InSAR for surface deformation detection. In particular, the studies showed that the potential of InSAR to detect surface deformations depends on the magnitude and the spatial scale of the crustal movement. Interferometric limitations such as surface preservation, maximum phase gradient, ambiguity estimation, swath width, pixel size, roughness of the topography put constraints on the upper and lower bound of the acceptable magnitude and spatial scale of the deformation. The most important results are summarised in the overview paper (Massonnet and Feigl 1998).

Since the exciting demonstration of the potential of InSAR for monitoring of co-seismic surface deformation (Massonnet et al. 1993) a number of more detailed studies have been conducted by the SSG. Among them are the Eureka Valley, California, earthquake in 1993 (Peltzer and Rosen 1995, Massonnet and Feigl 1995), the Northridge California earthquake in 1994 (Murakami et al. 1996, Massonnet et al. 1996), the Grevena, Northern Greece earthquake in 1995 (Meyer et al. 1996), the Kobe earthquake in 1995 (Ozawa et al. 1997), the North Sakhalin earthquake in 1995 (Tobita et al. 1998), the Neftegorsk, Northern Sakhalin earthquake in 1995 (Murakami et al. 1996, Nakagawa et al. 1997), and the Kagoshima-ken Hokusei-bu earthquake in 1997 (Tobita et al. 1998). Both ERS 1, ERS 2 and JERS 1 data have been processed, and sometimes SAR images acquired by both ERS and JERS are used providing more insight into the role of InSAR in earthquake-related studies (e.g., Massonnet et al. 1996). The similarity of the interferometric results with fake interferograms build from surface rupture measurements assuming an elastic behaviour of the crust has led to a wide acceptance of InSAR in the geophysical community. The results are not only convincing due to the complete picture over large scales InSAR gives but in particular due to surprisingly accurate results on by-phenomena such as tiny fault shifts triggered by the main shock. Often, these shifts have not been detected by GPS and terrestrial geodetic networks. Similar holds for other features like surface deformation patterns associated with individual aftershocks and surface offsets, features that would be very difficult, if not impossible, to detect on the ground. For the first time it was also possible to investigate the influence on the derived fault models of high spatial resolutions as provided by InSAR compared to typically sparse pointwise information provided by GPS: Massonnet et al. (1996) showed that a fault model based on GPS measurements fails to account for significant parts of the fringe patterns observed by InSAR for the co-seismic deformation field of the Northridge California earthquake in 1994. This was attributed to the low number of fault parameters estimable from the GPS measurements due to the poor spatial sampling of the GPS network. For the same reason GPS measurements did not give evidence of the effects of several aftershocks and localised ground motion. The interferogram, however, allowed to estimate a more detailed fault model, thus providing a much better fit to the data than the GPS derived model. In a study of the North Sakhalin earthquake, Tobita et al. (1998) concluded that GPS and terrestrial geodetic techniques do not provide efficient information to estimate slip distribution with high resolution (due to the coarse spatial sampling and the rapid decay of ground displacements from a fault movement), whereas InSAR does due to the high spatial sampling. In other cases, InSAR confirmed fault shifts observed in the field.

The studies have been extended to post-seismic deformation fields following the Landers California earthquake (Massonnet et al. 1996, Peltzer et al. 1996) and the North Sakhalin earthquake (Tobita et al. 1998). The major result is that InSAR maps the complex near-fault patterns of post-seismic deformation, which cannot be provided by GPS and terrestrial geodetic techniques without setting up an (impossible) dense and costly observation network. Moreover, various unexpected deformations near faults have been detected in interferograms spanning up to 3 years and different mechanisms have been proposed, which may produce the observed deformations. While InSAR agrees with GPS measurements the latter cannot decide between various geophysical models because of the strong spatial undersampling of the deformation field.

Unfortunately the SSG did not succeed in detecting precursory displacements in SAR interferograms assuming that such precursors exist. In addition, the interferometric limitations mentioned before often prevent mapping deformations very near the fault trace due to loss of coherence. Finally, it has been shown that not every earthquake creates clear interferometric fringes. Only co-seismic deformation fields with sufficient magnitude and proper orientation can be mapped. Mostly, moderate (M>5) earthquakes at shallow depth (< 10 km) with predominantly vertical surface displacements generate fringes allowing for an unambiguous interpretation (Massonnet and Feigl 1998). In co-operation with geophysicists models of the centroid and focal mechanism have been developed from the deformation fields mapped by InSAR for different earthquakes. It has been shown that the high spatial sampling of InSAR allows developing much more detailed fault models with less a priori assumptions. Usually the earthquake fault is modelled by a number of vertical planar elements, and each element is parameterised by up to 10 parameters. The fault parameters are estimated by minimising the difference between the observed and evaluated values of the surface deformations. Usually iterative linear least-squares schemes are used for the non-linear inversion with a priori covariance matrices. The major problem still to be solved is the suitable choice of the stochastic model for the SAR-derived deformation fields. Usually no correlation between the measured ground deformations are assumed and often only errors due to various types of decorrelation and residual topography are taken into account (e.g., Murakami et al. 1996). Nonetheless, the derived relatively detailed models are shown to be consistent with the results of seismic studies and field surveys.

Volcano monitoring offers a clear near term perspective in disaster prevention because many, perhaps most of the world’s volcanoes that actually do erupt experience significant pre-eruption surface deformation. In addition, the location of a volcano is well-known, the deformation is usually continuous and runs over time scales of months rather than years, and, finally, many volcanoes remain sufficiently coherent although it was observed that atmospheric distortions, steep topographic gradients, vegetation, and snow coverage may cause serious problems. The SSG studied various volcanoes among them the Mount Etna in Italy (Massonnet et al. 1995, Briole et al. 1997), the Long Valley Caldera, Eastern California (Thatcher and Massonnet 1997), the Kilauea volcano on Hawaii (Rosen et al. 1996), Vatnajokull volcano on Iceland (Thiel et al. 1997), and the Krafla volcano on Island (Sigmundsson et al. 1997). See also the review papers (Massonnet and Feigl 1998, Klees and Massonnet 1999). Typical deformation rates of several centimetres per month have been observed, which are easy to measure with monthly passes. Then, temporal decorrelation is not a major concern. For instance, several ERS 1 and JERS 1 images of Merapi volcano (Indonesia) have shown to remain coherent over a month despite heavy vegetation in a humid tropical region. Coherence also lasts over 3 years at La Palma, another tropical volcano. On the other hand, Rosen et al. (1996) found significant atmospheric signatures in interferograms of Kilauea on Hawaii introducing spurious apparent deformation signatures at the level of 12 cm peak-to-peak in the radar line-of-sight direction. They conclude that the atmospheric distortions are large enough to limit the interpretation of the results. In particular when being faced with centimetre-scale deformations spatially distributed over tens of kilometres it is very difficult to characterise them without simultaneous, spatially distributed measurements of refractivity along the radar line-of-sight. Studies of the coherence of SAR images also show that L-band is far superior to C-band in the vegetated areas, even when the observations are separated by only 1 day as during the ERS tandem mission and the SIR-C/X-SAR experiment (cf. Section 3.2).

The SSG also focussed on the monitoring of surface deformations due to anthropogenic processes such as withdrawal of water, oil or gas and mining activities (Carnec et al. 1996, Massonnet et al. 1997). Unlike the other applications addressed before, man-made activities involves subtle economical, strategic or even legal issues. Moreover, the related deformation processes are small scale and may run very slowly with deformation rates on the order of 1 centimetre a year. Temporal decorrelation and/or atmospheric disturbances have been identified as the major limitations for this type of application. Bree et al. (1999) conducted a very detailed study on the monitoring of land subsidence due to the extraction of natural gas in the area of Groningen, The Netherlands. The conditions were very unfavourable: slow subsidence rates of below 1 cm/yr combined with a humid climate and severe temporal decorrelation caused by agriculture. 18 ERS-1/2 SAR images were processed covering about 3 years of data. A new database structure for the SAR data was designed and a theoretical error analysis was performed, which included interferometric processing errors, erroneous orbit parameters, atmospheric distortions, topographic effects, and various types of decorrelation. A priori information about the deformation pattern was used to parameterise the deformation in space and time by an algebraic polynomial. InSAR and levelling data have been used to estimate the model parameters in a standard least squares approach. Large atmospheric effects and severe temporal decorrelation prevent to detect statistically significant deformations over the 3-year period. They conclude that dedicated filters are indispensable, which can separate subtle deformations from disturbing effects caused by the atmosphere, residual orbit errors, and (residual) topography.

The results obtained so far are encouraging but not satisfactory. But even when InSAR fails monitoring these small deformations over long time scales under rather unfavourable conditions it can help in optimising the location of geodetic networks in areas that effectively show ground movement.

With regard to glacier and ice sheet monitoring the SSG demonstrated that InSAR can provide high-resolution high-accuracy topographic maps of glaciers and ice sheets, measure ice flow velocity without any ground control, detect and monitor surface changes, and identify the line separating floating from grounded ice, e.g. Vachon et al. (1996a,b), Cumming et al. (1996a,b), Thiel et al. (1996), Wu and Thiel (1996), Thiel and Wu (1996), Thiel et al. (1997). Among the major problems that have been reported are the usually quite rapid movement of flowing ice, which requires short orbital and temporal separations between successive satellite passes, the alteration of the reflective ice surface by freeze, thaw, or precipitation and snow fall, which may reduce coherence even in 1 day interferograms, the proper reconstruction of the 3D surface flow field from the measured fringes, which is not possible without additional assumptions because InSAR only measures the line-of-sight component of the deformation vector, and the removal of the topography signal from the interferogram, which requires either a DEM or a third SAR image to be available. Thiel et al. (1996) estimated topography, differential tidal variations (assuming a steady ice flow) and horizontal ice movements (assuming no vertical component) for the region around the Hemmen Ice Rise in Artarctica (using ascending and descending SAR images and assuming zero vertical component and slang range changes during the 3 hours between the ascending and descending data acquisitions). The SAR images have been acquired during the ERS 1 Ice Phase with a repeat period of 3 days. Vachon et al. (1996a,b) reconstructed the 3D surface flow field of the mid-latitude Athabasca glacier in the Columbia Icefield in the Canadian Rocky Mountains from the radar line-of-sight component extracted from ERS tandem phase SAR images assuming a plastic flow model and flow vectors pointing downslope, in the direction of the maximum basal slope. This assumption can only provide reasonable results near the centreline of the glacier but not near the glacier's margins. The downslope direction was determined from an airborne SAR DEM. A comparison with in situ measured point velocities derived from historical and more recent point displacement measurements showed an excellent agreement to within 10%. Moreover, they showed that the fine-scale structure of the glacier flow patterns are very repeatable. High scene coherence has proved to be associated with below freezing maximum temperatures, the absence of precipitation, and no blowing snow during the data collection interval. Therefore, InSAR appears to work best during winter when the potential of daytime melting is minimised. Another key problem is the removal of the topography phase from the interferogram. The usual double differencing approach of taking two interferograms with different baselines and/or different data take intervals requires the assumption that the glacier velocity is constant between the two pairs of data takes and that coherence remains sufficiently high. The latter however is often not guaranteed over glacier and ice sheet surfaces. The second approach uses a DEM (if it exists at all) and a satellite geometry model to compute the topography phase. Residual topographic errors may be minimised using short baseline SAR images for flow field mapping. Here, airborne InSAR DEM's are especially well-suited. The same strategy was applied by Cumming et al. (1996) for the neighboured Saskatchewan Glacier and quite similar results were obtained, see also (Vachon et al. 1996a,b). Although these studies showed that InSAR is a promising technique for monitoring glaciers and ice sheets, we are not in the position yet to fully exploit its potential. Too many problems have not been solved yet. For instance, present satellites carrying a SAR do not fully cover polar regions (ERS satellites leave a gap of about 8 degrees at the poles). In addition, Greenland and polar regions suffer from severe weather conditions, which may lead to complete decorrelation within a few days, e.g. due to snow storms, melting, and blowing snow. Atmospheric disturbances may corrupt the interferograms. Finally, the mapping geometry (angle between across-track direction and flow direction) and the line-of-sight component provided by InSAR can make the reconstruction of the 3D surface flow field very difficult and require additional assumptions such as a surface-parallel flow assumption, which ignore for instance submergence and emergence velocities.

Outlook

SAR interferometry will become increasingly important over the next decade with the development of airborne and space-borne sensor systems. Improved antenna design, RF electronics, digital electronics and data processors will allow exploiting optimally this technology. At the same time, the commercial application of SAR interferometry will increase, as well, offering new perspectives for geodesists. Currently four SAR satellites are in orbit (ERS 1 and 2, RADARSAT and JERS 1) and a few airborne InSAR systems are operated by national organisations and private companies (cf. Bamler and Hartl (1998) for an overview). The next European satellite-borne SAR will be the ASAR system on board ENVISAT, a C-band system like ERS but with considerably higher flexibility. At least two other systems are approved and planned for launch in the first years of the next millenium, among them NASA's LightSAR. They will be smaller, lighter, cheaper, with dual frequencies and shorter revisit cycles.

Phase unwrapping will continue to be an important issue. A good description of the quality of each pixel of the given phase data set seems to be a crucial point since the quality guides several of the path-following algorithms and is necessary for some of the weighted minimum norm algorithms. Up to now the correlation is widespread used to describe the quality of each pixel but there are also other candidates such as the variance of the phase value, the phase derivative variance, the second differences of the phase data, and the maximum phase gradient. In practise the quality measure may depend on the situation; a quality measure that works fine in one situation may fail in another one. Other areas where further work needs to be done are the development of techniques for the evaluation of phase unwrapping results and the proper choice of the norm in minimum norm solutions. The latter may be related to solution phase gradients that deviate from the measured phase gradients in as few places as possible, where the magnitude of the deviation is of no concern, sometimes called L^0-norm solution (cf. Ghiglia and Pritt 1998).

Research on atmospheric effects has to be intensified. As elimination of these effects concerns weather radar data should be further analysed and compared with observed phase delays in the interferograms and a functional relationship between both types of data should be established as a starting point towards the elimination of localised anomalies in SAR interferograms. The synergy of various sensors on board of future satellite missions carrying a SAR antenna should be investigated. For instance, for ENVISAT it would be important to study the use of MERIS in this context. Moreover, it is important to continue research towards the use of permanent GPS tracking networks for estimating tropospheric and ionospheric path delay with applications to SAR interferometry. Finally it has been demonstrated by Hanssen et al. (1999) that spaceborne SAR interferometry may also be used to infer high-resolution maps of integrated atmospheric water vapour, which can be readily related to meteorological phenomena. This opens new perspectives for local and regional operational meteorology. The proper use of airborne and spaceborne SAR systems with short repeat periods, which may become available in the future, could improve the meteorological understanding and forecasting.

The combination of GPS and InSAR observations and the development of methods for deformation analysis using different types of geodetic and geophysical data are important issues. Since INSAR-derived deformation maps provide only line-of-sight changes with (currently) poor temporal resolution GPS data from well-selected sites are needed to provide information about the three-dimensional deformation vector and to provide a continuous data record against which the SAR data can be compared.

Internal consistency and quality of the InSAR observations are currently derived from statistical variations of the phase estimates based on the S/N ratio, by empirically determined statistical variations over various test areas in the interferogram or by comparison with field measurements. Sometimes, simple atmospheric models and assumptions about residual topographic errors have been taken into account. What is still missing is a proper error propagation starting from raw or SLC data to geo-coded topography or deformation maps. A realistic quality description of InSAR-derived end products is also the basis for the optimal combination with deformation maps provided by other geodetic techniques such as GPS and terrestrial measurements. The stochastic model of the phase values should also include the atmospheric behaviour on different scales.

Applications in geo-sciences in particular for hazard monitoring still require a number of future studies. For instance, more experiences have to be gained about the degree to which temporal decorrelation limits the applicability of InSAR for various types of terrain, the expected decorrelation due to weathering, and the effects of vegetative ground cover on the topographic and deformation signature of the radar interferometer. Moreover, the studies on the phase stability of single scatters, which carry the information about the deformation in otherwise completely de-correlated interferograms should be extended to other types of man-made features and should also be extended to natural objects.

Moreover, more effort has to go into exploring the potentials of InSAR in the commercial and industrial sector, in particular the development of rapid and cost effective airborne and spaceborne mapping systems, near-real time interferometric processor development, automatic mosaicking, and mapping and feature extraction.

References

Ghiglia, D.C., M.D. Pritt (1998), Two-Dimensional phase unwrapping – theory, algorithms, and software, John Wiley & Sons, New York.

Massonnet, D., M. Rossi, C. Carmona, F. Adragna, G. Peltzer, K. Feigl, T. Rabaute (1993), The displacement field of the Landers earthquake mapped by radar interferometry, Nature 364, 138-142.

Wegmueller, U. and C.L. Werner (1995), SAR interferometric signatures of forest, IEEE Trans. Geosci. Remote Sens. 33, 1153-1161.

7.Bibliography :

Armour B. and Farris-Manning P. and Vachon P.W., The suitability of RADARSAT's orbit for repeat pass SAR interferometry, Geomatics in the ERA of RADARSAT (GER'97), CD-ROM Proceedings, 27-30, Ottawa, Ont., Canada, May 1997, 1997

Bamler R., X-SAR interferometry, Proc. Progress in Electromagnetic Research Symposium (PIERS), Seattle, 1995

Bamler R., Adapting precision standard SAR processors to ScanSAR, Proc. Int. Geoscience and Remote Sensing Symposium, Florence, Italy, 1995

Bamler R., Spaceborne SAR interferometry: principles, sensors and potentials, Proc. The space congress, Bremen, Germany, 1995

Bamler R., Adapting precision standard SAR processors to ScanSAR, Int. Geoscience and Remote Sensing Symp. IGARSS'95, Florence, Italy, pages 2051-2053, 1995

Bamler R. and Eineder M., ScanSAR processing usig standard high precision SAR algorithms, IEEE Trans. Geosci. Remote Sens., volume 34, pages 212-218, 1996

Bamler R. and Davidson G.W. and Adam N., On the nature of noise in 2-D phase unwrapping, pages 216-225, volume 2958, series Microwave sensing and synthetic aperture radar SPIE, 1996

Bamler R.and Eineder M. and Breit H., The X-SAR single-pass interferometer on SRTM : expected performance and processing concept, Proc. EUSAR'96, K\"onigswinter, pages 181-184, 1996

Bamler R., On the mystery of lost fringes in 2-D phase unwrapping by least squares estimation, Proc. Progress in Electromagnetics Research Symposium (PIERS), Innsbruck, Austria, 1996

Bamler R. , The X-SAR single-pass interferometer on SRTM: expected performance and processing concept, Proc. European conference on synthetic aperture radar EUSAR, K\"onigswinter, Germany, 1996

Bamler R. and Davidson G.W., Multiresolution signal representation for phase unwrapping and interferometric SAR Processing, Int. Geoscience and Remote Sensing Symp. IGARSS'97, Singapore, pages 865-868, 1997

Bamler R. and Hanssen R. , Decorrelation induced by interpolation errors in InSAR, Int. Geoscience and Remote Sensing Symp. IGARSS'97, Singapore, pages 1710-1712, 1997

Bamler R., Digital terrain models from radar interferometry, Photogrammetric Week '97, D. Fritsch and D. Hobbie (eds.), Wichmann, Karlsruhe, pages 93-105, 1997

Bamler R. , Multiresolution signal representation for phase unwrapping and inerferometric SAR processing, Proc. Int. Geoscience and Remote Sensing Symp. IGARSS'97, Singapore, 1997

Bamler R. and Hanssen R., Decorrelation induced by interpolation errors in InSAR, Proc. Int. Geoscience and Remote Sensing Symp. IGARSS'97, Singapore, 1997

Bamler R. and Adam N. and Davidson G.W. and Just D., Noise-induced slope distortion in 2-D phase unwrapping by linear estimators with application to SAR interferometry, IEEE Trans. Geosci. Remote Sensing, volume 36, pages 913-921, 1998

Bamler R. and Hartl Ph., Synthetic aperture radar interferometry, Inverse Problems, volume 14, pages R1-R54, 1998

Bamler R., Global minimization methods for interferometric phase unwrapping, Proc. Progress in Electromagnetics Research Symposium (PIERS), Nantes, 1998

Breit H. and Bamler R., An InSAR processor for on-board performance monitoring of the SRTM/X-SAR interferometer, Proc. Int. Geoscience and Remote Sensing Symp. IGARSS'98, Seattle, 1998

Briole P. and Massonnet D. and Delacourt C., Post-eruptive deformation associatedwith the 1986-87 and 1989 lava flows of Etna, detected by radar interferometry, Geophys. Res. Lett., volume 24/1, pages 37-40, 1997

Carnec C. and Massonnet D. and King C., Two examples of the application of SAR interferometry to sites of small extent, Geophys. Res. Lett., volume 23/24, pages 3579-3582., 1996

Cumming I. , Valero J.-L. and Seymour M. and Vachon P. and Mattar K. and Geudtner D. and Gray L. , Glacier flow measurements with ERS tandem mission data, Proc. ESA FRINGE'96 Workshop, Zürich, 1996

Cumming I. and Valero J.-L. and Vachon P.W. and Brugman M. and Seymour M. and Gray A.L., Results of ERS interferometry measurements of alpice glaciers, Proc. 18th Canadian symposium on remote sensing, 25-29 March, Vancouver, Canada, 1996

Cumming I. and Valero J.L. and Vachon P.W. and Mattar K. and Geudtner D. and Gray L., Glacier flow measurements with ERS tandem mission data, Fringe'96 Workshop on ERS SAR Interferometry, Remote Sensing Laboratories, University of Zurich, Switzerland, ESA SP-406, pages 353-362, 30 Sept.-2 Oct. 1996, 1997

Davidson G.W. and Bamler R., Robust 2-D phase unwrapping based on multiresolution, pages 226-237, volume 2958, Microwave sensing and synthetic aperture radar SPIE, 1996a

Davidson G.W. and Bamler R., A multiresolution approach to improve phase unwrapping, Int. Geoscience and Remote Sensing Symp. IGARSS'96, Lincoln, Nebraska, pages 2050-2053, 1996b

Davidson G.W. and Bamler R., Multiresolution phase unwrapping for SAR interferometry, IEEE Trans. Geosci. Remote Sensing, volume 37, number 1, pages 163-174, 1999

D'Iorio M.A. and Brisco B.G. and Budkewitsch P.A. and Geudtner D. and Vachon P.W. and Wolfe J., Geological and morphological control on ERS-1 SAR coherence images of Bathurst Island, pages 107-111, Proc. of the 26th International Symposium on Remote Sensing of Environment/18th Annual Symposium of the Canadian Remote Sensing Society, 1996

Fujiwara, S. and Rosen P.A. and Tobita M. and Murakami M., Crustal deformation measurements using repeat pass JERS-1 SAR interferometry near the IZU-Peninsula, Japan, JGR, volume B2, pages 2411-2426, 1998,

Fujiwara S. and Rosen P.A. and Tobita M. and Murakami M., Crustal deformation measurements using JERS-1 SAR interferometry near the Izu peninsula, Japan, J. Geophys. Res, volume 103, pages 2411-2426, 1998

Galloway D.l. and HudnutK.W. and Ingebritsen S.E. and Phillips S.P. and Peltzer G. and Rogez F. and Rosen P.A., INSAR detection of aquifer-system compaction and land subsidence, Antelope Valley, Mojave Desert, California, Water Resources Res., 1998

Galloway D.l. and Hudnut K.W. and Ingebritsen S.E. and. Phillips S.P. and Peltzer G. and Rogez F. and Rosen P.A., INSAR detection of aquifer-system compaction and land subsidence, Antelope Valley, Mojave Desert, California, Water Resources Res., 1998

Geudtner D. and Winter R. and Vachon P.W., Flood monitoring using ERS-1 SAR interferometry coherence maps, pages 966-968, Int. Geoscience and Remote Sensing Symp. IGARSS'96, Lincoln, Nebraska, 27-31 May 1996, 1996

Geudtner D.and Vachon P.W. and. Mattar K.E. and Gray A.L., RADARSAT repeat-pass SAR interferometry: Results over an arctic test site, Geomatics in the ERA of RADARSAT (GER'97), CD-ROM Proceedings, 27-30 May 1997, Ottawa, Ont., Canada, 1997

Granberg H.B. and Vachon P.W., Delineation of discontinuous permafrost at Schefferville using RADARSAT in interferometric mode, 7th Int. Conf. on Permafrost, 22-26 Juni 1998, Yellowknofe, NWT, Canada, 1998

Gray A.L. and Mattar K.E. and Geudtner D and P.W. Vachon P.W., Experiments at CCRS using ERS tandem mode data, 3rd ERS Symposium on Space at the Service of our Envirenment, Florence, Italy, 17-21 March 1997, ESA SP-414, volume 2, pages 1001-1006, 1997

Gray A.L. and Mattar K.E and Vachon P. and Bindschadler R. and Jezek K.C. and Forster R.R and Crawford *J.*P., InSAR results from the RADARSAT antarctic mapping mission data: Estimation of glacier motion using a simple registration procedure, Int. Geoscience and Remote Sensing Symp. IGARSS'98, 6-10 July 1998, Seattle, Washington, USA, pages 1638-1640, 1998

Gray A.L. and Mattar K.E and Vachon P.W and Bindschadler R. and Jezek K.C. and Forster R.R. and Crawford *J.P.*, Glacial ice motion in Antarctica using RADARSAT antarctic mapping mission data, 20th Canadian Symposium on Remote Sensing, 10-13 May, Calgary, Alt., Canada, pages 119-122, 1998

Gray A.L. and Mattar K.E. and Vachon P.W., RADARSAT interferometric ESAR results obtained over Antarctic terrain, CEOS Workshop, ESA-ESTEC, February 1998, Noordwijk, The Netherlands, 1998

Hanssen R. and Feijt A., A first quantitative evaluation of atmospheric effects on SAR interferometry, Proc. ESA FRINGE'96 Workshop, Zürich, 1996

Hanssen R. and Usai S., A time series approach for monitoring slow deformation processes, 3rd ERS Workshop, Florence, Italy, 17-21 May, 1997

Hanssen R., Atmospheric heterogeneities in ERS tandem SAR interferometry, Delft University Press, DEOS Report no. 98.1, 1998

Hanssen R. and Weckwerth T.M. and Zebker H.A and Klees R., High-resolution water vapor mapping from interferometric radar measurements, SCIENCE, volume 283, pages 1297-1299, 1999

Hanssen R. and Bamler R. , Evaluation of Interpolation Kernels for SAR Interferometry, IEEE Trans. Geosci. Remote Sensing, volume 37/1, pages 318-321, 1999

Hartl Ph. and ThielK.H. and Wu X. and Xia Y., Earth observation by means of SAR present state and future possibilities, Photogrametric Week '95, Wichmann Verlag, pages 102-106, 1995

Hartl P.h. and Hug C.h. and K\"alberer U. and Wehr A., Integriertes Laser-/Radar zur Erfassung von Gel\"andeoberfl\"achen, Allgemeine Vermessungsnachrichten, volume 2/96, pages 62-72, 1996

Hartl P.H. and Thiel K.H., Das Nutzungspotential der Satellitentechnik für wissenschaftliche und praktische Anwendungen, Akademie-Journal, volume 2/96, pages 22-29, 1996

Hartl Ph. and Thiel J.H., Satellitengest\"utzte Ortung und Navigation, Spektrum der Wissenschaft, pages 102-106, 1996

Hernandez B. and Cotton F. and Campillo M. and Massonnet D., A comparison between short-term (co-seismic) and long term (one year) slip for the Landers earthquake: measuments from strong motion and SAR interferometry, Geophys. Res. Lett., volume 24/13, pages 1579-1582, 1997

Just D. and Bamler R., Spaceborne SAR interferometry: principles, sensors, and potentials, Proc. European Space Congress, Hamburg, Germany, 1995

Just D. and Adam N. and Schw\"abisch M. and Bamler R., Comparison of phase unwrapping algorithms for SAR interferograms, Int. Geoscience and Remote Sensing Symp. IGARSS'95, Florence, Italy, pages 767-769, 1995

Hirose T.and Vachon P.W., Demonstration of ERS tandem mission SAR interferometry for mapping land fast ice evolution, Can. J. Rem. Sens., 1998

Klees R. and Massonnet D., Deformation measurements using SAR interferometry: potential and limitations, Geologie en Mijnbouw, 1999

Lanar R. and Hensley S. and Rosen P.A., Chirp z-transform based SPECAN approach for phase-preserving ScanSAR image generation, IEE Proc.-Radar, Sonar, Navig., volume 145/5, 1998

Livingstone C.E. and Gray A.L. and Hawkins R.K. and Vachon P.W. and Lukowski T.I. and LaLonde M., The CCRS airborne SAR systems: radar for remote sensing research, Canadian Journal of Remote Sensing, volume 21, pages 468-491, 1995

Massonnet D. and Vadon H., ERS-1 internal clock drift measured by interferometry, IEEE Trans. Geoscience and Remote Sensing, volume 33/2, pages 401-408, 1995

Massonnet D. and Feigl K.L., Discriminating of geophysical phenomena in satellite radar interferograms, Geophys. Res. Lett., volume 22/12, pages 1537-1540, 1995

Massonnet D. and K. Feigl, Satellite radar interferometric map of the coseismic deformation field of the M=6.1 Eureka Valley, California earthquake of 17 May 1993, Geophys. Res. Lett., volume 22/12 pages 1541-1544, 1995

Massonnet D. and Briole P. and. Arnaud A., Deformation of Mount Etna monitored by spaceborne radar interferometry, Nature, volume 375, pages 567-570, 1995

Massonnet D. and Adragna F. and Xenofontov E. and Elissavetine I., Advanced use of Almaz radar data, Acta Astronautica, volume 35/7, pages 461-465, 1995

Massonnet D. and Thatcher W. and Vadon H. Detection of postseismic fault zone collapse following the landers earthquake, Nature, volume, 382, pages 612-616, 1996

Massonnet D. and K. Feigl and Vadon H. and M. Rossi, Coseismic deformation field of the M=6.7 Northridge, California earthquake of January 17, 1994 recorded by two radar satellites using interferometry, Geophys. Res. Lett., volume 23/9, pages 969-972, 1996

Massonet D. and Boutry J., Le futur du radar: Imagerie en trois dimensions, Science et Défense 96 - Nouvelles avancées scientifiques et techniques, pages 297-307, 1996

Massonnet D., Tracking the Earth's surface at the centimetre level: an introduction to radar interferometry, journal Nature and Resources (UNESCO), 1996

Massonnet D. and Vadon H. and Rossi M., Reduction of the need for phase unwrapping in radar interferometry, journal IEEE Trans. Geosci. Remote Sens., volume 34, pages 489-497, 1996

Massonnet D., Satellite radar interferometry, Scientific American, 1997

Massonnet D. and Feigl K., Radar interferometry and its applications to changes in the earth's surface, Review of Geophysics, pages 441-500 ,volume 36, number 4, 1998

Massonnet D., The future of interferometry: new users and new missions, Proc. 2nd Workshop on SAR Interferometry, Tsukuba, Japan, pages 143-153, 1998

Massonnet D. and Holzer T. and Vadon H., Land subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry, Geophys. Res. Lett., volume 24, pages 901-904, Correction, Geophys. Res. Lett., 25, 3213, 1998

Mattar K.E. and Gray A.L. and Geudtner D. and. Vachon P.W., Interferometry for DEM and terrain displacement: Effects of inhomogeneous propagation, mission SAR interferometry for mapping land fast ice evolution, Can. J. Rem. Sens., 1998

Mattar K.E. and Vachon P.W. and Geudtner D. and Gray A.L. and Cumming I. and Brugman M., Validation of alpine glacier velocity measurements using ERS trandem-mission SAR data, IEEE Trans. Geoscience Rem. Sens., volume 36, pages 974-984, 1998

Meyer B. and Armijo R. and Massonnet D. and de Chabalier J.B. and Delacourt C. and. Ruegg J.C. and. Achache J. and Briole P. and Papanastassiou D., The 1995 Grevena (Northern Greece) earthquake: fault model constrained with tectonic observations and SAR interferometry, Geophys. Res. Lett., volume 23/9, pages 2677-2680, 1996

Murakami M. and Fujiwara S. and Saito T., Detection of crustal deformations associated with the 1995 Hyogo-ken-nanbu earthquake by interferometric SAR (in Japanese), Biannu. Rep. Geogr. Surv. Inst., volume83, pages 24-27, 1995

Murakami M. and Tobita M. and Nakagawa H. and Nitta K. and Murakami M. and Shimada M.and Oaku H. and Isono K. and Rosen P.A. and Fujiwara S., Crustal deformations associated with 1995 Neftegorsk, Northern Sakhalin, Earthquake detected by JERS-1/SA interferometry, Proc. of the 86th meeting of the Geodetic Society of Japan, Kochi, Japan, 1996,

Murakami M. and Tobita M. and Fujiwara S. and Saito T. and Masaharu H., Coseismic crustal deformations of 1994 Northridge, California earthquake detected by interferometric JERS 1 synthetic aperture radar, J. Geophys. Res., volume 101, pages 8605-8614, 1996

Murakami, M. and Fujiwara S. and Tobita M. and Nitta K.and Nakagawa H.and Ozawa S. and Yarai H., Progress in SAR interferometry for the detection of crustal deformations by the Geographical Survey Institute, Proc. Second Workshop on SAR Interferometry, Tsukuba, Japan, November 18-20, pages 157-166, 1998

Moreira J. and Schw\"abisch M. and Fornaro G. and Lanari R. and Bamler R. and Just D.and Stein-Brechter U. *and Breit H. and Franceschetti M. and Geudtner D. and Rinkel H.,* X-SAR interferometry: first results, IEEE Trans. Geosci. Remote Sensing, volume 33, pages 950-956, 1995

Moon W.M. and Ristau J. and Vachon P. and Tanaka A. and Yamaguchi Y., Investigation of Nahanni Earthquake tectonics using spaceborne SAR techniques, Proc. Second Workshop on SAR Interferometry, Tsukuba, Japan, November 18-20, pages 209-219, 1998

Moorman B. and Vachon P.W., Detecting ground ice melt with interferometric synthetic aperture radar, 20th Canadian Symposium on Remote Sensing, 10-13 May, Calgary, Alt., Canada, pages 145-148, 1998

Nakagawa H. and Tobita. and Fujiwara S. and. Ozawa S. and. Nitta K. and Murakami Mas. and Murakami Mak. and. Shimada M. and Rosen P.A., Fault model of the 1995 Neftegorsk, Northern Sakhalin Earthquake based on crustal deformation detected by JERS-1/SAR interferometry, Proc. Int. Geoscience and Remote Sensing Symp. IGARSS'97, Singapore, 1997

Ozawa S. and Murakami M. and Fujiwara S. and Tobita M., Synthetic aperture radar interferogram of the 1995 Kobe earthquake and its geodetic inversion, Geophys. Res. Letter, volume 24/18, pages 2327-2330, 1997

Ozawa T. and Nakagawa H. and Nitta K. and Murakami Mak. and Murakami Mas. and Tobita M. and Fujiwara S. and Doi K. and Shibuya K., Detection of ice sheet motion by JERS-1 SAR interferometry, Proc. Second Workshop on SAR Interferometry, Tsukuba, Japan, November 18-20, pages 243-248, 1998

Peltzer G. and Rosen P.A., Surface displacement of the 17 May 1993 Eureka Valley, California, earthquake observed by SAR interferometry, SCIENCE, volume 268, pages 1333-1336, 1995

Peltzer G. and Rosen P.A. and Rogez F. and. Hudnut K., Post-seismic rebound in fault step-overs caused by pore fluid flow, SCIENCE, volume 273, pages 1202-1204, 1996

Peltzer G. and Rosen P.A. and Rogez F. and Hudnut K., Poro-elastic rebound along the Landers 1992 earthquake surface rupture, J. Geophys. Res. Accepted for publication, 1998

Rossi M. and Rogron B. and Massonnet D., JERS-1 SAR image quality and interferometric potential, IEEE Trans. Geoscience and Rem. Sensing, volume 34/3, pages 824-827, 1996

Rosen P.A. and Werner C. and Fielding E. and Hensely S. and. Buckley S. and Vincent P., Aseismic creep along the San Andreas fault northwest of Parkfield, California, measured by radar interferometry, Geophys. Res. Lett., volume 25, pages 825-828

Rosen P.A. and Hensley S. and Zebker H.A. and. Webb F.H. and. Fielding E.J., Surface deformation and coherence measurements of Kilauea Volcano, Hawaii from SIR-C radar interferometry, J. Geophys. Res., volume 101, pages 23,109-23,125, 1996

Rudant J.P. and Bedidi A. and Calonne R. and Massonnet D. and Nesti G. and Tarchi D. , Laboratory experiments for the interpretation of phase shift in SAR interferograms, Proc. ESA FRINGE'96 Workshop on Applications of ERS SAR Interferometry, 1996

Schmidt M., Moderne Methoden der Signalanalyse, Interner Bericht des Deutschen Geod\"atischen Forschungsinstituts, volume MS/67/95, 1996

Schmid M., Moderne Methoden der Signalanalyse, Zeitschrift f\"ur Vermessungswesen, volume 7/96, pages 315-325, 1996

Schulz-Stellenfleth J. and Lehner S. and Bamler R. and Horstmann J., A model for ocean wave imaging by a single-pass cross track interferometric SAR (InSAR) - The SINEWAVE Experiment,
Proc. Int. Geoscience and Remote Sensing Symp. IGARSS'98, Seattle, 1998

Schulz-Stellenfleth J. and Lehner S. and Bamler R., Ocean wave imaging by cross track interferometry - The SINEWAVE experiment, Proc. CEOS SAR Calibration Workshop, ESA/ESTEC, Noordwijk, 1998

Sigmundsson F. and Vadon H. and Massonnet D., Readjustment of the Krafla spreading segment to crustal rifting measured by Satellite Radar Interferometry, Geophys. Res. Lett., volume 24/15, pages 1843-1846, 1999

Tarayre H. and Massonnet D., Atmospheric propagation heterogeneities revealed by ERS-1 interferometry, Geophys. Res. Lett., volume 23/9, pages 989-992, 1996

Thatcher W. and Massonnet D., Crustal deformation at Long Valley Caldera, Eastern California, 1992-1996 inferred from satellite radar interferometry, Geophys. Res. Lett., volume 24/20, pages 2519-2522, 1997

Thiel K.H. and Hartl P.H. and Wu X., Monitoring the ice movements with ERS SAR interferometrie in the antarctic region, Proc. 2nd ERS Applications Workshop, London, volume ESA SP-383, pages 219-223, 1996

Thiel K.H. and Wu X., Monitoring ice movement in Antarctica, Proc. of the Sixth International Offshore and Polar Engineering Conference, Los Angeles, Vol. II, pages 401-405, 1996

Thiel K.-H. and Wu X. and Hartl P.H., ERS tandem interferometric observation of volcanic activities in Iceland, 3rd ERS Workshop, Florence, Italy, 17-21 May, volume ESA SP-414/II, pages 475-481, 1997

Tobita M. and Fujiwara S. and Ozawa S. and Rosen P. and Fielding E.J. and Warner C.L, Deformation of the 1995 North Sakhalin Earthquake, Earth Planets Space, volume 50, pages 313-325, 1998

Tobita M. and Fujiwara S. and Yarai H. and Ozawa S. and Murakami M. and Nakagawa H. and Nitta K and Rosen P.A., and Werner C.L. and Shimada M., Crustal defromation association with the March 1997 Kagoshima-ken Hokusei-bu earthquake detected by InSAR and GPS, Proc. Second Workshop on SAR Interferometry, Tsukuba, Japan, November 18-20, pages 221-228, 1998

Tobita M. and Fujiwara S. and Ozawa S. and Rosen P.A. and Fielding E.J. and Werner C.L. and Murakami M. and Nakagawa H. and Nitta K. and Murakami M., Deformation of the 1995 North Sakhalin earthquake detected by JERS-1/SAR interferometry, Earth Planets Space, volume 50, pages 313-325, 1998

Touzi R. and Lopes A. and Vachon P.W., Estimation of the coherence function for interferometric SAR applications, pages 242-244, Proc. EUSAR'96, 1996

Touzi R. and Lopes A. and Bruniquel J. and Vachon P., Unbiased estimation of the coherence from multi-look SAR data, Proc. IEEE, pages 662-664, 1996

Touzi R. and Lopes A. and Bruniquel J. and Vachon P.W., Coherence estimation for SAR imagery, journal IEEE Trans. Geoscience Rem. Sens., accepted for publication, 1998

Usai S. and Hanssen R., Long time scale InSAR by means of high coherence features, 3rd ERS Workshop, Florence, Italy, May 17-21, 1997

Usai S. and Klees R., On the feasibility of long time scale InSAR, Int. Geoscience and Remote Sensing Symp. IGARSS'98, Seattle, 6-10 July, volume 5, pages 2448-2450, 1998

Usai S. and Klees R., An analysis of the interferometric characteristics of anthropogenic features, submitted for publication to IEEE Trans. Geosci. Remote Sens., 1999

Vachon P.W. and Gray A.L. and Geudtner D., ERS-1 SAR repeat-pass interferometry: Temporal coherence and implications for RADARSAT, 17th Canadian Symposium on Remote Sensing, Saskatoon, Sask., Canada, pages 803-898, 1995

Vachon P.W. and Geudtner D. and Gray A.L. and Touzi R., ERS-1 synthetic aperture radar repeat-pass interferometry studies: Implications for RADARSAT, Canandian Journal of Remote Sensing, volume 21, pages 441-454, 1995

Vachon P.W. and Geudtner D. and Mattar K. and Gray A.L. and Brugman L. and Cumming I., Differential SAR interferometry measurements of Athabasca and Saskatchewan Glacier flow rate, Canadian Journal of Remote Sensing/Journal Canadien de teledetection, volume 22/3, pages 287-296, 1996

Vachon P.W. and Geudtner D. and Gray L. and Mattar K. and Brugman M. and Cumming I. and Valero J.L., Airborne and spaceborne SAR interferometry: Application to the Athabasca glacier area, pages 2255-2257, Int. Geoscience and Remote Sensing Symp. IGARSS'96, Lincoln, Nebraska, 27-31 May 1996, 1996

Vachon P.W. and Gray A.L. and Mattar K.E., RADARSAT and ERS repeat-pass interferometry at CCRS, Proc. Second Workshop on SAR Interferometry, Tsukuba, Japan, November 18-20, pages 173-182, 1998

Vachon P.W. and Gray A.L. and Mattar K.E., RADARSAT and ERS repeat-pass interferometry at CCRS, Proc. Second Workshop on SAR Interferometry, Tsukuba, Japan, November 18-20, pages 173-182, 1998

van Bree R.J.P. and Gens R. and Groot J.S. and van Halsema D. (ed.) and Hanssen R.F. and van den Hout P. and *Klees R. and de Min and Schrama E.J.O and Usai* S., Deformation measurements with SAR, TNO Physics and Electronics Laboratory, Delft, The Netherlands, 1999

Werner C.L. and Rosen P.A. and Hensley S., Interferometric SAR systems development at JPL: sensors and processing techniques, Proc. 2nd Workshop on SAR Interferometry, Tsukuba, Japan, pages155-156, 1998

Wu X. and Thiel K.-H., The use of tandem data in the Antarctic area, Proc. ESA FRINGE'96 Workshop, Zurich, 1996

Wu X. and Thiel K.-H. and Hartl P., Estimating ice changes by SAR interferometry, Proc. 3rd Int. Airborne Remote Sensing Conf. and Exhibition, Copenhagen, pages 110-117, 1997

Zebker H.A .and Rosen P.A. and Hensley S. and Mouganis-Mark P.J., Analysis of active lava flows on Kilauea Volcano, Hawaii, using SIR-C radar correlation measurements, journal Geology, volume 24, page 495, 1995

Zebker H. and Rosen P.A. and Hensley S. and Mouginis-Mark P.J, Analysis of active lava flows on Kilauea volcano, Hawaii, using SIR-C radar correlation measurements, Geology, volume 24, number 6, pages 495-498, 1996

Zebker H.A. and Rosen P.A. and Hensley S., Atmospheric effects in interferometric synthetic aperture radar surface deformation, J. Geophys. Res., volume 102, pages 7547-7563, 1997

Zink M. and Bamler R. and Moreira A. and Papathanassiou K. and Scheiber R. and \"Ottl H., Status of SAR interferometry and its applications at DLR, Proc. 7th ISPRS symposium physical measurements and signatures in remote sensing, Courchevel, France, 1997

SPECIAL STUDY GROUP 2.161 REPORT REPORT

PROBING THE ATMOSPHERE BY GPS

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Introduction

It is now well established that space-based Global Positioning System (GPS) receivers can be used to profile Earth's ionosphere and neutral atmosphere with high accuracy and vertical resolution. The first proof-of-concept mission has been successfully completed and its data have been analyzed. Two follow-on missions have been launched during the first half of 1999 and a series of more ambitious missions to profile the atmosphere using the GPS limb sounding technique are planned for launch within the next 4 years. This report summarizes the dramatic progress in space-borne profiling during the last several years. We will review the most important results and accomplishments from the proof-of-concept GPS/MET mission; summarize future GPS occultation missions and challenges, and discuss applications of these data to meteorology, space weather, and climate studies.

GPS/MET

Scientists at Stanford University and the Jet Propulsion Laboratory (JPL) developed the radio occultation sounding technique for the remote sensing of planetary atmospheres. The GPS/MET (GPS/Meteorology) program[9] was established by the University Corporation for Atmospheric Research (UCAR) in 1993, jointly with the University of Arizona and JPL, to demonstrate active limb sounding of the Earth's neutral atmosphere and ionosphere using the radio occultation technique. The demonstration system observed occulted GPS satellite signals received on a LEO satellite, MicroLab-1 (ML-1), launched April 3, 1995. From raw GPS/MET observations, vertical profiles of ray bending angle and refractivity were retrieved; from which ionospheric electron density, neutral atmospheric density, pressure, temperature, and moisture profiles were computed.[10] The program has been exceptionally successful, having accomplished nearly all of the proof of concept goals, plus a number of additional ones. As a direct result, GPS/MET technology is now widely recognized as a potential candidate for a new, accurate global observing system in support of weather

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[9] The GPS/MET Program was sponsored primarily by NSF, with additional funding provided by the Federal Aviation Administration (FAA) and the National Oceanic and Atmospheric Administration (NOAA). In addition, the National Aeronautics and Space Administration (NASA) provided significant "in kind support" via funding provided directly to JPL for support of GPS/MET. Orbital Sciences Corporation accommodated the GPS/MET payload on its MicroLab-1 Satellite and provided a Pegasus rocket launch. Allen Osborne Associates, Inc. worked with GPS/MET investigators to convert its commercial Turbo Rogue GPS receiver for use in space.

[10] The techniques, algorithms, and assumptions used to process GPS/MET observations are described for example by Hoeg et al. (1996), Kursinski et al. (1996, 1997), Hajj and Romans, 1998, Rocken et al. (1997) and Hocke (1997), Schreiner et al. 1998. More references are given below.

prediction, climate change research and space weather. Several groups at JPL, the University of Arizona, UCAR, the Danish Meteorological Institute (DMI), the University of Graz, the Geoforschungszentrum, Potsdam (GFZ), the Institute of Atmospheric Physics, Moscow (IAP), the Institut d'Estudies Espacials de Catalounya, the University of Kyoto, and others, developed data inversion and analysis software for the GPS/MET data. In addition to studies based on GPS/MET data, a team at Stanford University conducted detailed investigations on error sources affecting the occultation technique. Studies on the assimilation of occultation data into numerical atmospheric models were conducted primarily at the National Center for Atmospheric Research (NCAR), Florida State University (FSU), the National Center for Environmental Prediction (NCEP), and the Max Plank Institute (MPI). The participation in GPS/MET and the use of its data was much broader than originally anticipated when the special study group (SSG2.161) on atmospheric sounding with GPS was formed at the 1995 IUGG in Boulder, Colorado.

A summary of key GPS/MET results based on studies by these groups from research institutions all over the world is presented in the following table:

• 62,000 neutral atmospheric soundings were processed to level 1 (GPS phase, range and amplitude data), 11,000 processed to Level 3 (high-resolution profiles of temperature, pressure, refractivity, humidity, geopotential height) and published on the web for A/S on and A/S off time periods. Several thousand soundings were compared to data from independent operational weather analyses and other observing systems.
• The high theoretical temperature accuracy was verified (approximately 1K) in the range from the surface to 40 km.
• Accurate retrieval of water vapor was demonstrated with use of ancillary temperature data.
• High vertical resolution of approximately 500 m for sensing of the tropopause and upper level fronts was demonstrated.
• New processing techniques were developed to reduce diffraction and multipath effects and to improve the vertical resolution beyond the Fresnel zone limit.
• All weather (including aerosols, clouds and precipitation) sounding capability was verified.
• Determination of accurate geopotential heights of ~10 m was demonstrated.
• Detection of gravity waves from the middle troposphere to the stratosphere was demonstrated
• Over 40,000 electron density profiles were processed and compared to ionosonde data
• Techniques were developed to account for horizontal gradients in the electron density distribution
• Accurate retrieval of vertical electron density profiles was demonstrated by ~10% level agreement with foF2 frequency data from the global ionosonde network
• Tomographic techniques were developed and tested to combine occultation data and ground based GPS observations to reconstruct global 4-D electron density grids.
• GPS/MET orbit data were used in the development of the new Earth Gravitational Model EGM96 (Lemoine et al., 1998).
• Observing systems simulation experiments and real-data assimilation experiments have indicated a likely positive impact of GPS/MET data on model initialization and weather prediction.
• A total of 123 data use agreements were issued for access through the GPS/MET web site, which still receives about 40,000 "hits"/month *(http://cosmic.gpsmet.ucar.edu/gpsmet)*.
• The data have been used extensively and internationally for science and planning of follow-on missions.
• A large number of peer-reviewed publications have been written using the GPS/MET data.

All of these accomplishments were achieved by scientists world-wide independently and in collaboration during the last 4 years - a truly remarkable advancement in atmospheric and occultation science. The extensive list of references at the end of this report points to detailed descriptions of this work.

Below is a list of names and email addresses of the individuals that are part of the special study group and/or contributed to the scientific results summarized in this report. Many others made significant contributions and this is not a complete list.

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The next Missions

The next table provides a list of mission names, their launch dates, number of daily soundings, and a comment about the most important aspect of the occultation part of the mission. Note that for most of these missions the GPS atmospheric sounding instrument is just one of many experiments and that the primary objective of these missions is generally not atmospheric sounding.

Mission Name	Launch Date	# of daily profiles	comment
GPS/MET	April 1995	125	Proof of concept
Ørsted	Feb 1999	125	Similar GPS receiver as GPS/MET
Sunsat	Feb. 1999	125	Similar GPS receiver as

			GPS/MET
CHAMP	Jan. 2000	250	Improved GPS tracking receiver
SAC-C	Jan. 2000	500	Setting and rising occultations
GRACE	May 2001	500	
COSMIC	Nov. 2002	4000	Operational demonstration
METOP	2003	500 - 1000	May track GLONASS plus GPS

- *Ørsted* was successfully launched in Feb. 1999. It is managed by the DMI and carries a JPL-developed GPS receiver that is a slightly refined version of the GPS/MET instrument. The receiver uses less power than GPS/MET has better data compression and some performance enhancements. This receiver only tracks setting GPS occultations and its data quality is strongly degraded (as was the case for GPS/MET) when the GPS signals are encrypted by Anti Spoofing measures (A/S), which is presently the normal mode of operation. The main purpose of the GPS soundings collected by Ørsted is its use for climate research and to advance the occultation technology.
- *Sunsat* is a South African mission that is flying the same GPS receiver as Ørsted.
- *CHAMP* is a German mission that will fly an enhanced JPL-developed receiver, called "BlackJack". The main advantage of this next generation receiver is a 3-dB signal-to-noise ratio (SNR) improvement over the previous tracking techniques under weak signal conditions. It is expected that this receiver will surpass the GPS/Met A/S off tracking performance even when A/S is on. Thus this receiver will track the occultation signal more reliably in the lower troposphere than its predecessors.
- *SAC-C* is an Argentine led mission that will use the same GPS instrument as CHAMP. SAC-C will be the first mission to attempt tracking setting and rising occultations. Tracking of rising occultations is more demanding because the receiver needs to pick up faint signals from behind Earth's limb as the GPS satellite appears in the (approximate) direction of the low earth orbiter's velocity vector.
- *GRACE* is a U.S./German mission that will fly a JPL-developed receiver with added capability to track a Ka-band crosslink ranging signal between the two GRACE satellites and to determine precise attitude from an integrated digital star camera.
- *COSMIC* is Taiwan/U.S. mission that will fly 8 satellites to measure 4000 soundings each day globally. The main goal of COSMIC is to demonstrate the operational value of occultation data to numerical weather prediction and space weather monitoring. To achieve this goal the data from this mission shall be analyzed and delivered to operational and research centers worldwide within 3 hours of data collection. COSMIC plans to fly JPL-developed receivers adapted from the "BlackJack" generation instrument.
- *METOP* is a European operational satellite that will carry a European - developed GPS/Glonass receiver. METOP occultation data will be used for operational weather prediction.

Applications and Challenges

The main characteristics of space-based GPS atmospheric sounding data and their applications are summarized below.

Characteristic	Meteorology	Climate	Ionosphere
Limb sounding geometry complementary to ground and space nadir viewing instruments	X	X	X
High Accuracy	X	X	X
High vertical resolution	X	X	X
Consistency of horizontal and vertical scales of observations	X	X	
All weather-not affected by clouds or precipitation	X	X	X
Independent height and pressure	X	X	
Requires no first guess sounding	X	X	X
Independent of radiosonde or other calibration	X	X	X
No instrument drift		X	
No satellite-to-satellite bias		X	
Top and bottom side sounding			X

Because of these characteristics occultation data have the potential to significantly benefit meteorology, climate and ionospheric research and forecasting. In order to achieve these benefits the community has to (a) collect a large amount of high quality occultation data, and (b) develop the techniques to assimilate these observations into physical models of the atmosphere and ionosphere.

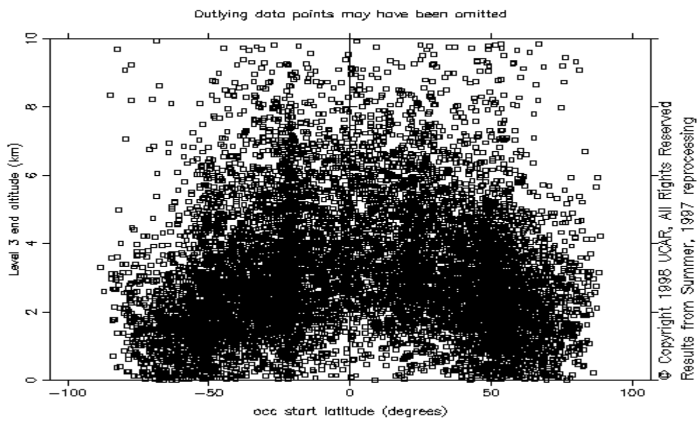

Figure 1 GPS Sounding penetration for ~10,000 GPS/MET occultations as a function of latitude

The upcoming missions promise to provide the needed data volume and density to demonstrate forecasting impact. In addition to more data, the data from these missions will also have to be of higher quality than what was produced by GPS/MET. Figure 1 shows the depth to which GPS/MET occultations penetrated Earth's atmosphere. It can be seen that most occultation stopped as high as 3 km above the surface and in the equatorial region hardly any soundings probed the lowest km. It is of the highest importance that future missions provide data that reliably penetrate to near the surface. This shall be achieved with a combination of improved GPS occultation instruments and higher gain antennas flown in future missions.

New and improved algorithms will also have to be developed to deal with lower tropospheric data that will be affected by strong refractivity gradients due to water vapor.

Summary

The research community has made impressive gains over the last 4 years in the field of atmospheric sounding from space with GPS. New satellite missions will provide much more data in the near future and we can look forward to witnessing improvements in weather and space weather forecasting due, in part, to this sensing technique. Important challenges lie ahead to collect and correctly interpret data near the ground, and to develop optimal data assimilation techniques.

References

Ahmad, B., *Accuracy and Resolution of Atmospheric Profiles Obtained from Radio Occultation Measurements*, Ph.D. Dissertation, Stanford University, December, 1998. Also available as Scientific Report No. DPD811-1998-1, Space, Telecommunications, and Radio Sci. Laboratory, Department of Electrical Engineering, Stanford University, California, 94305-9515, October, 1998.

Ahmad, B., and G. L. Tyler, The two-dimensional resolution kernel associated with retrieval of ionospheric and atmospheric refractivity profiles by Abelian inversion of radio occultation phase data, *Radio Sci*., *33*, (1), 129-142, 1998.

Ahmad, B., and G. L. Tyler, Systematic errors in atmospheric profiles obtained from Abelian inversion of radio occultation data: Effects of large-scale horizontal gradients, *J. Geophys. Res.*, *104*(D4), 3971-3992, 1999.

Anderson, J., and G. North, Testing climate models: An approach. *Bull. Amer. Met. Soc., 79*, 2541-2549, 1998.

Anthes, R., M. Exner, C. Rocken, and R. Ware, Results from the GPS/MET Experiment and Potential Applications to GEWEX, *GEWEX News*, 7, 1997.

Anthes, R., W. Schreiner, S. M. Exner, D. Hunt, Y. Kuo, S. Sokolovskiy, R. Ware and X. Zou, GPS Sounding of the Atmosphere from Low Earth Orbit: Preliminary Results and Potential Impact on Numerical Weather Prediction, Augmenting the GPS Infrastructure for Earth, *GPS for the Geosciences*, National Academy Press, pp.114-124, 1997a.

Belloul, B. and A. Hauchecorne, Effect of periodic horizontal gradients on the retrieval of atmospheric profiles from occultation measurement. *Radio Sci*., 32(2), 469-478, 1997.

Bengtsson, L., J.R. Eyre, G. Kirchengast, A. Hauchecorne, P. Silvestrin, and P. Ingmann, Atmospheric Profiling Mission --- a candidate Earth Explorer mission (report for assessment), *ESA Spec. Publ. SP-1196 (7)*, 58 p., ESA/ESTEC, Noordwijk, NL, 1996.

Bertiger, W., and S.C. Wu, Single Frequency GPS Orbit Determination for Low Earth Orbiters, paper presented at the National Technical Meeting, Inst. Of Nav., Santa Monica, Calif., Jan., 1996.

Businger, S., S. Chiswell, M. Bevis, J. Duan, R. Anthes, C. Rocken, R. Ware, M. Exner, T. VanHove, and F. Solheim, The promise of GPS in atmospheric monitoring, *Bull. Amer. Met. Soc***.,** *77*, 5-18, 1996.

Dymond, K., S.E. Thonnard, R.P. McCoy, and R.J. Thomas, An optical remote sensing technique for determining nighttime F region electron density, *Radio Sci., 32(5)*, Sept., 1997.

ESA, 1996: Atmospheric Profiling Mission. *ESA SP-1196(7*). The Nine Candidate Earth Explorer Missions. European Space Agency, ESA Publications Division, Noordwijk, The Netherlands, 58.

Feng, D., B. Herman, M. Exner, B. Schreiner, R. Anthes, and R. Ware, Space-borne GPS remote sensing for atmospheric research, *Proceedings from Synthetic Aperture Radar and Passive Microwave Sensing, 2584***,** 448-455, 1995.

Fjeldbo, G., A. J. Kliore, and V. L. Von Eshelman, The neutral atmosphere of Venus as studied with the Mariner V radio occultation experiments, *Astron. J., 76*, 123-140, 1971.

Flores A., G.Ruffini, A.Rius, Tropospheric tomography using GPS slant delays, submitted to *Geophys. Res. Lett*., 1998.

Foelsche, U., and G. Kirchengast, Space-Time resolution conditions for atmospheric imaging involving GNSS occultation: A quantitative study, *IMG/UoG Techn. Rep. for ESA/ESTEC No. 3/'97*, 33 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1997.

Gorbunov, M. E., Solution of inverse problems of remote atmospheric refractometry on limb paths, *Izv Acad. Sci. USSR: Atmos. Oceanic Phys*., Engl. Transl., 26, 86-91, 1990.

Gorbunov, M., and S. Sokolovskiy, Remote sensing of refractivity from space for global observations of atmospheric parameters, *Rep. 119*, 58 pp., Max Planck Inst. for Meteorol., Hamburg, Germany, 1993.

Gorbunov, M. E., A. S. Gurvich, and L. Bengtsson, Advanced algorithms of inversion of GPS/MET satellite data and their application to reconstruction of temperature and humidity, *Rep. 211*, 40 p., Max Planck Inst. for Meteorol., Hamburg 1996.

Gorbunov, M.E., S. V. Sokolovsky and L. Bengtsson,: Space refractive tomography of the atmosphere: Modeling of direct and inverse problems. *Rep. 210*, 59, Max Planck Inst for Meteorol., Hamburg, 1996a.

Gorbunov, M.E., and A.S.Gurvich, Microlab-1 Experiment: Multipath effects in the lower troposphere, *J. Geophys. Res.*, *103*, (D12), 13819-13826, 1998.

Gurvich, A. S., and S. V. Sokolovskiy, Reconstruction of a pressure field by remote refractometry from space, *Izvestya, Atm. Ocean. Phys., 21,* 7-13, 1983.

Hajj, G. A., and L. J. Romans, Ionospheric electron density profiles obtained with the Global Positioning System: Results from the GPS/MET experiment, *Radio Sci*., *33*(1), 175-190, 1998.

Hajj, G. A., R. Ibanez-Meir, E. R. Kursinski, and L. J. Romans, Imaging the ionosphere with the Global Positioning System, *Int. J. Imaging Syst. Technol*., *5*, 174-184, 1994.

Hardy, K. R., G. A. Hajj, E. R. Kursinski, and R. Ibanez-Meier, Accuracies of atmospheric profiles obtained from GPS occultations, in *Proceedings of the ION GPS-93 Conference*, 1545-1556, Inst. of Navig., Alexandria, Va., 1993.

Hernandez-Pajares, M., J. M. Juan, J. Sanz, J. G. Sole, Global observation of the ionospheric electronic response to solar events using ground and LEO GPS data, *J. Geophys. Res. 103*(A9), 20789-20796, 1998.

Ho, C. M., B. D. Wilson, A. J. Mannucci, U. J. Lindqwister, and D. N. Yuan, A comparative study of ionospheric total electron content measurements using global ionospheric maps of GPS, TOPEX radar, and the Bent model, *Radio Sci*., *32*(4), 1499-1512, 1997.

Hocke K., Inversion of GPS meteorology data, *Ann. Geophys*., *15*, 443-450, 1997.

Hocke K., G. Kirchengast, A. Steiner: Ionospheric correction and inversion of GNSS occultation data: problems and solutions, *IMG/UoG Technical Report for ESA/ESTEC*-No. 2/1997, Graz, Austria, 1997.

Hoeg, P., A. Hauchecorne, G. Kirchengast, S. Syndergaard, B. Belloul, R. Leitinger, and W. Rothleitner, Derivation of atmospheric properties using a radio occultation technique, *Sci. Rep., 95-4*, Danish Meteorol. Inst., 1996.

Howe, B. M., K. Runciman, and J. A. Secan, Tomography of the ionosphere: Four-dimensional simulations, *Radio Sci*., *33*(1), 109-128, 1998.

Hurrell, J.W. and K.E. Trenberth, Spurious trends in satellite MSU temperature from merging different satellite records. *Nature, 386(3*),1997.

Hurrell, J.W. and K.E. Trenberth, Difficulties in obtaining reliable temperature trends: Reconciling the surface and satellite microwave sounding unit records. *J. Climate, 11(5)*, pp. 945–967, 1998.

Climate change 1995. The science of climate change. Contribution of WGI to the second assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 572 pp., IPCC,1996.

Jakowski N., J. Wickert , K. Hocke , Ch. Reigber, Ch. Förste, R. König, Atmosphere/Ionosphere sounding onboard CHAMP, paper presented at 1998 Western Pacific Geophysics Meeting, Taipei/Taiwan, 21-24 July 1998, Session G42B, Abstr. publ. in EOS Suppl., *Transactions, AGU, 79(24*), W20, 1998.

Jakowski N., Scientific Goals and Objectives – Ionosphere, *Proc. IGS-GFZ-JPL Workshop on Low Earth Orbiter* Missions, Potsdam, Germany , March 9-11,1999.

Juan, J.M., M. Hernandez-Pajares, A. Rius, J. Sanz, A two-layer model of the ionosphere using Global Positioning System data, *Geophys. Res. Lett., 24(4*), 393-396, 1997.

Karayel, E.T. and D. P. Hinson, Sub-Fresnel vertical resolution in atmospheric profiles from radio occultation, *Radio Sci*. 32(2), 411-423, 1997.

Kirchengast, G., End-to-end GNSS occultation performance simulator functionality definition, *IMG/UoG Techn. Rep. for ESA/ESTEC No. 1/'96*, 25 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1996.

Kirchengast, G., End-to-end GNSS occultation performance simulator overview and exemplary applications, *Wissenschaftl. Ber. No. 2/1998*, 142 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1998.

Kirchengast, G., und H.-P. Ladreiter, Das Potential der Radio-Okkultationstechnik basierend auf GPS/ *GLONASS*-Signalen zur Bestimmung fundamentaler atmosphaerischer Parameter, *Kleinheubacher Ber., 39*, 677-686, 1996.

Kirchengast, G., M. Gorbunov, N. Jakowski, L. Kornblueh, U. Mallow, A. Rius, C. Rocken, M. Rothacher, G. Schmidtke, M. Sust, J. Ward, and A. Wernik, ACLISCOPE --- Atmosphere and Climate Sensors Constellation Performance Explorer (ESA Earth Explorer Opportunity Missions proposal), *Wissenschaftl. Ber. No. 4/1998*, 60 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1998.

Kirchengast, G., and J. Ramsauer, Impact of an atmospheric profiling mission on NWP: Assessment of mission scenarios and definition of OSSE study test missions, *IMG/UoG Techn. Rep. for ESA/ESTEC No. 3/1999*, 16 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1999.

Kuo, Y.-H., X. Zou, and W. Huang, The impact of Global Positioning System data on the prediction of an extratropical cyclone: an observing system simulation experiment, *J. Dyn. Atmos. Oceans*, *27*, 439–470, 1997.

Kuo, Y.-H., X. Zou, and Y.-R. Guo, Variational assimiliation of precipitable water using a nonhydrostatic mesoscale adjoint model. Part I: moisture retrieval and sensitivity experiments., *Mon. Wea. Rev.*, *124*, 122-147, Jan. 1996.

Kuo, Y.-H., X. Zou, F. Vandenberghe, W. Huang and R. Anthes, Assimilation of GPS/MET data for Numerical Weather Prediction. *Terrestrial, Atmospheric and Oceanic Sciences*, (this issue), 1999.

Kursinski, E. R., G. A. Hajj, K. R. Hardy, L. J. Romans and J. T. Schofield, Observing tropospheric water-vapor by radio occultation using GPS, *Geophys. Res. Lett. 22*, 2365-2368, 1995.

Kursinski, E. R., G.A. Hajj, W. I. Bertiger, S. S. Leroy, T. K. Meehan, L. J. Romans, J. T. Schofield, D. J. McCleese, W. G. Melbourne, C. L. Thournton, T. P. Yunck, J. R. Eyre, R. N. Nagatani, Initial results of radio occultation observations of earth’s atmosphere using the global positioning system, *Science, 271*, 1107-1110, 1996.

Kursinski, E.R., G.A. Hajj, J.T. Schofield, R.P. Linfield and K.R. Hardy, Observing the Earth’s atmosphere with radio occultation measurements using the Global Positioning System, *J. Geophys. Res*, *102(D19)*, 23429-23465, 1997.

Kursinski, E. R. and G. A. Hajj, An examination of water vapor derived from global positioning system occultation observations during June-July 1995, Part I: Zonal Means, *J. Geophys. Res*., in press, 1998.

Ladreiter, H.-P., and G. Kirchengast, GPS/GLONASS sensing of the neutral atmosphere: Model independent correction of ionospheric influences, *Radio Sci, 31,* 877-891, 1996.

Leitinger, R., and G. Kirchengast, Inversion of the plasma signal in GNSS occultations --- simulation studies and sample results, *Acta Geod. Geophy. Hung*., *32*, 379-394, 1997.

Leitinger, R., H.-P. Ladreiter, and G. Kirchengast, Ionosphere tomography with data from satellite reception of Global Navigation Satellite System signals and ground reception of Navy Navigation Satellite System signals, *Radio Sci*., *32*(4), 1657-1669, 1997.

Lemoine, F.G., C. Kenyon, J.K. Factor, R.G Trimmer, N.K. Pavlis, D.S. Cinn, C.M. Cox, S.M. Klosko, S.B. luthke, M.H. Torrence, Y.M. Wang, R.G. Willamson, E.C. Pavlis, R.H. Rapp, and T.R. Olsen, The development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, *NASA/TP-1998-206861*, 1998.

Leroy, S., The measurement of geopotential heights by GPS radio occultation, *J. Geophys. Res.*, *102*, 6971-6986, 1997.

Leroy, S. S., Detecting climate signals: Some Bayesian aspects, *J. Clim.*, *11*, 640-651, 1998.

Leroy, S.S., Optimal detection of global warming using temperature profiles: A methodology, *J. Climate*, in press, 1998.

Lindall, G.F., J.R. Lyons, D.N. Sweetnam, V.R. Eshleman, D.P. Hinson, G.L. Tyler, The atmosphere of uranus: results of radio occultation measurements with voyager 2, *J. Geophys. Res.*, *92*, 14987-15001, 1987.

Lindzen, R.S. and M. Fox-Rabinovitz, Consistent vertical and horizontal resolution. *Mon. Wea. Rev.*, *117*, 2575-2583, 1989.

Lindzen, R.S., Some coolness concerning global warming, *Bull. Amer. Met. Soc. 71*, 288, 1990.

Meehl, G.A., W. Collins, B. Boville, J.T. Kiehl, T.M.L Wigley, and J.M. Arblaster, Factors affecting climate sensitivity and climate change in the NCAR Climate System Model. *J. Climate*, in preparation, 1998

Melbourne, W., E. Davis, C. Duncan, G. Hajj, K. Hardy, E. Kursinski, T. Meehan, L. Young, T. P. Yunck, The application of space borne GPS to atmospheric limb sounding and global change monitoring, *JPL Publ*., *94-18*, 147 pp., 1994.

Melbourne W.G, E.S. Davis, C.B. Dunkan, G.A. Hajj, K.R. Hardy, E.R. Kursinski, T.K. Meehan, L.E. Young, T.P. Yunck, The application of spaceborne GPS to atmospheric limb sounding and global change monitoring, *JPL Publ*., *94-18*, NASA, JPL, Californian Institute of Technology, Pasadena, CA, 1994.

Melbourne, W. G., T. P. Yunck, L. E. Young, B. H. Hager, G. F. Lindal, C. H. Liu, and G. H. Born, GPS geoscience instrument for EOS and Space Station. *JPL proposal to NASA AO* OSSA-1-88, 81, 1988.

Melbourne, W.G., Sensing atmospheric and ionospheric boundaries in GPS radio occultation observations from a low Earth orbiter, Part 1, *JPL Publication 99-5*, Jet Propulsion Laboratory, Pasadena, CA, 1998.

Melbourne, W.G., Sensing atmospheric and ionospheric boundaries in GPS radio occultation observations from a low Earth orbiter, Part 2, *JPL Publication 99-5*, Jet Propulsion Laboratory, Pasadena, CA, 1999.

Mortensen D.M., and P.Hoeg, Inversion of GPS Radio Occultation Measurements Using Fresnel Diffraction Theory, *Geophys. Res. Lett*., *25(13)*, 2441-2444, 1998.

Mortensen, M. D., R. P. Linfield and E. R. Kursinski, Resolution approaching 100m for GPS occultations of the Earth's atmosphere, *IEEE Trans. on Geoscience and Remote Sensing, 1998.*

North, G. R., and M. J. Stevens, Detecting climate signals in the surface temperature record, *J. Climate*, *11*, 563-577, 1998.

NRC, *Global environmental change-Research pathways for the next decade.* National Academy Press, Washington, D.C., 69, 1998.

Pavelyev, A., K. Hocke, O. Yakovlev, N. Jakowski, J. Wickert, S. Matugov, A. Kucherjavenkov, A. Wehrenpfennig, A. Zakharov: Radioholographic method for atmosphere sounding using small satellites, for earth observation: *Digest of 2nd IAA Symposium*, ed. by H.P. Roser et al., Wissenschaft und Technik Verlag, Berlin, 199-202, 1999.

Pavelyev, A.G., On possibility of radio holographic investigation at radio communication link satellite-to-satellite, *Radioteknika i elektronica 43*, 939-944 (in Russian), 1998.

Phinney, R. A., and D. L. Anderson, On the radio occultation method for studying planetary atmospheres, *J. Geophys. Res.*, *73*(5), 1819-1827, 1968.

Ramsauer, J., and G. Kirchengast, Impact of an atmospheric profiling mission on NWP. Review of sampling requirements and mission scenario study, *IMG/UoG Techn. Rep. for ESA/ESTEC No. 1/1999*, 70 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1999.

Reigber, Ch., Bock, R., Förste, Ch., Grunwaldt, L., Jakowski, N., Lühr, H., Schwintzer, P., Tilgner, C., CHAMP Phase B - Executive Summary, *Scientific Technical Report STR96/13*, GeoForschungsZentrum Potsdam,1996.

Reigber Ch., R. Galas , R. König , N. Jakowski , J.Wickert , A.Wehrenpfennig, GFZ and DLR contribution to GPS ground network supporting CHAMP mission, Towards an integrated global geodetic observing system, *Proc. Internat. Symp. of IAG*, 5-9 October 1998, München.

Rind, D., Latitudinal temperature gradients and climate change, *J. Geophys. Res., 103(D6),* 5943-5971, 1998.

Rind, D., Just add water vapor, *Science, 281*, 1152, 1998.

Rius, A., G. Ruffini, and L. Cucurull, Improving the vertical resolution of ionospheric tomography with GPS occultations, *Geophys. Res. Lett.*, *24*(18), 2291-2294, 1997.

Rius, A., G. Ruffini, and A. Romeo, Analysis of ionospheric electron density distribution from GPS/MET occultations, *IEEE Trans. on Geoscience and Remote Sensing, 36(2*), Mar 1998.

Rocken, C., R. Anthes, M. Exner, D. Hunt, S. Sokolovskiy, R. Ware, M. Gorbunov, W. Schreiner, D. Feng, B. Herman, Y. Kuo, and X. Zou, Analysis and validation of GPS/MET data in the neutral atmosphere, *J. Geophys. Res*, *102(D25)*, 29849-29866, 1997.

Rocken, C, et al., COSMIC system overview *Terrestrial, Atmospheric and Oceanic Sciences*, 1999.(submitted).

Ruffini, G., Flores, A., Rius, A., GPS tomography of the Ionospheric Electron content with a correlation functional, *IEEE Transactions on Geoscience and Remote Sensing, 36(1),* January 1998.

Ruffini, G., E. Cardellach, A. Flores, L. Cucurull and A. Rius, Ionospheric calibration of radar altimeters using GPS tomography, *Geophys. Res. Lett., 25(20),* 1998.

Ruffini, G., Cucurull, L., Flores, A., Rius, A., A PIM-Aided Kalman Filter for GPS tomography of the ionospheric eletron content, *Phys. Chem. Earth (C), 24(4),* 365-369, 1999. (http://xxx.unizar.es/abs/physics/9807026)

Salby, M.L. and P. Callaghan; Sampling error in climate properties derived from satellite measurements: Consequences of undersampled diurnal variability. *J.. Climate*, *10*, 18-36, 1997.

Schreiner, W.S.., D.C. Hunt, C. Rocken, S. Sokolovskiy, Precise GPS data processing for the GPS/MET radio occultation mission at UCAR, *Proc. Of the Institute of Navigation- Navigation 2000, Long Beach, CA*, pp. 103-112, Jan 21-23, 1998.

Schreiner, W.S., S. Sokolovskiy, C. Rocken, R. Ware, Analysis and validation of GPS/MET radio occultation data in the ionosphere, *accepted in Radio Sci.,* 1998.

Schutz, B., P. Abusali, C. Schroeder, B. Tapley, M. Exner, R. McCloskey, R. Carpenter, M. Cooke, S. McDonald, N. Combs, C. Duncan, C. Dunn, and T. Meehan, GPS tracking experiment of a free-flyer deployed from space shuttle, *Proceedings of GPS-95, Institute of Navigation,* 1995.

Steiner, A.K., High resolution sounding of key climate variables using the radio occultation technique (Ph.D. thesis), *Wissenschaftl. Ber*. 3, 170 p., Inst. Meteorol. Geophys., Univ. Graz, Austria, 1998.

Steiner, A.K., G. Kirchengast, and H.-P. Ladreiter, Inversion, error analysis, and validation of GPS/MET occultation data, *Ann. Geophys.*, *17,* 122-138, 1999.

Steiner, A.K., and G. Kirchengast, Gravity wave spectra from GPS/MET occultation observations, *J. Atmos. Oceanic Technology, 16*, in press, 1999.

Steurer, P., Six Second Upper Air Data, TD-9948. National Climatic Data Center, Asheville, NC, 17 p, February 1996.

Stevens, M.J., Optimal climate signal detection in four dimensions, *J. Geophys. Res. - Atmos.*, 104, D4, pp 4089-4099, Feb., 1999.

Syndergaard, S., Modeling the impact of the Earth's oblateness on the retrieval of temperature and pressure profiles from limb sounding, *J. of Atmos. Solar-Terres. Phys., 60*, 171-180, 1998.

Tsuda, T., Nishida N., Rocken C. and R. Ware, A global morphology of gravity wave activity in the stratosphere revealed by the GPS occultation data (GPS/MET), *J. Geophys. Res. (submitted)* 1998a .

Tsuda, T., Nishida N., Rocken C. and R. Ware, Verification of temperature profiles obtained by the GPS occultation technique (GPS/MET) with radiosonde and LIDAR measurements in tropical and subtropical regions, *J. Geophys. Res.* (*submitted)*, 1998b.

Vorob'ev, V.V., and T. G. Krasil'nikova, Estimation of the accuracy of the atmospheric refractive index recovery from Dopler shift measurements at frequencies used in the NAVSTAR system, Phys. Atmos. Oceans, *29*, 602-609, 1994.

Ware, R., GPS Sounding of Earth's Atmosphere*, GPS World, 3***,** 56- 57, 1992.

Ware, R., M. Exner, B. Herman, W. Kuo, and T. Meehan, Active atmospheric limb sounding with an orbiting GPS receiver, *Trans. Amer. Geophys. Union*, *EOS, 74*, 336, 1993.

Ware, R., The University Navstar Consortium, Global Positioning for Geosciences Research, *IGS Special Topics and New Directions, Workshop Proceedings*, Potsdam, 40-48, 1995.

Ware, R., and S. Businger, Global positioning for geosciences Research, *EOS, 76*, 187, 1995.

Ware, R., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovskiy, F. Solheim, X. Zou, R. Anthes, S. Businger, and K. Trenberth, GPS sounding of the atmosphere from low earth orbit: Preliminary results*, Bull. Amer. Met. Soc.*, *77,* 19-40, 1996.

WCRP, Stratospheric Processes and Their Role in Climate. *World Climate Research Programme Report 105,* World Meteorological Organization, Geneva, 131 pp., 1998.

Yuan, L., R. A. Anthes, R. H. Ware, and W. Bonner, Using the Global Positioning System in atmospheric sciences and for detecting climate change, *Proc. 2nd International Conference on East Asia and Western Pacific Meteorology and Climate*, 1992,

Yuan, L., R. A. Anthes, R. H. Ware, C. Rocken, W. Bonner, M. Bevis, and S. Businger, Sensing climate change using the Global Positioning System, *J. of Geophys. Res*., 98(14), 925- 14,937, 1993.

Zou, X. , Y.-H. Kuo, and Y.-R. Guo, Assimilation of atmospheric radio refractivity using a nonhydrostatic mesoscale model, *Mon. Wea. Rev., 123,* 2229-2249, 1995.

Zou, X., F. Vandenberghe, B. Wang, M.E. Gorbunov, Y.-H. Kuo, S. Sokolovskiy, J.C. Chang, J.G. Sela, and R.A. Anthes, Direct assimilation of GPS/MET refraction angle measurements: Part I: Concept and results of raytracing, *J. Geophys. Res*, accepted for pub. Sept., 1998.

Zou, X., B. Wang, F. Vandenberghe, M.E. Gorbunov, Y.-H. Kuo, J.C. Chang, J.G. Sela, and R.A. Anthes, Direct assimilation of GPS/MET refraction angle measurements: Part II Adjoint of raytracing and results of variational analysis, *J. Geophys. Res*, accepted for pub. Sept., 1998.

THE INTERNATIONAL GPS SERVICE (IGS)

1995 TO 1999

REPORT TO THE INTERNATIONAL ASSOCIATION OF GEODESY

ADVANCED SPACE TECHNOLOGY SECTION II

IGS Central Bureau
Jet Propulsion Laboratory
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ABSTRACT

The International GPS Service (IGS), formerly the International GPS Service for Geodynamics, is an approved service of the International Association of Geodesy (IAG) since 1994. The primary objective of the IGS is to provide a service to support, through GPS data products, geodetic and geophysical research activities. This report will chronicle the past four years of history of the IGS. (See the IAG Travaux 1996, Tome 30 edited by P. Willis for the report on the formative years of the IGS).

KEY DEVELOPMENTS OF THE IGS 1995-1999

<u>1995</u> - The 'Special Topics and New Directions Workshop' held at GeoForschungsZentrum Potsdam (GFZ), Germany in May initiated the extension of the IGS to various applications, especially exploring atmospheric and climate monitoring. Discussions and decisions at this meeting resulted in shortening IGS Rapid Orbit Production in 1996 and planning for the production of predicted orbits. First meeting between the Permanent Service for Mean Sea Level (PSMSL) and IGS at the GLOSS (Global Ocean Observing System) meeting in Bordeaux, France investigating the use of GPS and the IGS for monitoring sea level. Number of stations in IGS network: 112.

<u>1996</u> - IGS became a recognized service of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). A 'Call for Participation' was released in January for IGS Regional Network Associate Analysis Centers (RNAAC) for the regional densification of the terrestrial reference frame in support of the ITRF. The IGS Predicted Orbit Combination was made available in early March. The Silver Spring Analysis Center Workshop in March dealt with a variety of issues such as orbit and clock combination processes, phase-centers values and antenna calibration, EOPs, ionospheric and tropospheric applications, etc. A standard format termed 'Solution INdependent Exchange Format' (SINEX) was adopted as the exchange format for submission of

analysis centers solutions into a global combination enabling the IGS ‘polyhedron’ solution. Rather than simultaneous processing of all stations data in rapidly growing global and regional networks, this approach permits the combination of multi-station solutions produced by different analysis centers (today this is being extended to a multi-technique solutions). During June significant processing changes with IGS orbits occurred when the IGS combinations discontinued polar motion alignment of the different analysis centers (AC) orbit solutions. IGS AC polar motion precision at or below 0.1mas. Number of stations in IGS network: 144 stations.

1997 - The Analysis Center Workshop in March in Pasadena focused on the potential of low Earth orbiter applications within the IGS and interest in GLONASS data handling/analysis within the IGS infrastructure. First joint workshop between the PSMSL and the IGS held in Pasadena, CA. IGS hosted a GLOSS GRE meeting after the joint workshop. The Pilot Project for Precise Time and Time Transfer joint with the Bureau de Poids et Mesures (BIPM) was given conceptual approval at the Governing Board meeting in Rio De Janeiro. The first IGS retreat was held in Napa Valley in December generating many recommendations for continued improvement of the service. IGS analysis focused on length of day/UT and clock correction combinations. In order to facilitate combined prediction products the IGS Rapid orbit delivery was pushed from 24 to 22 hours. Best orbit solutions at or below 5 cm for Final solutions, and 5-10 cm for Rapid solutions. Prediction orbit precision RMS median of ~50cm compared to the Broadcast orbit at ~200cm. Number of stations in IGS network: 167 Stations.

1998 - Two key and successful workshops were held this year, the Analysis Center Workshop in February in Darmstadt and the Network Systems Workshop held in November in Annapolis. A number of recommendations resulted from each workshop and are contained in the respective workshop proceedings (see IGS Publication list below). The list of IGS fiducial sites for reference frame control were expanded from the original 13 to 47 stations. Call for Participation in the International GLONASS Experiment (IGEX) joint with CSTG was announced. Reorganization of the Central Bureau (CB) was initiated due to IGS Napa Valley ‘97 retreat recommendations, including establishment of the IGS Network Coordinator within the CB. The IGS Annual Report Series was revised to a two volume document, the summary Annual Report and a detailed companion volume documenting the IGS Technical Reports for each year. At the May meeting of the Governing Board in Boston, a policy was adopted for the establishment of IGS projects and working groups. At the December meeting in San Francisco a number of changes took place: the Terms of Reference revised under the guidance of Prof. Ivan Mueller was adopted; working group chairs and project heads become non-voting members of the Governing Board; and Prof. Christoph Reigber of GeoForschungsZentrum (GFZ) Potsdam, Germany was unanimously elected as Chairman of the IGS Governing Board, succeeding Prof. Gerhard Beutler from the University of Bern, Switzerland. Prof. Beutler served as Chair of the IGS Oversight Committee (1991-1993) and as Chair of the IGS Governing Board for five years (1994-1998). The responsibilities of Analysis Coordinator transferred from Dr. Jan Kouba of Natural Resources of Canada to Dr. Tim Springer of the University of Bern, Switzerland. Jan Kouba was the AC Coordinator since 1993 and is largely credited with fostering the incredible cooperation and friendly competition of the ACs that resulted in the continual improvement of IGS products. IGS orbits in 1998 continue at the ~5cm level, while some of the best analysis centers are approaching the 3cm level of orbit precision. Adoption of the 47 stations for fiducial control earlier in the year resulted in marked improvement in orbits, AC clocks, ERP and coordinate solutions. IGS subnetwork concept was established, and the flow of hourly GPS data files was formalized. Number of stations in IGS network: 200 stations (see Figure 1).

1999 - In March an IGS workshop dedicated to low Earth orbiter (LEO) missions was held at GFZ Potsdam, Germany. This was a pivotal workshop for the IGS raising questions and increasing awareness of the potential role that IGS could play for operational support of LEO satellites with on-board GPS flight receivers for purposes of precise orbit determination, atmospheric occultation, ionospheric tomography and how these observations will be used by the atmospheric and meteorological community. In June the first meeting of the new Governing Board under the leadership of Prof. Reigber was held one day prior to the Analysis Center workshop in San Diego, California. The workshop focused on real-time applications and long term stability and accuracy. The 'Travaux" in the year 2003 will be able to describe the resulting status of recommendations stemming from the past three IGS workshops. That there have been three IGS workshops in only eight months demonstrates an unusually active period! (starting with the Network Workshop in November of 1998).

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Creator : Robert Liu,238-635,4-1836
CreationDate : Wed Jun 30 13:55:59 1999

Figure 1. Station locations of the IGS Tracking Network, July 1999.

IGS GOVERNING BOARD MEMBERS AND INSTITUTIONS 1999			TOTAL SER\
MEMBER	**INSTITUTION & COUNTRY**	**FUNCTIONS**	**TERM** (current: 4 yea
Christoph Reigb	*GeoForschungsZentrum Potsdam, Germany*	Chair, Appointed (IGS)	1999-2002
Gerhard Beutler	*University of Bern, Switzerland*	Appointed (IAG)	1996-1999
Mike Bevis	*University of Hawaii, USA*	Appointed (IGS)	1998-2001
Geoff Blewitt	*University of Newcastle upon Tyne, UK*	Analysis Center Representative	1998-2001
Yehuda Bock	*Scripps Inst. of Oceanography, USA*	Analysis Center Representative	1996-1999
Claude Boucher	*Institut Geographique National, ITRF, France*	IERS Representative to IGS	---
John Dow	*ESA/European Space Operations Center, Germany*	Network Representative	1996-1999
Bjorn Engen	*Statens Kartverk, Norway*	Network Representative	1998-2001
Joachim Feltens	*ESA/European Space Operations Center, Germany*	Ionosphere Working Group Chair	1999-2000
Remi Ferland	*Natural Resources Canada*	IGS Reference Frame Coordinator	1999-2000
Gerd Gendt	*GeoForschungsZentrum Potsdam, Germany*	Troposphere Working Group Chair	1999-2000
Jan Kouba	*Natural Resources Canada*	Analysis Center Representative	1996-1999
John Manning	*Australian Survey and Land Information Group*	Appointed (IGS)	1996-1999
Bill Melbourne	*Jet Propulsion Laboratory, USA*	IGS Representative to IERS	---
Ivan Mueller	*Ohio State University, USA*	IAG Representative	1996-1999
Ruth Neilan	*Jet Propulsion Laboratory, USA*	Director of IGS Central Bureau	---
Carey Noll	*Goddard Space Flight Center, USA*	Data Center Representative	1998-2001
Jim Ray	*U. S. Naval Observatory, USA*	Precise Time Transfer Project, Chair	1999-2000
Tim Springer	*University of Bern, Switzerland*	Analysis Center Coordinator	1999-2000
Robert Serafin	*Natl. Center for Atmospheric Research, USA*	Appointed (IGS)	1998-2001
Michael Watkins	*Jet Propulsion Laboratory, USA*	Low Earth Orbiter Working Group Chair	1999-2000
Pascal Willis	*Institut Geographique National, France*	International GLONASS Experiment CSTG/IGS Chair	1999-2000

FORMER IGS GOVERNING BOARD MEMBERS AND INSTITUTIONS		TOTAL SER\
Martine Feissel	*International Earth Rotation Service, France*	1994-1995
Teruyuki Kato	*ERI, University of Tokyo, Japan*	1994-1995
Gerry Mader	*Geosciences Reasearch and Development Laboratory, National Oceanic and Atmospheric Administration, USA*	1994-1997
David Pugh	*Southhampton Oceanography Center, UK*	1996-1998
Bob Schutz	*Center for Space Research, University of Texas-Austin, USA*	1994-1997

Table 1. The IGS Governing Board Members and Former Members, terms as noted. Terms begin on January 1 of the stated year and conclude on December 31 of the stated year. Terms of office are generally 4 years for the elected members, and two years for working group or project chairs.

ORGANIZATION OF THE IGS

The history and development of the IGS demonstrate the unique capability of international groups and agencies to work successfully together for a common goal. In the organization of the IGS, each component has specific responsibilities, and each is dependent on the others to meet performance standards in order for the whole system to operate smoothly and effectively.

The organization of the IGS is depicted in Figure 2. The satellites of the NAVSTAR Global Positioning System are shown in the upper left corner of the figure. The GPS stations shown below the satellites are permanently installed and operate continuously receiving and recording the L-band, dual-frequency signals transmitted by the 24 NAVSTAR GPS satellites. The station data is accessed by Operational Data Centers (see Table 2) through various communication schemes, and the Operational Centers monitor and validate the data, format it according to standards and forward the data sets to the Regional or Global Data Centers. The Regional Data Centers collect all data of interest to people in a particular region, while the IGS Global Data Centers provide primary access and archiving for IGS data and products. The Analysis Centers (Table 3) retrieve the data sets from the Global Data Centers and each produce GPS ephemerides, station coordinates, and earth rotation parameters. These products are then sent to the Analysis Center Coordinator who uses an orbit combination technique to produce the official IGS orbits. The products are sent to the Global Data Centers and the Central Bureau for archival and access by users. IGS Associate Analysis Centers are groups producing special products such as station positions and velocities, ionospheric maps, etc. (Table 4 lists the GNAACs and RNAACs). Working groups and projects (Table 5) are groups with initiative to build on the structure of the IGS for further scientific applications. The Central Bureau acts as the executive arm of the Governing Board and is responsible for the overall coordination and management of the service; the International Governing Board is the oversight body that actively makes decisions determining the activities and direction of the IGS. IGS Associate Members (Table 6) are those people who spend a significant part of the work supporting IGS processes, they are also responsible for electing specific representatives to the Governing Board.

IGS NETWORK STATIONS

The IGS network consists of GPS stations that observe the GPS satellites on a continuous, 24-hour basis. These globally distributed stations are funded, implemented and operated by one of the IGS participating agencies shown in Table 7. At the end of 1998, 167 stations were listed as part of the IGS network. These stations have precision geodetic quality dual-frequency GPS receivers and ancillary equipment that enable transmission of the data set within a one hour to a few hours. Currently, the classic data files span a 24-hour period with 30 second data samples. A subset of the IGS network is generating hourly data files at the 30-second sample rate, and a similar subset is operating at 1-second samples in support of high-rate applications such as the LEO missions.

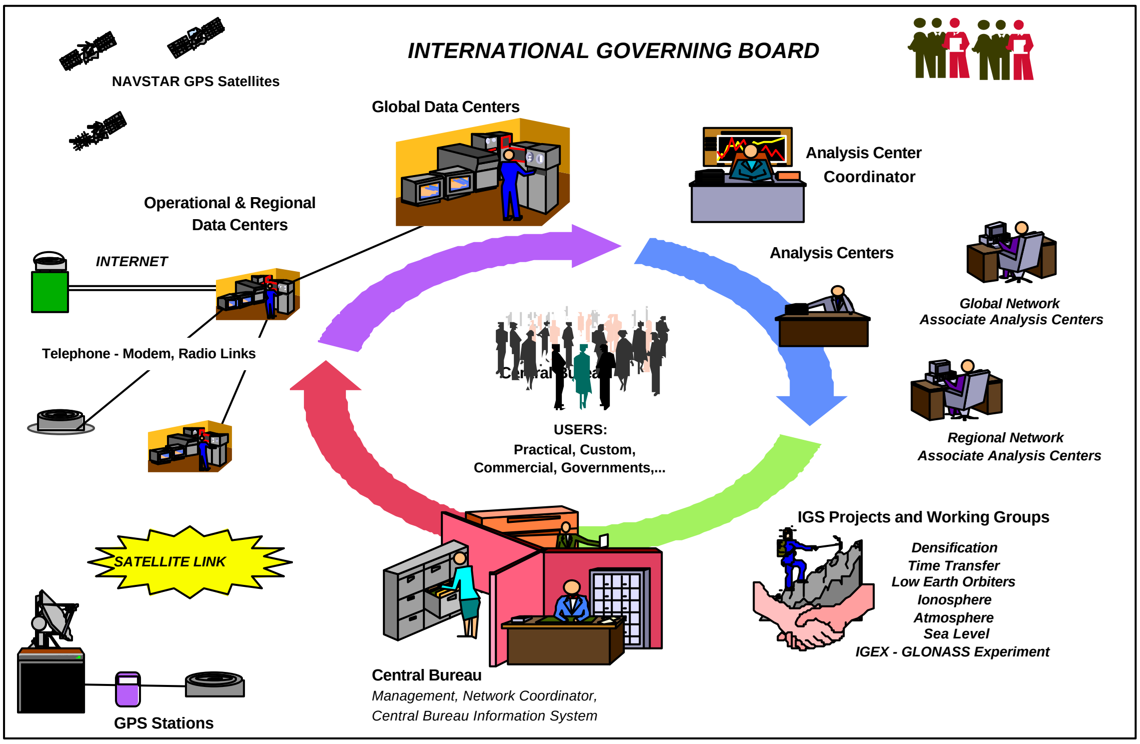


Figure 2. Schematic diagram of the organization of the IGS depicts addition of Associate Analysis Centers, Working Groups, Pilot Projects and the new Network Coordinator role within the Central Bureau.

Operational Data Centers	
ASI	Italian Space Agency
AUSLIG	Australian Surveying and Land Information Group
AWI	Alfred Wegener Institute for Polar and Marine Research, Germany
CNES	Centre National d'Etudes Spatiales, France
DUT	Delft University of Technology, The Netherlands
ESOC	European Space Agency (ESA) Space Operations Center, Germany
GFZ	GeoForschungsZentrum, Germany
GSI	Geographical Survey Institute, Japan
ISR	Institute for Space Research, Austria
JPL	Jet Propulsion Laboratory, USA
KAO	Korean Astronomical Observatory
NGI	National Geography Institute, Korea
NIMA	National Image and Mapping Agency, USA
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada
RDAAC	Russian Data Analysis and Archive Center

SIO	Scripps Institution of Oceanography, USA
UNAVCO	University NAVSTAR Consortium
USGS	United States Geological Survey
Regional Data Centers	
AUSLIG	Australian Surveying and Land Information Group
BKG	Bundesamt fuer Kartographie und Geodasie, Germany
JPL	Jet Propulsion Laboratory, USA
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada
Global Data Centers	
CDDIS	Crustal Dynamics Data Information System, NASA GSFC, USA
IGN	Institut Geographique National, France
SIO	Scripps Institution of Oceanography, USA

Table 2. Data Centers Supporting the IGS in 1999.

IGS Analysis Centers	
CODE Astronomical Institute-University of Bern	Switzerland
European Space Operations Center / European Space Agency	Germany
FLINN Analysis Center, Jet Propulsion Laboratory/Caltech,NASA	USA
GeoForschungsZentrum Potsdam	Germany
National Geodetic Survey, Geosciences Research Lab, NOAA	USA
Natural Resources Canada	Canada
Scripps Institution of Oceanography	USA

Table 3. The Seven IGS Analysis Centers.

GLOBAL NETWORK (GNAAC)	
Jet Propulsion Laboratory	USA
Massachusetts Institute of Technology	USA
University of Newcastle	UK
REGIONAL NETWORK CENTERS FOR THE DENSIFICATION OF THE TERRESTRIAL REFERENCE FRAME (RNAACS)	
Australian Survey & Land Information Group (AUSLIG)	Australia
EUREF-IAG Commission X - Global and Regional Geodetic Networks, Subcommission for Europe (European Coordinating RNAAC):	
Centers within EUREF:	
Bundesamt fur Landestopographie (L+T)	Switzerland
Center for Orbit Determination in Europe	Switzerland
Geodetic Observatory Pecny (GOP)	Czech Republic
Bundesampt für Kartographie und Geodæsie (BKG)	Germany
International Commission for Global Geodesy of the Bavarian Academy of Sciences	Germany

Nordic Geodetic Commision	Scandinavia
Nuova Telespazio S.p.A., Space Geodesy Center	Italy
Observatory Lustbuehel Graz	Austria
Royal Observatory of Belgium	Belgium
Warsaw University of Technology	Poland
Geographical Survey Institute of Japan	Japan
Geophysical Institute of the University of Alaska	USA
Onsala Space Observatory	Sweden
Pacific Geosciences Center	Canada
SIRGAS, Deutsches Geodatishes Forschungsinstitut	Germany

Table 4. IGS Associate Analysis Centers for Reference Frame Densification.

IGS Working Groups and Pilot Projects		
	Chair	*Agency & Country*
IGS Reference Frame Coordinator	Remi Ferland	NRCan, Canada
IGS/BIPM Time Transfer Project	Jim Ray, Co-Chair, IGS, Gerard Petit, Co-Chair	US Naval Observatory, USA BIPM, France
Working Group on IGS Ionosphere Products	Joachim Feltens	European Space Operations Center, Germany
IGS Combination of Tropospheric Estimates	Gerd Gendt	GeoForschungsZentrum Potsdam(GFZ)
Working Group on Low-Earth Orbiters	Michael Watkins	Jet Propulsion Laboratory (JPL)
International GLONASS Experiment (IGEX) Joint with CSTG	Pascal Willis	Institut Geographique National ENSG/LAREG
Tide Gauges, CGPS, and the IGS (Seed Activity)	Mike Bevis Phil Woodworth	University of Hawaii Permanent Service for Mean Sea Level, UK

Table 5. Working Groups and Pilot Projects established by the IGS

	ASSOCIATE MEMBERS OF THE IGS, JUNE 1999	
First	Last Name	Institution
Zuheir	Altamimi	Institut Geographique National, Paris, France
Boudewijn	Ambrosius	Delft University of Technology, Netherlands
Yoaz	Bar-Sever	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
John	Beavan	Institute of Geological and Nuclear Sciences, New Zealand
Gerhard	Beutler	Astronomical Institute, University of Bern, Switzerland
Mike	Bevis	University of Hawaii
Geoff	Blewitt	University of Newcastle upon Tyne, UK
Graeme	Blick	Land Information New Zealand
Yehuda	Bock	Scripps Institution of Oceanography, San Diego, CA, USA
Claude	Boucher	Institut Geographique National, Paris, France
Carine	Bruyninx	Royal Observatory of Belgium
Alessandro	Caporali	University of Padova, Italy

Miranda	Chin	Geosciences Research and Development Lab, National Geodetic Survey, USA
Loic	Daniel	Institut Geographique National, Paris, France
Jeff	Dean	Scripps Institution of Oceanography, San Diego, CA, USA
John	Dow	European Space Operations Center, Germany
Herb	Dragert	Pacific Geoscience Center, Geological Survey of Canada, NRCan, Canada
Herman	Drewes	Deutsches Geodäetisches Forschungsinstitut, Munich, Germany
Maurice	Dube	Goddard Space Flight Center, USA
Robert	Duval	Natural Resources of Canada, Ottawa, Canada
Bjorn	Engen	Statens Kartverk, Norwegian Mapping Authority, Honefoss, Norway
Peng	Fang	Scripps Institution of Oceanography, San Diego, CA, USA
Martine	Feissel	Paris Observatory, International Earth Rotation Service, Paris, France
Joachim	Feltens	European Space Operations Center, Germany
Meng-hua	Feng	National Bureau of Surveying and Mapping, Beijing, China
Remi	Ferland	Natural Resources of Canada, Ottawa, Canada
Luis Paulo	Fortes	Instituto Brasileiro de Geografia de Estatistica, Brazil
Roman	Galas	GeoforschungsZentrum, Potsdam, Germany
Daniel	Gambis	Paris Observatory, International Earth Rotation Service, Paris, France
Carlos	Garcia-Martinez	European Space Operations Center, Germany
Gerd	Gendt	GeoforschungsZentrum, Potsdam, Germany
Ramesh	Govind	Australian Survey and Land Information Group, Canberra, Australia
Werner	Gurtner	Astronomical Institute, University of Bern, Switzerland
Heinz	Habrich	Bundesamt fuer Kartographie und Geodaesie, Germany
Rune	Hanssen	Statens Kartverk, Norwegian Mapping Authority, Honefoss, Norway
Yuki	Hatanaka	Geographical Survey Institute, Tsukuba, Japan
Michael	Heflin	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Martin	Hendy	Australian Survey and Land Information Group, Canberra, Australia
Pierre	Heroux	Natural Resources of Canada, Ottawa, Canada
Thomas	Herring	Massachusetts Institute of Technology, Boston, MA, USA
David	Jefferson	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Jan	Johansson	Onsala Space Observatory, Sweden
Teruyuki	Kato	Earthquake Research Institute, University of Tokyo, Japan
Mark	Kaufman	Institute for Metrology of Time and Space, Mendeleevo, Russia
Jan	Kouba	Natural Resources of Canada, Ottawa, Canada
Ulf	Lindqwister	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Jingnan	Liu	Wuhan Technical University, China
Rob	Liu	Raytheon STX, Pasadena, CA, USA
Chi-cheng	Liu	Institute of Earth Science, Academy of Science, Taiwan
Gerry	Mader	Geosciences Research and Development Lab, National Geodetic Survey, USA
Bo	Madsen	NationalSurvey and Cadastre, Copenhagen, Sweden
John	Manning	Australian Survey and Land Information Group, Canberra, Australia
Tomas	Martin-Mur	European Space Operations Center, Germany
Dennis	McCarthy	U.S. Naval Observatory, Washington, D.C., USA
Chuck	Meertens	University NAVSTAR Consortium, Boulder, CO, USA
Bill	Melbourne	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Yves	Mireault	Natural Resources of Canada, Ottawa, Canada
Ivan	Mueller	Ohio State University, Columbus, Ohio USA
Angelyn	Moore	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Ruth	Neilan	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA

Carey	Noll	Goddard Space Flight Center, USA
Pil-ho	Park	Korean Astronomy Observatory, Taejon, Korea
Matti	Paunonen	Finnish Geodetic Institute,Helsinki, Finland
Peter	Pesec	Insitute for Space Research, Austrian Academy of Sciences, Graz, Austria
Hans-Peter	Plag	Statens Kartverk, Norwegian Mapping Authority, Honefoss, Norway
Jim	Ray	US Naval Observatory, Washington, D.C., USA
Svein	Rekkedal	Statens Kartverk, Norwegian Mapping Authority, Honefoss, Norway
Christoph	Reigber	GeoforschungsZentrum, Potsdam, Germany
Chris	Rocken	University NAVSTAR Consortium, Boulder, CO, USA
Markus	Rothacher	Astronomical Institute, University of Bern, Switzerland
Mark	Schenewerk	Geosciences Research and Development Lab, National Geodetic Survey, USA
Wolfgang	Schlueter	Bundesamt fuer Kartographie und Geodaesie, Germany
Mike	Schmidt	Pacific Geoscience Center, Geological Survey of Canada, NRCan, Canada
Bob	Schutz	Center for Space Reserach, Univ. of Texas-Austin, USA
Bob	Serafin	National Center for Atmospheric Research
Andrew	Sinclair	Royal Greenwich Observtory, UK
Jim	Slater	National Imagery and Mapping Agency, Washington, D.C., USA
Janusz	Sledzinski	Warsaw University of Technology, Poland
Tim	Springer	Astronomical Institute, University of Bern, Switzerland
David	Stowers	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Suryia	Tatevian	Astronomical Institute, Russian Academy of Sciences
Pierre	Tetreault	Natural Resources of Canada, Ottawa, Canada
Francesco	Vespe	Italian Space Agency, Matera, Italy
Mike	Watkins	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA
Urs	Wild	Bundesamt für Landestopographie (Federal Topography), Switzerland
Pascal	Willis	Institut Geographique National, Paris, France
Shuhua	Ye	Chinese Academy of Sciences, China
Vjacheslav	Zalutsky	East-Siberian Research Institute for Physico- and Radiotechnical Measurements, Irkutsk, Russia
Wen-yao	Zhu	Shanghai Astronomical Observatory, China
James	Zumberge	Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA

Table 6. Associate Members of the IGS dated June 1999.

	CONTRIBUTING AGENCIES OF THE IGS 1999
AIUB	Astronomical Institute, University of Bern, Switzerland
ALO	Astronomical Latitude Observatory, Poland
AWI	Alfred Wegener Institute, Germany
AUSLIG	Australian Survey and Land Information Group, Australia
BKG	Bundesamt fuer Kartographie und Geodaesie, Germany
BfL	Bundesamt für Landestopographie (Federal Topography), Switzerland
CSR	Center for Space Research, University of Texas at Austin, USA
CNES	Centre National de Etudes, Toulouse, France
CEE	Centro de Estudios Espaciales, Chile
CICESE	Centro de Investigación Científica y de Educación Superior de Ensenada, Mexico
CAS	Chinese Academy of Sciences, China
CDDIS	Crustal Dynamics Data Information System, GSFC/NASA, USA

CMMACS	CSIR Centre for Mathematical Modeling and Computer Simulation, Bangalore, India
DUT	Delft University of Technology, Netherlands
DLR/DFD	Deutsche Forschungsanstalt für Luft-und Raumfahrt e.V., Neustrelitz, Germany
ERI	Earthquake Research Institute, University of Tokyo, Japan
VS NIIFTRI	East-Siberian Research Institute for Physicotechnical and Radiotechnical Measurements, Irkutsk, Russi
ESA	European Space Agency, Germany
ESOC	European Space Operations Center, Germany
FGI	Finnish Geodetic Institute, Finland
FOMI	FOMI Satellite Geodetic Observatory, Budapest, Hungary
GOPE	Geodetic Observatory Pecny, Ondrejov, Czech Republic
GSD	Geodetic Survey Division, NRCan, Canada
GFZ	GeoForschungsZentrum, Potsdam, Germany
GSI	Geographical Survey Institute, Tsukuba, Japan
GIUA	Geophysical Institute, University of Alaska, Fairbanks, AK, USA
GRDL	Geosciences Research and Development Laboratory, NOAA, Silver Spring, MD, USA
GSFC	Goddard Space Flight Center / NASA, USA
HRAO	Hartebeesthoek Radio Astronomy Observatory, South Africa
IRIS	Incorporated Research Institutions for Seismology, USA
ICC	Institut Cartografic de Catalunya, Barcelona, Spain
IGN	Institut Geographique National, Paris, France
IMVP	Institute for Metrology of Time and Space, GP VNIIFTRI, Mendeleevo, Russia
ISAS	Institute for Space and Astronautic Science, Sagamihara, Japan
ISRO	Institute for Space Research Observatory, Graz, Austria
IAA	Institute of Applied Astronomy, St. Petersburg , Russia
INASAN	Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia
IESAS	Institute of Earth Sciences, Academia Sinica, Taiwan
IGNS	Institute of Geological and Nuclear Sciences, New Zealand
IBGE	Instituto Brasileiro de Geografia de Estatistica, Brazil
INPE	Instituto Nacional de Pesquisas Espaciais, Brazil
IDA	International Deployment of Accelerometers / IRIS, Scripps Institution of Oceanography, USA
ASI	Italian Space Agency, Matera, Italy
JPL	Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
KAO	Korean Astronomy Observatory, Taejon, Korea
KMS	Kort & Matrikelstyrelsen, National Survey and Cadastre, Denmark
LINZ	Land Information New Zealand, Wellington
MIT	Massachusetts Institute of Technology, USA
NASA	National Aeronautics and Space Administration, USA
NCAR	National Center for Atmospheric Research
NBSM	National Bureau of Surveying and Mapping, China
NGRI	National Geophysical Research Institute, Hyderabad, India
NIMA	National Imagery and Mapping Agency, USA
INGM	National Institute in Geosciences, Mining and Chemistry (INGEOMINAS), Colombia
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada, Ottawa, Canada
ROB	Observatoire Royal de Belgium, Brussels, Belgium
OUAT	Olsztyn University of Agriculture and Technology, Poland
OSO	Onsala Space Observatory, Sweden
GSC	Pacific Geoscience Center, Geological Survey of Canada, NRCan, Canada

IERS	Paris Observatory, International Earth Rotation Service, Paris, France
POL	Proudman Oceanographic Laboratory, UK
ROA	Real Instituto y Observatorio de la Armada, Spain
RGO	Royal Greenwich Observatory, UK
SIO	Scripps Institution of Oceanography, San Diego, CA, USA
SAO	Shanghai Astronomical Observatory, China
SCIGN	Southern California Integrated GPS Network, USA
SK	Statens Kartverk, Norwegian Mapping Authority, Norway
SOEST	School of Ocean and Earth Science and Technology, University of Hawaii,USA
UCAR	University Consortium for Atmospheric Research
USNO	U.S. Naval Observatory, USA
UFPR	University Federal de Parana, Brazil
UNAVCO	University Navstar Consortium, Boulder, CO, USA
UB	University of Bonn, Germany
CU	University of Colorado at Boulder, Boulder, CO, USA
NCL	University of Newcastle on Tyne, United Kingdom
UPAD	University of Padova, Italy
WUT	Warsaw University of Technology, Poland
WING	Western Pacific Integrated Network of GPS, Japan
WTU	Wuhan Technical University, China

Table 7. Contributing Agencies of the International GPS Service 1999

IGS PUBLICATIONS

Available through the Central Bureau (address below).

1998 IGS Annual Report
IGS Central Bureau
IGS Workshop Proceedings: 1998 IGS Network Systems Workshop
November 2-5, 1998, Annapolis, Maryland USA
C. Noll (GSFC), K. Gowey, and R. E. Neilan, eds.
1997 IGS Annual Report
IGS Central Bureau
1997 Technical Reports
I. Mueller, R. Neilan, K. Gowey, eds.
International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences
G. Beutler, M. Rothacher, T. Springer, J. Kouba, R.E. Neilan
32nd COSPAR Scientic Assembly, Nagoya, Japan, July 12 to 19, 1998.
IGS Workshop Proceedings: 1998 Analysis Center Workshop
February 9-11, 1998, ESA/ESOC Darmstadt, Germany
J. M. Dow (ESA), J. Kouba (NRCan), T. Springer (AIUB), eds.
IGS Workshop Proceedings: Workshop on Methods for Monitoring Sea Level
R. E. Neilan, P.A. Van Scoy, P. L.Woodworth, eds.
Pasadena, CA: Jet Propulsion Laboratory, 1997.
1996 IGS Annual Report
J. F. Zumberge, D. E. Fulton, and R. E. Neilan, eds.

IGS Workshop Proceedings: 1996 IGS Analysis Center Workshop
19-21 March 1996, Silver Spring, Maryland, USA
R. E. Neilan, P. Van Scoy, and J. F. Zumberge, eds

1995 IGS Annual Report
J. F. Zumberge, M. P. Urban, R. Liu, and R. E. Neilan, eds.

IGS Workshop Proceedings: Special Topics and New Directions
15-18 May 1995, GeoForschungsZentrum, Potsdam, Germany
G. Gendt and G. Dick, eds.

1994 IGS Annual Report
J. F. Zumberge, R. Liu, and R. E. Neilan, eds.

IGS Workshop Proceedings: Densification of the IERS Terrestrial Reference Frame through Regional GPS Networks
30 November-2 December 1994, Jet Propulsion Laboratory, Pasadena, California, USA,
J. F. Zumberge and R. Liu, eds.

IGS Workshop Proceedings: 1993 IGS Analysis Center Workshop
12-14 October 1993, Geodetic Survey Division, Natural Resources Canada, Ottawa, Canada
J. Kouba, ed.

IGS Workshop Proceedings: 1993 IGS Workshop
25-26 March 1993, Astronomical Institute, University of Bern, Switzerland
G. Beutler and E. Brockmann, eds.

The publications listed above along with brochures, resource information package, and the IGS Directory (printed annually), are available upon request. Send your request and mailing address to:

Carol Lorre
IGS Central Bureau
Jet Propulsion Laboratory, M/S 238-540
4800 Oak Grove Drive, Pasadena, CA 91109 USA
Phone: 818-354-2077
FAX: 818-393-6686
Email: carol.a.lorre@jpl.nasa.gov

These documents are also available at the IGS website (http://igscb.jpl.nasa.gov/overview/pubs.html)

ACKNOWLEDGMENTS

The Central Bureau would like to thank G. Beutler and J. Kouba for their significant contribution to the IGS and their leadership in the past five years. Their influence will continue to be felt. We also acknowledge the contributions of the participating agencies worldwide which have made the IGS such a successful organization. Part of the work described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology and sponsored by the National Aeronautics and Space Administration.

REPORT OF INTERNATIONAL ASSOCIATION OF GEODESY SECTION III

DETERMINATION OF THE GRAVITY FIELD

for the period 1995-99

OVERVIEW REPORT OF IAG SECTION III - "DETERMINATION OF THE GRAVITY FIELD"

Section President Rene Forsberg

1. Preface and highlights

According to the by-laws of IAG, Section III is responsible for the determination and modelling of earths's gravity field variations. This activity includes absolute and relative gravity measurements, gravity networks and control stations, non-tidal gravity variations, determination of the geoid and external gravity field from the multitude of gravity field data available (satellite measurements, gravimetry, deflections of the vertical, gradiometry, GPS-levelling etc.), and the reduction and estimation of gravity field quantities. It is a special challenge for Section III to encourage international cooperation in the area of gravity field mapping, and work towards the ultimate goal of physical geodesy: to have a complete coverage of reliable gravity field data over the entire earth.

The period 1995-99 has seen a healthy development in geodetic gravity field science. In the period the new joint NASA-OSU-NIMA spherical harmonic reference model EGM96 has been released, with testing carried out by an international evaluation panel as a special working group (headed by M. G. Sideris) of IGeC. The new model has included significant new terrestrial data sets, improved satellite altimetry and -tracking, and ensures good fits to satellite orbits, and will be a good base for numerous activities, especially the need for good geoid models. Similar models have since been developed by other researchers in both Europe and Russia (GAO-98).

It is a very important step forward that new gravity field satellite missions have finally been approved, and will make even better long-wavelength earth models in the future. The German CHAMPS satellite is planned for launch in 1999, the NASA GRACE mission in 2002, and (probably) the ESA GOCE mission in 2004. In the future it will be a challenge for Section III to utilize these satellite data along with other gravity field information and digital terrain models to obtain the best possible gravity field and geoid models, and linking the vertical datums on the continents to a uniform world height datum.

Other major developments have been the computations of large-scale geoid models for many major continental regions (e.g., Europe, US, Canada, Australia ..) by FFT methods, and in some countries the subsequnt GPS/levelling fitting, allows height determination down to 1 cm in some countries. The old dream of a 1 cm geoid is thus a reality .. at least relatively, and in areas with good gravity coverage, good vertical control and not too excessive topography.

On the data collection sides developments in absolute gravimetry continues to push routine gravity measurement accuracy (to the micro-gal level), allowing geodynamic gravity applications (e.g., monitoring of land uplift and mass changes, by co-location with geodynamic GPS measurements). Airborne gravimetry has matured in the period, and is now a routine tool for geodetic data collection, with major programs in the period taking place over the Arctic regions. Research into the use of airborne gravity for geoid determination has flourished, as has the push towards new sensor systems (INS units and gradiometry).

On the theoretical side topics such as wavelets, optimized kernels, faster collocation, improved BVP solutions continue to give new insight into improved gravity field modelling. For geoid determination IGeS geoid schools have widened international IAG cooperation in gravity field modelling. During the period IGeS geoid schools were held in Rio de Janeiro (1997) and in Milano (1999), attracting a large percentage of students from countries which are rarely active otherwise in IAG activities.

The availability of digital terrain models (land elevations, bathymetry etc.), import auxillary data for local gravity field modelling, have been improved in the period. Many countries have released dense DEM data for geodetic scientific use, and several projects have been underway to compile global DEM's at the 1 km level. Developments in Synthetic Aperture Radar projects (notably the planned NASA/NIMA Shuttle SAR topography mission), and new laser altimetry satellite missions, and regional compilations of ERS SAR data, promises to generate very dense DEM data in the coming years. It is antipated that much of this data will be publically available. It will be a challenge for Section III to coordinate these data in a suitable (thinned) format, to make data accessible with a limited work effort for global or regional gravity field approximation.

2. Section III organisation and meetings 1995-99

IAG Section III is divided into two Commissions (International Gravity Commission, IGC, and the International Geoid Commission, IGeC), which again has topical working groups (IGC) or regional working groups (IGeC). A number of Special Study Groups (SSG's) have been established in order to coordinate research in well-defined topical areas. Whereas Commissions are longer term structures, SSG's are concentrating on time-limited activities, typically over a 4-year period between IUGG general assemblys.

The Section III steering committee consists of the Section President (Rene Forsberg), Section Secretary (Michael G. Sideris, Canada), the presidents of the Commissions (I. Marson and H. Sunkel), and the SSG presidents (see below). The Steering Committee has mainly been communicating by E-mail, with more formal meetings in Rio (1997) and Trieste (1998).

A main task of Section III has been the preparation of the IAG scientific meetings in Rio de Janeiro, 1997 (proceedings "Geodesy on the Move - Gravity, Geoid, Geodynamics and Antarctica" published in the Springer Verlag IAG Series), and the IUGG symposium G3 in Birmingham, 1999.

Special workshops, sponsored by Section III, include the Intercomparison of Absolute Gravimetres (Sevres, 1997) and the "Airborne Gravity and the Polar Gravity Field" workshop held in Kangerlussuaq, Greenland, 1998. Relevant other activities include the IGeS geoid schools (Rio, 1997; Milano, 1999) and the Summer School of Theoretical Geodesy (Como, 1996) which to a large degree covered Section III-relevant science. Regional geoid workshops include a.o. the "Second Continental Workshop on the Geoid in Europe" (Budapest, 1998), geoid sessions at annual EGS and AGU meetings, and the yearly Canadian Geoid Workshops (Ottawa, 1997-99).

Commission reports, and the reports of the affiliated services (Bureau Gravimetrique, BGI; and International Geoid Service, IGeS) follows in the sequel.

The Commissions of Section III - IGeC and IGC - will in 1999 be joined into one commission: "International Gravity and Geoid Commission - IGGC", as decided by the IAG Executive Committee. The merger of IGC and IGeC are natural, since there is quite a large number of common scientists in the two Commissions, and topics are strongly interrelated. IGC and IGeC has held joint General Assemblys since 1994, during the present period in Tokyo 1996 ("Gravity, geoid and Marine Geodesy" (GRAGEOMAR) - Proceedings published in Springer Verlag IAG series), and in Trieste 1998 (IGC/IGeC General Assembly, proceedings in prep.). Both these meetings has attracted several hundred participants from around the world.

The Study Groups of Section III has all been working more or less succesfully, and generated new research, as evident from the chairman reports in the following. The following study groups were formed in 1995:

- SSG 3.163: Assessment and refinement of DTM's (chairman D. Arabelos, Greece)
- SSG 3.164: Airborne gravimetry instrumentation and methods (M. Wei, Canada)

- SSG 3.165: Global gravity field determination and evaluation (N. Pavlis, USA)
- SSG 3.166: Local gravity field modelling and interpretation) (T. Basic, Croatia)
- SSG 3.167: Regional land and marine gravity field modelling (H.van Gysen, South Africa)

The SSG 3.167 was taken over by I. Tziavos, Greece, after the death of Herman van Gysen, who was taken away by serious disease at a far too young age.

The SSG 3.166 was discontinued due to lack of activity by the IAG executive in 1997, and replaced by a new SSG:

- SSG 3.177: Synthetic modelling of earth's gravity field (W. Featherstone, Australia)

Finally in late 1998 a new SSG was formed and approved, to accomodate new gravity cooperation project in the Arctic region:

- SSG 3.178: Arctic Gravity Project (R. Forsberg, Denmark)

The reports of the SSG's follow in the sequel.

3. Acknowledgements

As departing Section President I wish to express my thanks for a good and constructive cooperation to the steering committe members (Secretary, Section and SSG presidents). It has been a pleasure to work with you! I also wish good success for the coming 4 years for the new Section III leadership (nominated for election: President M. G. Sideris, Canada; Secretary G. Boedecker, Germany; IGGC President: M. Vermeer, Finland). Cheers for a healthy and developing gravity field science!

INTERNATIONAL GRAVITY COMMISSION
ACTIVITY REPORT 1995-1999

Iginio Marson, president of IGC (marson@univ.trieste.it)

The International Gravity Commission (IGC) has fulfilled the duties through the actions of the members in the framework of the overall Commission activities and through the action of four Working Groups: WG-2 World Gravity Standards, WG-6 Intercomparison of Absolute Gravimeters, WG-7 Monitoring of Non Tidal Gravity Variations, WG-8 Relative Gravity network for 1997 Absolute Gravimeter Intercomparison.

According to the bylaws, the IGC has organised the General Assembly as a joint meeting with the International Geoid Commission. 113 participants have attended the meeting, which was held in Trieste from September 5 to September 12, 1998 and has strengthened the relationships between the two Commissions of Section III. To enlarge the attendance to the meetings of the two commissions, a midterm meeting has been co-sponsored as well. The meeting (Gravity, Geoid and Marine Geodesy) was held in Tokyo from September 30 to October 5 1996 and has been attended by about 200 participants from 27 countries. The idea to organise midterms meeting in different continents has proved to be positive since it allows a wider participation of scientists and will be continued also for the future. A second midterm meeting of the two commissions has been in fact already announced for the year 2000 in Canada.

Relevant progress has been made also in two regional gravity initiatives. The IGC has given the scientific support to the realisation of an international project aimed at the establishment of absolute gravity sites in many countries of Central Europe (Czech republic, Croatia, Estonia, Hungary, Latvia, Lettonia, Poland and Slovenia). Secondly, continuing the activities in training young scientists from Africa initiated several years ago, the IGC has supported a training course in gravimetry, held in Cairo (Egypt), which was well attended by scientists from Arab and African countries. Previous courses have been held in the Ivory Coast and Nigeria.

National representatives of member countries have reported ongoing activities. To summarise, the focus of the researches is on absolute gravimetry (establishment of reference sites) on absolute and superconducting gravimetry (to study time-dependent gravity variations induced by sea level variations, seismic and volcanic activities, ground level variations, post glacial rebound) and on national networks. A vast variety of regional gravity surveys has been reported as well.

The activities of WG-2 World Gravity Standards (Chairman G. Boedecker) have been particularly devoted to the establishment of an International Absolute Gravity Basestation network (IAGBN). The Network includes two subsets: IAGBN-A was intended as a closed set of stations for which 36 sites had been selected to support both the needs of reference sites and studies on global changes. For these reasons many of them were proposed for collocation at space geodetic sites. In the IAGBN catalogue 20 IAGBN-A stations have been already included. The remaining sites are situated in Siberia, Africa and on remote islands. Activities to promote the establishment of these sites are in progress. IAGBN-B has been created as an open collection of stations where absolute gravity has been observed that are not merely experimental observations but warrant a good standard. WG-2 has been also active in the field of national gravity base networks with assistance in the establishment of the national nets of Iran, Ghana and Egypt. WG-2 has also launched a “call for interest” for the adjustment of a Unified European Gravity Network, which is aimed at the unification of the national networks of European countries.

WG-6 Intercomparison of Absolute Gravimeters (L. Robertsson) has held the fifth international intercomparison in Sevres in autumn 1997. Fifteen absolute gravimeters participated. As the accuracy of absolute gravimeters is now starting to exceed the precision of relative gravimeters, the comparison was made by both a relative network and by having each absolute meter measure at multiple locations. A relevant contribution to the success of the intercomparison campaign has been given by the activity of WG-8 Relative Gravity network for 1997 Absolute Gravimeter Intercomparison (Chairman M. Becker). Twenty-five participants using twelve relative gravimeters made transfer and gradient measurements. A calibration line and the BKG moving platform were also used. The final results of both absolute and relative intercomparison have shown that absolute gravimetry is able to determine the gravity acceleration with an accuracy of 3.3 μgal.

WG-7 Monitoring of Non-Tidal Gravity Variations (Chairman B. Richter) has presented a project entitled “a gravity network for ground truth for satellite missions”. The project targets Europe with an action plan for the next two years to a) improve the network of superconducting gravimeters in Europe; b) recompute the existing data sets in a uniform manner; c) collect and analyse data sets from European Stations.

INTERNATIONAL GEOID COMMISSION

Activity Report 1995 - 1999

prepared by

H. Sünkel

Preface

The International Geoid Commission (IGeC) was formed by the International Association of Geodesy (IAG) at the XIXth General Assembly of the International Union of Geodesy and Geophysics in Vancouver, 1987. It operates as Commission XII of Section III of IAG. The presidents and secretaries of IGeC since 1987 were

Period	*President*	*Secretary*	*Secretary*
1987 - 1991	R.H. Rapp	A.H.W. Kearsley	C.C. Tscherning
1991 - 1995	H. Sünkel	A.H.W. Kearsley	C.C. Tscherning
1995 - 1999	H. Sünkel	A.H.W. Kearsley	D.G. Milbert

An Executive Committee was established to support the Commission in forming directions. For the time being 44 countries are represented in IGeC.

In the sequel the main activities of the Geoid Commission in general and of geoid related activities in particular are reported.

1. The International Geoid Service (IGeS)

The International Geoid Service (IGeS) was established at the Politecnico di Milano and became operative on September 1, 1992. IGeS is supported by the Consiglio Nazionale delle Ricerche of Italy, the Dipartimento del Territorio, the Istituto Geografico Militare Italiano, the Istituto Nazionale di Geofisica of Italy, the Telespazio S.p.A., and by Politecnico di Milano. IGeS is presided by F. Sansò and has four staff members.

IGeS has been designed as the working arm of IGeC. In particular, IGeS works as a nonprofit organization for the benefit of the international geoscientific community. Its main duties and goals are as follows:

- Collection of data related to geoid determinations that are not already systematically collected by other agencies or services, making sure that all data sets provided to IGeS are properly documented.

- Collection of available software for geoid determinations, giving room to the wide pluralism of methodologies, and verifying that the software is properly documented and complete with test examples.

- Collection and testing of global geopotential models and the corresponding software to produce various functionals of the geopotential at prescribed locations.

- Collection and documentation of preprocessing software, including the first statistical tests on data, rejection of outliers, and data gridding.

- Computation of geoids in exceptional cases, as defined by the Executive Committee (EC) of the IGeC, in support of national and scientific objectives.

- Pursuing both theoretical and practical work towards the merging of regional geoids into larger solutions.

- Dissemination of available geoid-related documented data sets and software upon request.

- Organization of courses on special demand for users who would like to acquire the necessary knowledge to perform geoid computations on their own.

- Participation in outstanding international research projects related to geoid determination such as ESA's gravity gradiometry mission GOCE.

- Establishment of a close cooperation with the Bureau Gravimetrique International (BGI), starting with a pilot project aiming at the collection and homogeneization of digital elevation models for Europe for the purpose of geoscientific applications.

- Preparation and distribution of a bi-annual bulletin describing the current activities and the information available at IGeS.

- Pursuing any other task that the EC of the IGeC would assign to it.

Since its foundation IGeS has issued 9 IGeS Bulletins.

2. Foundation of Sub-Commissions

During the reporting period the following sub-commissions of IGeC were formed:

Year	*Region*
1995	South-East Asia
1996	South America
1997	North America

3. **Scientific Meetings and Schools**

During the reporting period 1995 - 1999 the following scientific meetings and schools related to geoid determination were organized:

- International Summer School of Theoretical Geodesy, Como, May 27 - June 7, 1996
- International Symposium on Gravity, Geoid, and Marine Geodesy, Tokyo, September 30 - October 5, 1996
- Second International School for the Determination and Use of the Geoid, Rio de Janeiro, September 10 - 16, 1997
- Second Continental Workshop on the Geoid in Europe, Budapest, March 10 - 14, 1998
- Second Canadian Geoid Workshop, Ottawa, May 14 - 15, 1998
- Second Joint Meeting of the International Gravity Commission and the International Geoid Commission, Trieste, September 7 - 12, 1998
- Third International School on the Determination and Use of the Geoid, Milan, February 15 - 19, 1999

3. National geoid activities

Apart from the mammoth task of the development of the Earth Gravity Field Model EGM96 by NASA, NIMA, and OSU and the geoid determination for Europe, which was pursued by the Hannover group with W. Torge and H. Denker, a huge number of geoid related activities went on worldwide.

From available progress reports and the submitted national reports the following information can be extracted:

- The strongly growing GPS application community has a strong demand for an accurate and detailed geoid. Many countries have responded to this demand by providing a national geoid with a resolution of the order of a few kilometers.

- Local and regional geoid determination has become feasible in numerous well observed areas with a relative accuracy of fractions of 10^{-6} with a resolution of a few kilometers half wavelength.

- Geoid heights derived by GPS + orthometric heights are used extensively both to control national geoid solutions and to get hold on long wavelength errors which are mainly due to the shortcoming of the used global models.

- GPS/levelling derived geoid heights are furthermore used as geoid observations for geoid determination purposes.

- Altimeter derived sea surface heights combined with gravity data are used both for geoid determination in maritime countries and to separate the geoid from the sea surface topography.

- Very high resolution digital terrain models (100 m or less) are becoming available in various countries, and are being used extensively for data reduction purposes.

- The remove-restore technique (in various modifications) has become a standard procedure in context with gravity field determination in general and geoid determination in particular.

- Spectral domain techniques such as FFT, the Hartley transform and the 1-D FFT technique proved to be extremely powerful and have become widely used by the international geodetic community for geoid determination purposes in many countries.

- The EGM96 solution has proved to be a very significant leap forward in gravity field research and is being used by many organizations very successfully in context with geoid determination.

- The geoscientific community is anxiously waiting for the realization of the three dedicated gravity field missions CHAMP (2000), GRACE (2001), and GOCE (2004). A successful completion of the missions presumed, the static gravity field, represented by the geoid, will become available with a resolution of the order of 80 km half wavelength and an accuracy of the order of 1 - 2 cm on a global scale. In addition, the temporal variations of the gravity field in the low to medium frequency range will be detected. These missions represent a quantum leap in gravity field research and will have an enormous impact on geoscientific research in general and on geodesy, oceanography, and solid Earth physics in particular.

Graz, July 1999

H. Sünkel

THE BUREAU GRAVIMETRIQUE INTERNATIONAL 1995-1999

Director of BGI - G. Balmino (balmino.uggi@cnes.fr)
(edited by R. Forsberg)

1. INTRODUCTION

In geodesy, gravity values play a great part in the modelling of the Earth gravity field, which is of permanent use for computation of precise satellite orbits. It is also an essential information for the determination of the geoid, and for the study of the global ocean circulation. In geophysics, the interpreation of the gravity field anomalies allows to study density variations in the lithosphere or mantle, with applications in oil and mineral prospecting.

The Bureau Gravimetrique International (BGI) is one of the offices of the Federation of Astronomical and Geophysical data analysis Services (FAGS), which operates under the auspices of the International Council of Scientific Unions (ICSU) and UNESCO. It may also be considered as an executive arm of the International Gravity Commission (IGC).

The idea of a service for gravity data and related matters originated during the 1951 IUGG General Assembly in Brussels, and BGI was created in 1953. Its offices have been located in France since the beginning, when pioneering works were being done by its first directors: Reverend Father Lejay from the Society of Jesus, and then Professor Levallois. The central office has been in Toulouse since 1980, in the premises of the Observatoire Midi-Pyrenees, with other French supporting organizations being Centre National d'Etudes Spatiales (CNES), the Institut Geographique National (IGN), the Centre National de la Recherche Scientifique (CNRS), and the Bureau de Recherches Geologiques et Minieres (BRGM).

The address of the office is : Bureau Gravimetrique International 18, Avenue Edouard Belin 31401 Toulouse Cedex 4, France Phone : (33) [0]5 61 33 29 80 Fax : (33) [0]5 61 25 30 98, web page http://bgi.cnes.fr:8110/.

2. OBJECTIVES AND TERMS OF REFERENCE

The main task of BGI is to collect, on a worldwide basis, all existing gravity measurements and pertinent information about the gravity field of the Earth, to compile them and store them in a computerized data base in order to redistribute them on request to a large variety of users for scientific purposes. The data consist of : gravimeter observations (mainly location - three coordinates, gravity value, corrections, anomalies ...), mean or point free air gravity values, gravity maps, reference station descriptions, publications dealing with the Earth's gravity. BGI also has at its disposal through one of this host agencies : grids of satellite altimetry derived geoid heights, presently from the Geosat, Topex-Poseidon, ERS1 and ERS2 missions ; spherical harmonic coefficients of current global geopotential models ; mean topographic heights. These data are sometimes used internally for data validation and geophysical analysis. BGI has been developing various algorithms and software for data validation and analysis, as well as its own data management system based on ORACLE 7. A variety of services are offered to the users (see below). All kinds of gravity data can be sent to BGI, with or without restrictions of redistribution to be specified by the contributors, sometimes in the form of a protocol of usage.

3. BGI ORGANISATIONAL MATTERS

The BGI operations were reviewed in 1998, and the IAG has after an international call for proposals approved the offer of the French National Committee to continue to host BGI. The new director of BGI from 1999 (after formal confirmation at the IUGG General Assembly) will be Dr. Jean-Pierre Barriot (from the Space Center and GRGS group in Toulouse). G. Balmino retires after twenty years of service to the BGI (/thanks, George/).

The BGI Directing Board did in the period 1995-99 consist of the following voting members:

I. Marson	*Italy*	*IGC President*	*Voting Member*
G. Boedecker	*Germany*	*IGC Vice-President and WG chairman*	*Voting Member*
J. Makinen	*Finland*	*IGC Vice-President*	*Voting Member*
G. Balmino	*France*	*BGI Director*	*Voting Member*
R. Forsberg	*Denmark*	*IAG Section III President*	*Voting Member*
J.E. Faller	*USA*	*elected*	*Voting Member*
E. Groten	*Germany*	*elected*	*Voting Member*
P.P. Medvedev	*Russia*	*elected*	*Voting Member*
S. Takemoto	*Japan*	*elected*	*Voting Member*
L. Robertsson	*France*	*Chairman of WG6 of IGC*	*Non-voting Member*
B. Richter	*Germany*	*Chairman of WG7 of IGC*	*Non-voting Member*
M. Becker	*Germany*	*Chairman of WG8 of IGC*	*Non-voting Member*
N. Courtier	*Canada*	*Secretary*	*Non-voting Member*
E. Klingele	*Switzerland*	*Secretary*	*Non-voting Member*
H. Sunkel	*Austria*	*President, Int. Geoid Commission*	*Ex-officio Member*
F. Sanso	*Italy*	*Director, International Geoid Service*	*Ex-officio Member*
P. Paquet	*Belgium*	*FAGS Representative*	*Ex-officio Member*

The BGI Directing Board has met on an annual basis.

BGI staff , as of early 1999, consists of:
G. Balmino - Director (part time, to be replaced by J.P. Barriot)
N. Lestieu - Secretary, CNRS (part time)
G. Balma - Technician, IGN
M. Sarrailh - Engineer, CNES
D. Toustou - Analyst & Surveyor, IGN

BGI has been helped for a long time by Working Groups (WG) of the International Gravity Commission, which provided guidance, methologies, and sometimes software to accomplish some of the Bureau activities. Most of these WGs, having terminated their role, were closed. New ones emerged which goals are more in line with modern scientific objectives of IGC, with which BGI continues to link in the framework of its mandate. The IGC Working Groups are to-day : WG2 : World Gravity Standards (Chairman : G. Boedecker) WG6 : Intercomparison of Absolute Gravimeters (Chairman : L. Robertsson) WG7 : Global Gravity Monitoring Network (Chairman : B. Richter) WG8 : Relative Gravity Network for 1997 Absolute Gravimeter Intercomparison (Chairman : M. Becker)

4. THE BGI BULLETIN D'INFORMATION

The office issues a Bulletin d'Information twice a year (generally in June and December). It contains : - general information in the field, about the Bureau itself, about new available data sets, contributing papers in gravimetry, - communications at meetings dealing with gravimetry (e.g. IGC meeting). Every four years, an issue (which may be an additional one) contains the National Reports of Activities in Gravimetry. The catalogue of the holdings is issued approximately every two years. The Bulletin is sent free of charge to individuals, institutions which currently provide information, data to the Bureau. In other cases, information and subscription prices can be obtained on request. There exists 84 issues and approx. 350 subscribers as of July 1999.

5. PROVIDING DATA TO BGI

Essential quantities and information for gravity data submission are :
(a) Position of the site : - latitude, longitude (to the best possible accuracy), elevation or depth (for land data : elevation of the site on the physical surface of the Earth) ; for water stations : water depth).
(b) Measured (observed) gravity, corrected to eliminate the periodic gravitational effects of the Sun and the Moon, and the instrumental drift.
(c) Reference (base) station(s) used. For each reference station (a site occupied in the survey where a previously determined gravity value is available and used to help establish datum and scale for the survey), give name, reference station number (if known), brief description of location of site, and the reference gravity value used for that station. Give the datum of the reference value ; example : IGSN71.
Give supplementary elevation data for measurements made on towers, on upper floor of buildings, inside of mines or tunnels, atop glacial ice. When applicable, specify whether gravity value applied to actual measurement site or it has been reduced to the Earth's physical surface (surface topography or water surface). Also give depth of actual measurement site below the water surface for underwater measurements. For marine gravity stations, gravity value should be corrected to eliminate effects of ship motion, or this effect should be provided and clearly explained. Additional information are optional, but welcome.

The BGI holdings now total 12,702,874 point measurements, consisting of 10,534,635 marine measurements (validated by internal consistency tests in each cruise) and 2,168,239 land measurements (validated source by source, by means of collocation).

6. BGI SERVICES

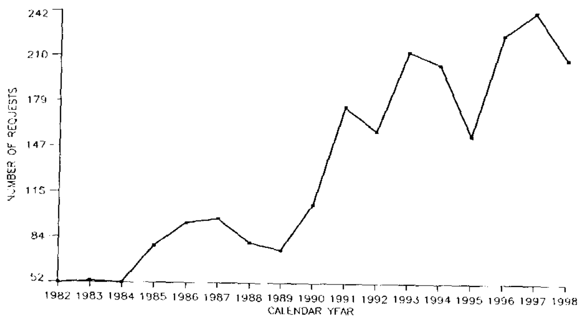
The most frequent service BGI can provide is data retrieval over a limited area. Data are sent on tapes or diskettes or printouts. Data coverage plots may also be provided, usually over 20° x 20° areas. Since the end of 1995, BGI has been providing non confidential land and marine point gravity measurements on CD-ROMs, together with retrieval software for UNIX systems . The records information are limited to the most essential quantities (location, g-value, measurement type, free-air and Bouguer anomalies, terrain correction when available, epoch of observation). Other services include : data screening, provision of gravity base station information, data evaluation and gridding, computation of mean values, contouring, supply of, or information on existing maps (catalogue available). The costs of the services have been established in view of the categories of users-mostly contributors of measurements and scientists, and also considering the large amount of our host organizations. The charging policy is explained in detail in the Bulletin d'Information. Some of the services may be provided free of charge upon request, to data contributors, individuals working in universities, such as students, and generally to any person who can contribute to our activities on a data or documentation exchange basis.

7. BGI DATA ACTIVITIES AND DATA VALIDATION EFFORTS

A great deal of effort have been directed at validating data for several years. BGI software was converted to JAVA in 1997 to allow future portability and easier upgrading. Data validation software upgrades have been continuing in the period 1995-99 with the interactive SEAVALID software.

BGI has continued to distribute data on CD-ROM, and a new JAVA version has been made, making the CD-ROM product more portable.

The number of data requests has continued to rise through the period, see the attached graph.



BGI data requests 1982-1998.

A number of data sets have been contributed to BGI in the period 1995-99, including new airborne data (Switzerland, Greenland mean values) and surface data (Taiwan, Nepal, Indian Ocean Islands, Indonesia a.o.).

BGI has recently computed a new marine gravity field from satellite altimetry from raw 20 Hz measurements, including ice-covered polar areas.

BGI has assisted in various geoid determination activities (Madagascar, Morocco, Jordan, France...)

BGI has participated in regional gravity projects such as the African Gravity Project (AGP), South American Gravity Project (SAGP), and European/Asian projects (SEAGP, WEEGP). BGI has copies of these classified data sets, and has participated in data validation etc.

The BGI various data activities has been reported extensively in the BGI Bulletin d'Information.

8. PROGRAM OF ACTIVITIES FOR THE NEXT FOUR YEARS

- Continue publication of the Bulletin d'Information.
- Continue data collection, archiving and distribution : emphasis will be on those countries which have not, or seldom, contributed to the BGI data bank. First priority is given to careful data evaluation. Marine data validation, after some experiments were conducted with methods using cross-over difference minimization (over different legs and cruises), is to be based on the gravity field derived from satellite altimetry data.
- Assist IGGC (new International Gravity and Geoid Commission) in setting up the International Absolute Gravity Base Station Network (IAGBN), and assist in the intercomparisons of instruments.
- Establish simple procedures for the collection and archiving of absolute measurements, in the continuation of the work of former Working Group 2 of IGC.
- Link with the IGGC in data preparation in view of geoid computations and evaluations to be performed by the International Geoid Service (IGeS).
- Assist in promoting satellites techniques to improve our global knowledge of the Earth's gravity field : satellite-to-satellite tracking, satellite gradiometry, etc ...

A FEW SELECTED REFERENCES (1995-99)

Adjaout, A., Sarrailh, M, 1997: A new gravity map, a new marine geoid around Japan and the detection of the Kuroshio current. Journal of Geodesy, 71, pp. 725-735.

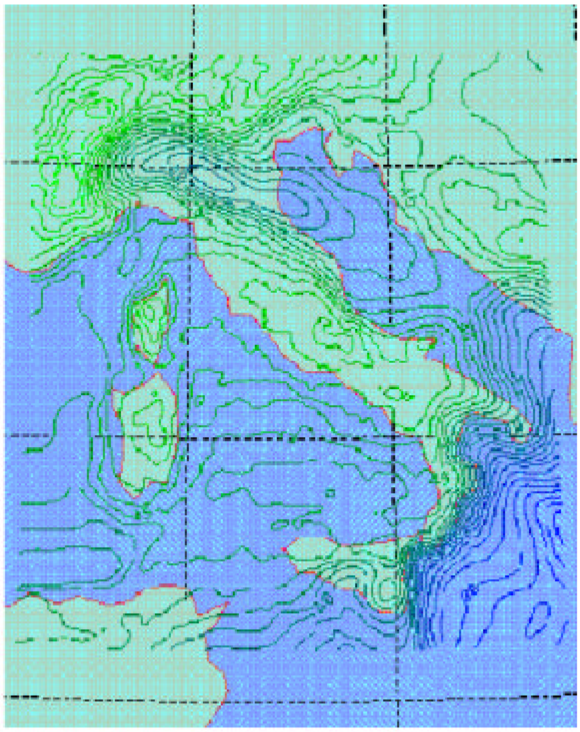
Balmino, G., Chen, J. Y. and N. Vales, 1996: Main 1^o x 1^o values of potential functionals over China. BGI Bulletin d'Information no. 79.

Olgiati, A., G. Balmino, M. Sarrailh, C. Green, 1995: Gravity anomalies from satellite altimetry. Bulletin Geodesique 69, pp. 252-260.

Sarrailh, M., G. Balmino, D. Doublet, 1997: The Arctic and Antarctic oceans gravity field from ERS-1 altimetric data. Proc. “Gravity, Geoid and Marine Geodesy”, Segawa et al. (eds.), IAG Symposium Series 117, Springer Verlag, pp. 437-444.

INTERNATIONAL GEOID SERVICE REPORT (1995 – 1999)

DIIAR - Politecnico di Milano, Prof. Riccardo Barzaghi



The aim of IGeS is to promote researches and teaching on geoid theory and estimation. This is pursued by organizing geoid schools, by issuing a Bulletin, by collecting and distributing geoid estimates, by managing and participating to projects on geoid computation.

The IGeS structure is based on a multilateral agreement which includes the Politecnico di Milano, the Istituto Geografico Militare, the Consiglio Nazionale delle Ricerche (Italian National Research Council), the Istituto Nazionale di Geofisica and Telespazio.

In the near future, this general agreement will be extended to the Dipartimento del Territorio (Italian National Cadastre) which has already expressed its wish to enter in the IgeS structure.

This general agreement has been then substanced by bilateral agreements, which account for the financial support, with the above mentioned structures.

As for the teaching activity, three schools have been organized and one will be held within February 2000. The aim of these schools is to give an introductory overview on the main theoretical items related to geoid estimation and to supply software for geoid computation.

The first school was held in Milano (Italy) in 1994, while the second one was organized in Rio de Janeiro (Brazil) in September 1997, during the International IAG meeting.

Thirty-one students attended the school coming from USA, Brazil, Colombia, Uruguay, Venezuela, Argentina, Ecuador, Trinidad, Norway, Denmark, Spain, Saudi Arabia and New Zealand. The topics of the school were on: “Fundamentals of geoid computation”, by F. Sansò; “Geopotential models”, by N. Pavlis; “Collocation”, by C.C. Tscherning; “Terrain effects on geoid”, by R. Forsberg; ; “FFT computation”, by M Sideris. The third school was again held in Milano in February 1999: twenty-three students participated to it, coming from Algeria, Bulgaria, Denmark, Egypt, Germany, Ghana, Hungary, Italy, Morocco, Mozambique, Spain and USA. The teachers involved in the lectures were: F. Sansò (A general introduction to physical geodesy and geoid computation), H. G. Wenzel (The computation and use of global models of high and ultra-high degree), C.C. Tscherning (The collocation solution for the geoid computation), B. Benciolini and R. Barzaghi (The terrain and residual terrain correction), M. Sideris (Fast Fourier techniques to perform the computation of the main formulas in physical geodesy).

Nine issues of the IGeS Bulletin have also been published in these years, covering most of the problems in geoid estimation. A special issue in 1997 was devoted to the validation of the global geopotential model EGM96; comparisons, carried out all over the world from different study groups, were collected and summarized in this special publication. Another special number has been published in June 1999, dedicated to South America and issued in Spanish or Portuguese language. In the near future, the Bulletin will became a reviewed publication with two issues per year.

Data collection is one of the main tasks of IGeS. Both global geopotential models and local geoid estimates have been stored in the IGeS Geoid Repository with three different access restrictions. Geoid data can be in fact stored as ON DEMAND, PRIVATE and PUBLIC files, according to the indication given by the data owner. An ON DEMAND file cannot be retrieved unless its owner agrees; if the owner gives this permission the file is released to whom asked for it. PRIVATE files can circulate within a restricted group of users (e.g. the participants to the GEOMED project). PUBLIC files are naturally free to anyone accessing the IGeS Web.

The available regional geoid estimates which are presently in the IGeS data base are: Africa, Alaska, Australia, Austria, Baltic region, Canada, Europe, France, Mediterranean Sea, Greenland, Hawaiian Islands, Italy, Mexico, Nordic Countries, Puerto Rico and Virgin Islands, South America, South-East Asia, Spain, Sudan, Switzerland and USA. The global geopotential models stored in the IGeS Web are: OSU91A, JGM-1, JGM-2, JGM-3, GEM-T3, GRIM4, GFZ93, GPM2, IFE88E2, EGM96, GFZ97.

The main projects which have been carried out in these four years by IGeS are briefly summarized in the following.

The first project which involved IGeS was the MANICORAL project; it was a EC financed project on scientific cooperation using multimedia hardware and software through internet connection.

Another relevant project was the validation of the EGM96 geopotential model; it was managed by IGeS under the supervision of Prof. Sideris from the University of Calgary. Many groups all over the world compared this geopotential model, complete up to degree and order 360, with local gravity and geoid to asses its overall quality. As mentioned before, the outcome of such a relevant work was then summarized in a special issue of the IGeS Bulletin.
The satellite geodesy field was also of interest for IGeS. An original satellite accelerometry mission was defined and proposed to the Italian Space Agency by an Italian team managed by IGeS. Although this project was not, in the end, chosen to pass to Phase B, it was considered by ASI a relevant attempt to define an Italian geodetic satellite mission.

Furthermore, in the near future, IGeS wants to develop and distribute freely its own software on geoid computation. The aim is to prepare a library of programs (written in FORTRAN and/or C languages) covering the basic topics of geoid computation (geopotential model evaluation, terrain effect computation, collocation and FFT).

Finally, the ITALGEO99 project to compute a geoid of centimetric precision in Italy started. The target is to obtain precise geoid undulation in the Italian area trying also to revise the remove-restore procedure. The last global geopotential model EGM96, a revised DTM, an updated gravity data base and surface density information are considered to reach this goal. Besides, the remove-restore procedure will be carefully reconsidered, both theoretically and numerically.

REPORT OF I.A.G. SSG 3.163:“ASSESSMENT AND REFINEMENT OF GLOBAL DIGITAL TERRAIN MODELS”

Chairman: D. Arabelos
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Aristotle University of Thessaloniki, GR-540 06 Thessaloniki

1. Introduction

The International Association of Geodesy (IAG) Special Study Group (SSG) 3.163 was established during the XXI General Assembly of the International Union of Geodesy and Geophysics (IUGG) held in Boulder, Colorado in 1995. The SSG 3.163 was composed of the 20 members and 6 corresponding members. This report outlines the SSG activities and some of the progress that has been made in this area during the period 1995-99. A SSG-3.163 page was establised (address: http://sg.topo.auth.gr/~arab/Miscellaneous/ssg3163.html) in order to share information, software and data to the members of the SSG.

2. Objectives

The main objective of the SSG are as follows:

- Comparisons between the global DTMs in various test areas.

- Refinement of the global DTMs taking advantage of the local (national scale) high resolution DTMs. Detection of possible shift of coordinates and of gross errors of the global models, by comparing global DTMs with local models of the same resolution.

- Incorporation of new data to the existing models.

- Enhancement of the DTM over ice sheets using satellite and airborne altimetry, GPS, SAR interferometry, etc.

- Tests in order to assess the quality of the improved DTMs. These tests will include prediction experiments in the gravity field by taking into account the topography/ bathymetry in terms of the well known reductions (e.g., residual terrain modeling). The ground truth should be used to investigate the prediction results' quality in both cases i.e., using the original or the improved DTM.

- Prediction of bathymetry by inverting the gravity field in areas with a good coverage with gravity measurements. In case of areas that lack of satisfactory surface data, this data shall be recovered by an inversion of satellite altimetry data. Combination of other existing geophysical information is optional. The smoothing effect of the resulting model of bathymetry on other kinds of data, related to the gravity field, such as altimeter data, could be a measure to the quality of the model.

3. Membership

Members: D. Arabelos (Greece, Chairman), R. Barzaghi (Italy), P. Berry (UK), H. Denker (Germany), S. Ekholm (Denmark), Y. Fukuda (Japan), Ch. Green (UK), R. Haagmans (The Netherlands), A M. Hittelman (U.S.A.), W. Kearsley (Australia), S. Kenyon (U.S.A.), P. Knudsen (Denmark), Li Li (China), R. Salman (U.S.A.), D. Sandwell (USA), G. Sarrailh (France), H.-W. Schenke (Germany), H. SŸnkel (Austria), C. C. Tscherning (Denmark), Gwo-Chyang Tsuei (Republic of China), I.N. Tziavos (Greece)

Corresponding members: Mustapha Bouziane (Algeria), Rene Forsberg (Denmark), Scott Luthcke (USA), Nikos Pavlis (USA), Michael G Sideris (Canada), Klaus-Peter Schwarz (Canada), Martin Vermeer (Finland), H.-G. Wenzel (Germany)

4. Meetings

A business meeting was held in Rio de Janeiro, Sept. 5, 1997 during the IAG Scientific Assembly in Rio de Janeiro, September 3-9, 1997.

In the frame of the EGS XXIV General Assembly, a session was organized, entitled “Topography and Bathymetry in Geodetic and Geophysical Applications”.

5. Summary of activities

5.1.New developments

NASA/GSFC-NIMA:
The global 5' elevation model JGP95E was made available to the members of the SSG by S. Kenyon and N. Pavlis. According to S. Kenyon, the updating of the model with new DTED is continued.

GETECH (Reported by Chris Green):

i. For Central and South America: 3' × 3' digital terrain model (DTM3)
ii. For Europe: 2.5'× 2.5' digital terrain model (DTM2.5)
iii. 5'× 5' DTM of the world (DTM5).

NGDC (Reported by Allan Hittelman)

The new global 30' DEM called GLOBE was recently released via the Web. David Hastings, a senior scientist in NOAA, chaired the international effort that developed this compilation. The relevant site at: http://www.ngdc.noaa.gov/seg/topo/globe.shtml is rich with numerous download options, documentation and images. A paper on this effort will be presented by A. Hittelman at the IUGG 99 (Symposium G3).

Hughes STX (Reported by N. Pavlis on behalf of Anita Brenner and Scott Luthcke)

i. Exploitation of satellite altimetry is to create digital elevation models of the polar ice sheets and land. 10 km digital elevations models of both Greenland and Antarctic ice sheets to 81.5^o latitude will shortly be available on CD-ROM from the National Snow and Ice Data Center. A 15’ DEM of South America using ERS-1 Geodetic Mission Data has been created.

ii. Satellite laser altimetry for ice sheets and land topography

5.2. Intercomparison of the global DTMs ETOPO5, TerrainBase and JGP95E

During the business meeting in Rio de Janeiro R.-H. Rapp suggested the assessment of the global DTMs through inter comparison of them. From the inter comparison, the following conclusions could be drawn (Arabelos, 1999):

The standard deviation of the differences between the three models (90 m, 112 m and 92 m) is of the order of 100 m. Taking into account that 60% of the data (the oceanographic data), are common for the three models, we must assume that the discrepancies of the continental data resulting in standard deviation higher than 100 m.

As it was expected, the larger discrepancies were observed in areas with data characterized by poor quality and coverage (Africa, Central Asia). In areas covered with good quality data (USA, West Europe, Australia, Japan, Corea) the convergence of the models is remarkable.

The standard deviation of the differences between topographic corrections of gravity anomalies due to the differences between the three DTMs varies in Central Africa from 6 to 9 mGal, with min and max values ranging from -119 to 87 mGal.

The reliability of the oceanographic data must be considered as comparable with that of the continental data. The fact that the three models include the same data in the oceanic areas (that of ETOPO5) and the lack of reliable oceanographic data, makes the assessment impossible without taking into account the quality information of the very original oceanographic measurements.

The quality of the models considered does not correspond to the recent requirements, for geodetic and other applications. On the other hand, the resolution of the 5' is very sufficient and necessary for many applications. Therefore, significant improvements are necessary in order to be created a reliable DTM with the same accuracy for all areas around the earth, proper for regional and global geodetic, geophysical and oceanographic applications.

The differences between the three models were visualized in $20^o \times 30^o$ blocks. These figures are available through the home page of the SSG-3.163 (http://sg.topo.auth.gr/~arab/SSGJPEG/hague992.html).

5.3. Spherical harmonic expansions

Ultra high degree spherical harmonic models of the Earth's topography, rock equivalent topography and topographic isostatic potential were developed by H.-G. Wenzel (personal communication, 1998) This development to degree 1800, was based on the global elevation model ETOPO5. Two major points should be discussed in the next:

i. If the data in the spherical harmonic expansion of the geopotential have been computed from mean values of blocks with size larger than $180/l_{max}$, where l_{max} the maximum degree of expansion, then the local variation is erroneous. It should therefore be compared to the variations of the topography: If the topography has a large variation, then an error in the gravity data may have been detected (Arabelos and Tscherning, 1999). The spherical harmonic expansion of the topography enabled this comparison.

   The standard deviation of the gravity versus the standard deviation of the topography is shown in Figure 1. For the computation of the standard deviation of gravity, the GPM98A geopotential model (Wenzel, 1998) was used from degree 61 to 1800. Gravity anomalies were computed on a 5'× 5' grid on 3^o equal areas. Then, the standard deviation for each 3o block was computed from the 25 point values. The same procedure was followed for the computation of the standard deviation of the topography. In this case the model used was the spherical harmonic model GTM3A, complete to degree and order 1800, based on the expansion of ETOPO5 (Wenzel, personal communication 1997). In Figure there are many points showing that it is possible to have erroneous values due to errors either in gravity or in the topography.

ii. C.C. Tscherning pointed out that the three first order terms of Wenzel's rock-equivalent topography are very large. The center of mass is many hundreds meters away from the gravity center. This - in combination with the results of the assessment of the global digital DTMs- must mean that there are very large errors in the topography, probably related to the ocean bottom uncertainty and the bottom topography and the ice-masses. An estimate of the missing mass could be made.

5.4. Use of space techniques for the development and assessment of DTMs

Satellite Altimetry from ERS-1, and ERS-2 Geodetic Mission has been used in an intensive attempt to create/improve DTMs of both the Greenland and Antarctic ice sheets as well on land. The accuracy of the models based only on satellite altimeter data over the ice sheet varies from several tens meters to several hundreds meters, depending of the slop of the surface. Better results were achieved by combining a variety of digital elevation data (e.g. Ekholm, 1996).

The current accuracy estimates of the shuttle laser altimeter for low slope terrain are of the order of 1.5 to 3.0 m.(S.Luthcke)

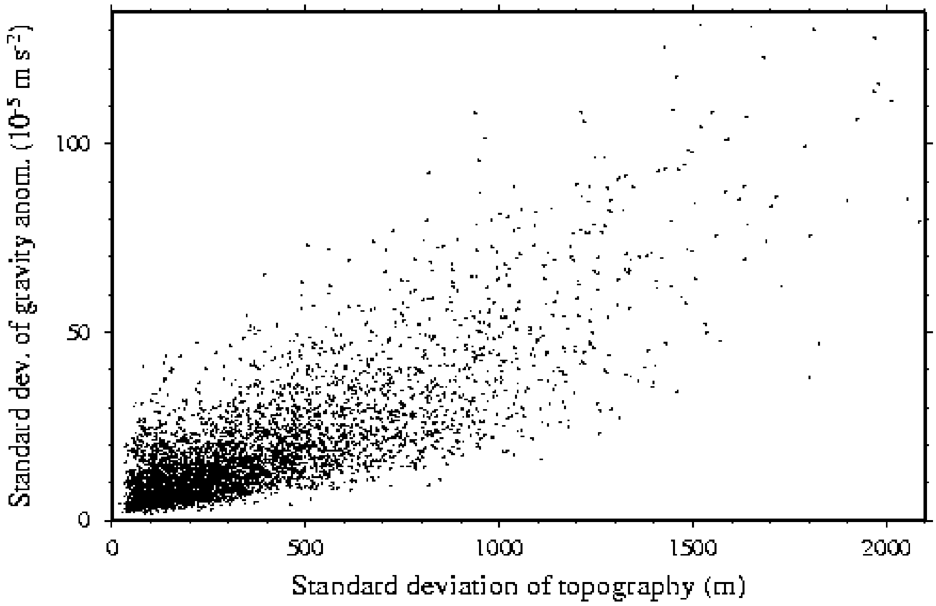

Figure 1. Standard deviation of the gravity versus standard deviation of the topography

Intensive studies on the possibility to obtain globally topography from land altimeter data showed that it is possible to improve on the topographic knowledge of the continents at least for those regions where poor elevation data currently exists (e.g. Brenner et al., 1997, Berry 1999).

5.5. Ground and space techniques for the improvement of ocean bottom topography

Satellite altimetry has earlier been recognized as a source of information that can provide valuable information about the bathymetry. Simultaneously with the method applied by Smith and Sandwell (1994) for the bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry, least squares collocation was used for the inversion of gravity data (Barzaghi et al. 1992, Knudsen 1993). The gravity data can be observed or predicted gravity anomalies from altimeter data in areas with poor coverage with observed gravity data. Taking advantage of the flexibility of this method, Tscherning et al. (1994) performed an experiment to estimate the bottom topography in a test area in the Mediterranean by inverting gravity data. The method was further used in global (Knudsen and Andersen, 1996) or regional experiments (Arabelos, 1997; Arabelos and Tziavos, 1998). These experiments showed that the isostatic compensation of the topography, mainly at the crust/mantle interface is important to consider. The comparison between bathymetric models derived by inverting gravity data with “observed” bathymetric maps showed that the main features of the see floor are clearly described by the predicted bathymetric models. Experiments using the estimated bottom topography to smooth data related to gravity field (through e.g. RTM reductions) showed that generally the estimated bottom topography gives better results that the "observed" bathymetric models. The estimated bottom topography could be used in gravity field modeling and in other applications in areas where no high quality observed depths of the sea floor are available.

Finally, intensive experiments using SAR interferometry are described in the recent literature. Using improved techniques and exploiting all the available information, InSAR is a very promising tool for the improvement of DEMs (e.g., Rocca et al., 1997; Tscherning 1997).

SSG-3.163 Literature

Anzidei, M.: Rapid bathymetric survey and DTM of the Panarea caldera (Aeolian Islands, Southern Tyrrhenian Sea). Presented at the 24th General Assembly of the EGS, The Hague, 19-23 April, 1999.

Arabelos, D.: Validation of ETOPO5U in the Hellenic area. Bull. Geod 68, 88-99, 1994.

Arabelos, D., I.N. Tziavos: Comparisons of the global ETOPO5U model with local DTMs. Proceedings INSMAP94, pp 132-141, 1994.

Arabelos, D.: On the possibility to estimate ocean bottom topography from marine gravity and satellite altimeter data: using collocation. IAG Symposia, Vol. 119, pp 105-112, 1997.

Arabelos, D., I.N. Tziavos: Gravity field improvement in the Mediterranean Sea by estimating the bottom topography using collocation. Journal of Geodesy, 72, 136-143, 1998.

Arabelos, D.: Intercomparisons of the global DTMs ETOPO5, TerrainBase and JGP95E. Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Bamber, J., Muller., J.P., Mandanayake., A., "A Global 5 arc minute Digital Elevation Model derived From The Geodetic Phase Of ERS-1" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Barzaghi, R., F. Sanso and C. Zenucchini: The collocation approach to the inversion of gravity data. Geophysical Prospecting, Vol. 40, 429-452, 1992.

Berry, P.A.M., M. Leigh: Towards validation and correction of global digital elevetion models with ERS-1 Altimetry. Proc. 3rd ERS Symp. on Space at the service of our Enviroment, Florence, Italy, 17-21 March 1997 (ESA SP-414, 3 Vols., May 1997.

Berry, P.A.M., R.F. Sanders, C. Leemans and E. Born: Generating Orthometric Heights from the ERS-1 Altimeter Geodetic Mission Dataset: Results from an Experts Systems Approach. IAG Symposia, Vol. 119, pp 113-118, 1997

Berry, P.A.M., R.A. Pinnock and J.I. Hoogerboorn: Land calibration of radar altimeter $sigma_o$. Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Berry, P.A.M., Bron, E., Sanders, R.F. & Leenmans, C., "Use of ERS-1 Land Altimetry to Validate the GLOBE Global Digital Elevation Model", IAG Symposium, Rio de Janeiro, September 1997.

Berry, P.A.M., Sanders, R.F., Leenmans, C. & Bron, E. "Generating Orthometric Heights From The ERS-1 Altimeter Geodetic Mission Dataset: Results From An Expert Systems Approach", IAG Symposium, Rio de Janeiro, September 1997.

Berry, P.A.M., Dowson, M. "Potential Of ERS-1 Derived Orthometric Heights To Generate Ground Control Points" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Berry, P.A.M., Bracke, H., Jasper, A. "Retracking ERS-1 Altimeter Waveforms Over Land For Topographic Height Determination: An Expert Systems Approach" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Berry, P.A.M., "Topography from land altimeter data: possibilities and restrictions". Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Berry, P.A.M., Hoogerboord, J.E. & Pinnock R.A., "Identification of Common Error Signatures In Global Digital Elevation Models". Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

racke, H., Berry, P.A.M. & Dowson, M., "Geodetic Applications of ERS-1 Altimeter Data Over Land" American Geophysical Union Fall Meeting, December 1996.

Brenner, A.C., R.A. Bindschadler, R.H. Thomas, H.J. Zwally: Slope-Induced Errors in Radar Altimetry Over Continental Ice Sheets. Journal of Geophysical Res., Vol. 88, 1983.

Brenner,A.C., H. Frey, J. DiMarzio, and L. Tsaoussi, "Topography over South America from ERS Altimetry". Proc. 3rd ERS Symp. on Space at the service of our Enviroment, Florence, Italy, 17-21 March 1997 (ESA SP-414, 3 Vols., May 1997).

ron, E.I., "Global DEM Comparison - A comparison between satellite altimeter data and the GLOBE dataset" Dissertation for M.Sc. Informatics, Leicester, August 1997

Carasco, D., Broquetas, D. & A., Arbiol, R., Castillo, M., Pola, V., "Ascending-descending orbit combination SAR interferometry assesment" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Cornet, Y., Dulliez, J.-Y., Moxhet, J., Closson, D., Kourgli, A., Ozer, P., Ozer, A., Derauw, D., "Use of ERS Tandem data to produce Digital Elevation Models by inetrferometry and study land movements by differential Inreferomtetry in Calabria and Jordan" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Constantini, M., "Validation of a novel phase unwrapp algorithm using true and simulated ERS tandem SAR interferometric data" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Cumming, I., Xu, W., "Comparison of phase unwrapping performance using a noisy interferogram" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Davis, C.H. C.A. Cluever, and B.J. Haines: Elevation Change of the Southern Greenland Ice Sheet. Science, Vol. 279, 1998.

Davis, C.H. and H.J. Zwally: Geographic and Seasonal Variations in the Surface Properties of the Ice Sheets by Satellite Radar Altimetry. Journal of Glaciology, Vol. 39, 1993.

Dixon, T.H., M. Naraghi, M.K. McNutt and S.M. Smith: Bathymetry prediction from SEASAT altimeter data. J. Geoph. Res. 88, 1563-1571, 1983.

Dowson, M. and P.A.M. Berry: Geodetic application of ERS-1 altimeter data over land. IAG Symposia, Vol. 119, pp 125-131, 1997

Dowson, M. and P.A.M. Berry:Global precision estimate of radar altimetry heighting over land. Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Doyle, F., "Thirty years of mapping from space" International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, Vienna 1996

Dupont, S., Nomin, P., Remouard, L., Pichon, G., Bignone, F., "Atmospheric artifacts in ERS-DTM Istars experience over multiple sites and large areas" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Ekholm, S.: A full coverage, high-resolution topographic model of Greenland computed from a variety of digital elevation data, J. Geophys. Res., 101, B10, 21,961-21,972, 1996.

Ekholm, S. and J.L. Bamber: A new, full coverage , topographic model of Greenland computed from Geodetic Mission radar altimetry, digital acrophotogrametry and other elevation information. Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Ferreti, A., Prati, C., Rocca, F., Guarnieri, M., "Multibaseline SAR Interferometry for Automatic DEM Reconstruction" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Frey, H. and A. C. Brenner, Australian Topography from Seasat Overland Altimetry, Geophysical Research Letters, Vol. 17, No. 10, pp1533-1536, (Sep 1990).

Goze, S., Blanc, F., Planes, J.G., Piau, P., Sylvander, S., Xavier, J.P., "Three dimensional exploitation of tandem imagery acquireed with Libreville mobile station" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Hittelman, A. M.: Gravity Earth System Data, NOAA, Alpha release, March 1992.

Huess, V. and O. Andersen: Near coastal altimetry in the Eastern North Sea. Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Knudsen, P.: Integrated inversion of gravity data. Final Report Norsk Hydro R&D Project, Kort og Matrikelstyrelsen, Geodetic Division, Technical Report No. 7, Copenhagen, 1993.

Knudsen, P. & O. Ba. Andersen: Ocean bottom topography from ERS-1 altimeter data. Earth Observation Quarterly, No. 51, pp. 16-18, 1996.

Lebertl, F., "The applicability of Satellite Remote Sensing to small and medium Scale Mapping" Proc., of an EARSel-ESA Symposium, Austria, April 1982

Lemoine F.G., Kenyon, S.C., Factor, J.K., Trimmer, R.G., Pavlis, N.K., Chinn, D.S., Cox, C.M., Klosko, S.M., Luthcke, S.B., Torrence, M.H., Wang, Y.M., Williamson, R.G., Pavlis, E.C., Rapp, R.H., Olson, T.R.: The development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96. NASA/TP-1998-206861, !998.

Light., D., "Characteristics of Remote Sensors For Mapping and Earth Science Applications" Photogrammetric Engineering & Remote Sensing, Vol. 36, December 1990

Lingle, C.S., L.-h. Lee, H.J. Zwally and T.C. Seiss: Recent Elevation Increase on Lambert Glacier, Antarctica, From Orbit Crossover Analysis of Satellite Radar Altimetry. Annals of Glaciology, 20, 1994.

Martin, T.V.,H.J. Zwally,A.C. Brenner, and R.A. Bindschadler: Analysis and Retracking of Continental Ice Sheet Radar Altimeter Waveforms. J. Geophys. Res.,88, C3, 1983.

Nielsen, C.S., Forsberg, R., Ekholm, S., Mohr, J.J., "Merging of Elevations from SAR Interferometry, Satellite Altimetry, GPS and Laser Altimetry in Greenland" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Nuth et al.:The application of radar altimeter to the problem of ice sheer thickness changes. Presented at the EGS XXIV General Assembly, The Hague, April 18-23, 1999.

Parsons, C.L: An Assessment of GEOS-3 Waveheight Measurements. Ocean Wave Climate, edited by M.D. Earle and A. Malahoff, Plenum, New York, 1979.

Rocca, R., C. Prati, A. Ferreti: An overview of ERS-SAR interferometry. Proc. 3rd ERS Symp. on Space at the service of our Enviroment, Florence, Italy, 17-21 March 1997 (ESA SP-414, 3 Vols., May 1997).

Sanchez, J.I., Laur, H., "The ERS-SAR performances, products, and systems" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Seymour, M., Cumming, I., "Improving DEMS using SAR Interferometry" Proc. Int. Geoscience and remore sensing symp.IGARSS '98, Seattle, July 1998.

Seymour, M., Cumming, I., "Pre-processing satellite SAR interferograms with DEMs. Submitted to IEE Trans. Geoscience and Remote Sensing, April 1998.

Smith, W.H.F. and D.T.Sandwell, Bathymetric prediction from dence satellite altimetry ans sparce shipboard bathymetry, J. Geophys. Res., 99, 21803-21824, 1994.

Smits, P.C., Trucco, A., Bo, G., Vernazza, G., "Iterative model reconstruction for phase unwrapping" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Tscherning C.C.: Evaluation of SAR-DTM by kinematic GPS. Presented at the SSG 3.163 Business Meeting, Rio de Janeiro, Sept. 5, 1997.

Tscherning, C.C., Forsberg, R., and Knudsen, P., 1994. First experiments with improvement of depth information using gravity anomalies in the Mediterranean Sea. In Proc. of Mare Nostrum - Geomed Report 4, (eds. D. Arabelos and I.N. Tziavos), pp. 133-148, Thessaloniki, Greece.

Yi, D. and C.R. Bentley: Analysis of Satellite Radar Altimeter Return Waveforms over the East Antarctic Ice Sheet, Annals of Glaciology, in press.

Wegmuller, U., Werner, C., "Gamma SAR processor and interferometry software" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Zebker, H.A., Goldstein, R., "Topographic Mapping From Interferometric Synthetic Aperture Radar Observations" Journal Of Geophysical Research, vol.91, No.B5, Pages 4993-4999, April 1986 Seymour, M., Cumming, I., "INSAR terrain height estimation using low-quality sparse DEMS" Proc. 3rd ERS Symp. On Space at the service of our environment, Florence, March 1997.

Zebker, H.A., C.L. Werner, P.A. Rosen and S.Helsey: Accuracy of topographic maps derived from ERS-1 interferometric radar. IEE Trans. on Geoscience and Remote Sensing, Vol. 32, No. 4, July 1994.

Zwally, H.J., A. C. Brenner,J. P. DiMarzio, and M. Giovinetto, "Ice Sheet Topography, Slopes, and Flow Directions from ERS Altimetry", presented the the 3rd ERS Symposium, Florence, Italy, March 1997.

Zwally,H.Jay, A. C. Brenner, J. P. DiMarzio, and T. Seiss, Ice Sheet Topography From Retracked ERS-1 Alimetry, Proceedings Second ERS-1 Symposium - Space at the Service of our Environment, Hamburg, Germany, ESA SP-361 (January) 1994.

Zwally, H.J, A.C. Brenner, J.A. Major, and R.A. Bindschadler, and J.G. Marsh: Growth of Greenland Ice Sheet: Measurement, Science Vol 246, 1989a.

Zwally, H.J: Growth of Greenland Ice Sheet: Interpretation, Science Vol 246, 1989b

Zwally, H.J, A.C. Brenner, J.A. Major, and R.A. Bindschadler: Satellite Radar Altimetry Over Ice, Vol 1,2, and 4, NASA Ref. Pub. 1233, 1990.

FROM AIRBORNE GRAVIMETRY TO AIRBORNE GEOID MAPPING
Report of SSG 3.164

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ABSTRACT

This paper summarizes some of the works done in the Special Study Group 3.164 "Airborne Gravimetry Instrumentation and Methods" over the last four years but it does not give a comprehensive overview of all activities. During the last four to five years, major advances in implementing airborne gravimetry as a production system have been made. The LaCoste & Romberg S-model gravimeter has been successfully used for airborne gravimetry by several groups. The inertial scalar gravimetry using inertial system in conjunction with DGPS has also reached a production level. The airborne gravity data over Greenland and parts of the Arctic and Antarctic has been used for determination of earth gravity model EGM96. The local geoid determination using airborne gravity data has achieved excellent results. All these progress shows that the roll of airborne gravimetry in geodesy, particularly in geoid determination, becomes more important.

After the review of the progress in airborne gravimetry, the paper discusses the different techniques for airborne gravimetry. The concept and algorithm to determine geoid, especially the regional or local geoid, using the airborne gravity data combined with other gravity data are also described in the paper. This opens a new subject – airborne geoid mapping, defined as determining geoid using airborne gravimetry data. Test results show that the local geoid determined by airborne gravity data has achieved an accuracy of 5 cm of the geoid undulation. Some important issues in airborne gravimetry and airborne geoid mapping are also included as conclusions.

INTRODUCTION

During the last 4-5 years, major advances in airborne scalar gravimetry as production system have been made. The accuracy and resolution of conventional air/sea gravimeter have been significantly improved. The development of other airborne gravimetry systems has made a breakthrough. The airborne inertial gravity system based on the combination of DGPS and strapdown INS technology has been used in an operational mode.

As the report of IAG Special Study Group 3.164 "Airborne Gravimetry Instrumentation and Methods", the paper first reviews the major progresses in airborne gravimetry, achieved by members of the IAG SSG 3.164. The paper then discusses some important issues in airborne gravimetry development and data processing in more details. Some key techniques of airborne geoid mapping investigated by SSG members are highlighted.

PROGRESS AND ACTIVITIES

First, the principle to airborne gravimetry is briefly described in the following. In general, airborne gravimetry techniques can be classified into:

- Airborne scalar gravimetry,
- Airborne vector gravimetry,
- Gravity gradiometry.

Depending on the approaches to establish the orientation of gravity sensors, the scalar gravimetry system can be divided into four groups:

- Airborne gravimeter based on damped two-axes platform,
- Schuler-tuned platform or inertial platform based airborne gravimeter,
- Airborne inertial gravimetry system,
- Strapdown airborne gravimetry system.

The Review in the following will concentrate on the airborne scalar gravimetry development. The research and development in airborne gravimetry in the last 4 years can be subdivided into two major areas: improvement of conventional airborne gravimeters and development of new airborne gravity systems or integrated airborne systems.

Following accomplishment of airborne gravity survey in Greenland in 1991 and 1992, the US Naval Research Laboratory (NRL) has continued the arctic airborne gravity measurement program during 1992, 1994 to 1997. Under the typical condition for P-3 aircraft, with speed of 450 km/hr and flight altitude of 300-600 m, the NRL airborne gravimetry system, based on LaCoste&Romberg air/sea gravimeter, has achieved an accuracy of about 2 mGal for the wavelength resolution of 10-15 km, Brozena et al. (1997a, 1997b). In 1997, NRL has carried out an airborne flight in the area southwest of San Diego for the experiment with higher resolution (8 km). During the test, three gravimeters, a LaCoste&Romberg S meter, a ZLS gravimeter and Bell BGM—5, were used for comparison of different gravimeters. During last 4 years, NRL has made significant improvements in the measurement system and data processing, Peters and Brozena (1995), Childers (1997).

During 1995/1996, the British Antarctic Survey has undertaken an airborne gravity survey in Antarctic Peninsula area using modified LaCoste&Romberg air/sea gravimeter, Jones (1997).

To extend the Greenland gravity coverage into the permanently ice-covered Arctic Ocean, the National Survey and Cadastre of Denmark (KMS) has carried out the airborne gravity survey in the North Greenland shelf region and the Disko bay using a

Lacoste&Romberg gravimeter (S-99) in 1998. By improving data processing, KMS 1998 survey shows excellent results, with an estimated RMS error of 2 mGal for resolution of 6 km, based both on crossover comparisons and independent check with surface gravity data, Forsberg et al. (1999).

During last four years a major progress has been made in the development of strapdown inertial scalar gravimetry (SISG). A prototype of the SISG system was developed by the University of Calgary, based on Honeywell LASEREF III inertial system. Two flight testes were carried out in June 1995 and September 1996. Compared to upward continued ground gravity data and crossover results, an accuracy of 2-3 mGal for the cut-off frequency corresponding to 120 seconds are achieved, Glennie and Schwarz (1997), Wei and Schwarz (1998). Glennie and Schwarz (1999) have compared different inertial systems for the airborne inertial gravity system.

Based on SATR-3i interferometry SAR system, Intermap has developed an airborne inertial gravity system with very high accuracy of gravity measurements, about 1-1.5 mGal for the cut-off frequency corresponding to 120 seconds, compared to upward continued ground gravity data and crossover results, Tennant et al. (1997).

The concept of rotation invariant scalar gravimetry (RISG) based on a triad of accelerometers has been investigated by Wei and Schwarz (1996). This opens an opportunity to develop an airborne gravimetry system without orientation platform. A strapdown airborne gravimetry system using three accelerometers has been developed and is under the test, Boedecker (1997,1998).

One objective of SSG 3.164 is to establish standard data sets for the software development and comparison. The airborne gravity data of the flight test in June 1995 has been published and stored on the University of Calgary FTP site. Many groups have used the test data for the processing development and analysis. Using this test data, OSU group has made prominent progress in the airborne vector gravimetry. Comparing the airborne results with available ground data demonstrates the accuracy of 7-8 mGal for horizontal components and 3 mGal for vertical component, Jekeli and Hwon (1999). This also shows the consistent accuracy of vertical gravity measurements from an airborne inertial gravimetry system using medium-accuracy strapdown inertial system.

Funded by the European Commision, the AGMASCO (Airborne Geoid Mapping System for Coastal Oceanography) project was carried out in a Noewegian-Danish-German-Portuguese cooperation, Forsberg et al. (1996), Hehl et al. (1997). The objective of the project is to develop an airborne geoid mapping system for the coastal oceanography from combined airborne gravity system/airborne altimetry system. Crossover analysis as well as comparisons with ground truth data shows the accuracy of about 2 mGal over wavelengths of 5-7 km, Bastos et al. (1997).

Organized by the National Survey and Cadastre of Denmark (KMS), the international workshop on “Airborne Gravity and Polar Gravity Field” was held in Kangerlussuaq of Greenland, from June2-4 1998, Forsberg (1998). Following the workshop, a joint test flight for LaCoste&Romber S meter along with inertial gravity unit of the University of Calgary and a strapdown accelerometer system of Bayerische Kommission für die International Erdmessung was carried out. This is first time for the direct comparison of different airborne gravity systems. The comparison of airborne gravity results is under investigation.

DATA PROCESSING IMPROVEMENT

Error Model

The error model for conventional airborne gravimeter and inertial scalar gravimetry is in principle the same. The significant errors affecting airborne scalar gravimetry are expressed as follows

$$dDg = f_n e_e - f_e e_n + df_u - d\dot{v}_u \tag{1}$$

where e_e and e_n are attitude errors, f_e and f_n are horizontal specific forces, df_u is the vertical acceleration error and $d\dot{v}_u$ is the GPS derived acceleration error. The off-leveling error for the conventional airborne gravimeter is expressed in the tilt direction, see Torge (1989), while equation (1) describes the attitude error in east and north direction.

Equation (1) indicates that the major error sources for airborne gravimetry are attitude-induced error, gravimeter sensor or accelerometer noise, and error of GPS derived acceleration. During last four years, many groups have made lost of effort to improve the correction of attitude-induced errors and reduce the sensor noise and errors in GPS derived acceleration by improving data processing.

Resolution Issue

The resolution of airborne gravity signal is a function of altitude due to the upward continuation effect of gravity signal. The gravity signal will be attenuated as the altitude increases. The resolution of airborne gravity signal describes the characteristics of gravity signal at flight altitude. Assuming the isotropic of the gravity field, the PSD of the gravity anomaly at the flight altitude *h* can be expressed using the PSD of gravity anomaly on zero level in the following

$$S_{Dg_h}(w) = exp\{-hw\} S_{Dg_0}(w) \tag{2}$$

where

Δg_h …	the gravity anomaly at the altitude *h*,
Δg_0 …	the gravity anomaly at zero level,
$exp\{-hw\}$ …	the Hankel transformation of upward continuation operation.

Equation (2) shows that the airborne gravity signal in the bandwidth of high frequency, or short wavelength, is rapidly attenuated. The RMS power of the airborne gravity anomaly in the bandwidth higher than ω_c can be computed by

$$\sigma_h = [\int_{\omega_c}^{\infty} \omega S_{\Delta g_h}(\omega) d\omega]^{1/2} \tag{3}$$

Using the covariance function of the ground gravity anomaly Δg, discussed in Moritz (1980), the wavelength λ_c corresponding to the frequency ω_c can be computed by

$$\lambda_c = \frac{h}{-ln[\frac{\sigma_h}{\sigma}(1 + 2h/B)]} \tag{4}$$

where σ_h / σ is the ratio of RMS power of the airborne gravity anomaly at altitude *h* and at zero level, *B* is parameter for the correlation length of the covariance function of gravity anomaly.

In equation (4), the ratio σ_h / σ indicates the attenuation of airborne gravity anomaly. It can be used as the criterion of detectable airborne gravity signal at flight altitude *h*. The wavelength λ_c in (4) can be defined as the minimum wavelength of detectable airborne gravity signal for the ratio σ_h / σ. Table 1 gives different wavelengths for the ratio σ_h / σ = 0.5.

Table 1. Wavelength of detectable airborne gravity signal

B (km)	h = 0.5 km	h = 2.5 km	H = 5.0 km
30	0.7	5	12
60	0.7	4	9

The basic factor to determine the resolution of airborne gravity measurement, is the cut-off frequency of low-pass filtering. Since the airborne gravity data is filtered along-track, the resolution of airborne gravity measurement is also a function of aircraft speed. The definition of the resolution of airborne gravity measurement may be confusion due to the issue of full-wavelength or half-wavelength.

Kinematic DGPS solution

During last ten years, differential GPS has been successfully used for the kinematic positioning and navigation. Determining aircraft acceleration from the DGPS solution is a fundamental part for the airborne gravimetry. The error of DGPS solution is still a major or dominated error source for the airborne gravimetry.

Beside the GPS noise, the multipath effect on the GPS observation is other major error source to the acceleration determination. The Study indicated that the mulipath effect on the airborne GPS antenna is somehow randomized due to the aircraft motion. The concept of multiple base stations to reduce the multipath effect and other error sources has been applied to the GPS acceleration determination, Klingelé et al (1997). However, To achieve accurate airborne gravity measurements for the short wavelength, mitigation of GPS multipath effect plays an important roll.

The discontinuity in the GPS solution due to changes in the satellite constellation can cause a significant jump in the GPS derived acceleration. To avoid this problem, the GPS processing for the positioning use should be modified for the acceleration determination. Because of the long distance of the baseline, 200 –500 km, the DGPS solution with floating ambiguities can give better results for the acceleration determination and reduce the discontinuity effect.

The Effect of Attitude Error

Attitude error characteristics depend on the system used for the attitude determination. Because of the short damping period (4 min.), the short term orientation error of the damped two-axes platform of LaCoste&Romberg gravimeter can be considerable big and the influence of the attitude error on gravity results can be significant. However, using horizontal specific force and GPS-derived acceleration, the title of the platform can be estimated. During last 4 years, lots of efforts have been made to improve the correction for horizontal accelerations and off-leveling errors, Paters et al (1995), Childers (1997), Olesen et al (1997) and Forsberg et al (1999). Based on the frequency dependent behavior of the damped platform, determining horizontal acceleration from the accelerometer output has been improved using FFT technique, Olesen et al. (1997).

The short-term attitude errors of an inertial system or Shuler-tuned platform are significantly attenuated due to the Schuler loop with a longer period (84 min.). The misalignment error, which is 10 – 20 arc seconds for a typical medium performance inertial system with DGPS update, will also cause considerable gravity error. The attitude-induced gravity errors depend on both the attitude errors and the specific force as indicated in equation (1). For the scalar gravimetry, only the horizontal accelerations have to be considered. The low-pass filtering will significantly reduce the effect of the phugoid motion on the horizontal acceleration, when the oscillation frequency of the phugoid motion is higher than the cut-off frequency of the filtering. For the straight flight line with constant speed, the specific force in the horizontal channel can be approximately a constant due to the Coriolis and centrifugal acceleration for 20-30 min flight. Within this time period, the attitude error of inertial system can be considered as a bias or linear drift. Therefore, the attitude-induced gravity error in interested bandwidth can be described by a first-order polynomial function, and estimated using crossover adjustment method.

Filtering Technique

To reduce the effect due to the differentiation process and measurement noise, the filtering technique is usually applied to the airborne measurements. There are three types of filtering algorithms used for the airborne gravity measurements. They are:

- Infinite impulse response (IIR) low-pass filtering,
- Finite impulse response (FIR) low-pass filtering,
- Model-based filtering approaches.

The IIR and FIR low-pass filter are frequency based filters and used for most airborne gravity processing. When a low-pass filter is applied, the useful gravity signal, gravity anomaly, is preserved in the bandwidth of low frequency. The advantage of using low-pass filtering is easy implementation and its spectral characteristics. Designing and applying a low-pass filter to the airborne measurements plays a fundamental roll in the airborne gravity processing. During last four years, an effort has been focused on improvement of the effeteness of low-pass filtering. The team of US NRL has combined R-C filter with a FIR filter to sharpen the frequency rolloff, Childers et al. (1997). The group of KMS of Denmark has design a new Butterworth filter for the airborne gravity data, Forsberg et al (1999). The FIR filter is applied to the inertial gravimetry data by the U of C and used for Intermap airborne inertial gravimetry system.

However, the low-pass filter is a non-model filtering technique. The signal and noise in the bandwidth of high frequency are attenuated when the low-pass filtering used. Thus, the useful gravity signal in the bandwidth of high frequency will be lost and the noise in the pass band remains. Besides the low-pass filtering, the model-based filtering approaches have been applied to the airborne inertial gravimetry measurements. This approach is based on the Kalman filtering and wave approach. The model-based filtering has been successfully applied by the LIGS group, Salychev (1995). The comparison between frequency based filtering and model-based filtering was investigated by Hammada and Schwarz (1997).

AIRBORNE GEOID MAPPING

The major contributions of airborne gravity measurements in geodesy are determination of the earth gravity model and local geoid determination. The airborne gravity measurements over Greenland and part of Arctic have made significant contribution to the global gravity model EGM96, Lemoine et al. (1996, 1998), Kenyon (1998).

In recent years the airborne gravity measurements are used for the determination of precise local or regional geoid, Forsberg and Brozena (1996), Kearsley et al. (1998), Wei et al. (1998). Comparing to the independently determined geoid shows that the accuracy of 5-10 cm for the geoid undulation determined by using airborne gravity measurement combined with global gravity model and terrain information can be achieved, Kearsley et al. (1998), Wei et al. (1998). Thus, the airborne gravity derived geoid can be used as precise vertical reference of orthometric height. This provides an efficient way to determine orthometric height without traditional leveling.

The principle and technique to determine the local or regional geoid using airborne gravity measurements has been described in Forsberg and Brozena (1996). The remove-restore technique is applied to minimize the errors due to limited spatial size. This method combines the airborne gravity measurements with global gravity model and surface terrain information.

The downward continuation of either airborne gravity anomaly or airborne geoid undulation plays a key roll in geoid determination using airborne gravity data. In principle, there are two downward continuation methods:

- FFT downward continuation technique,
- Least-squares collocation method.

As indicated in equation (2), the downward continuation is a very unstable process. Both the signal and noise in the high frequency bandwidth will rapidly increase by a downward continuation procedure, particularly for the higher flight altitude. To reduce the noise in the high frequency bandwidth, a filtering or smoothing technique is applied to the FFT downward continuation, Forsberg and Kenyon (1995). The regularization method can also be applied when the FFT downward continuation technique is used. The collocation method can be implemented in either spectral domain or spatial domain, Sideris (1995), Tscherning et al. (1997). The FFT downward continuation method provides an easy and fast process scheme. The advantage of collocation method is the possibility of combination with ground data or other heterogeneous data.

Other issue for downward continuation is the resolution of the airborne gravity derived geoid. As discussed above, the wavelength of detectable airborne gravity signal is determined by the flight altitude. The resolution of the geoid undulation computed by airborne gravity signal is also determined by the upward continuation characteristics.

CONCLUSIONS

During the last 4 years major progress in airborne gravimetry has been made. The accuracy and resolution of conventional airborne gravimeter have been significantly improved. The airborne inertial gravity system has been developed with competitive accuracy and used in an operational mode. Under the normal operational condition, an accuracy of 1-3 mGal over wavelength of 5-10 km for the airborne gravimetry system has been achieved.

The contributions of airborne gravity data with current accuracy to the geodesy become more important. The gravity data over Greenland and part of Arctic have provided significant improvement to the current global gravity model EGM96. Using the airborne gravity measurements, an accurate local geoid can be determined and used as a height reference. This leads to a new subject – airborne geoid mapping.

It is still very difficult to achieve a performance of 1-2 mGal over 1-2 km wavelength using the current airborne scalar gravimetry technique, to meet the requirement of geophysical exploration application. Error in GPS-derived acceleration using current GPS technique and processing algorithm seems to limit the accuracy of acceleration over short wavelength. When the cut-off frequency of low-pass filtering is higher than the frequency of the phugoid motion, the effect of the phugoid motion can be a critical issue and should be investigated.

Other way to increase the spatial resolution of airborne gravity data is combining airborne gravimetry system with a gravity gradiometer, as proposed by NRL, Brozena et al. (1997). This will merge the medium wavelength gravity signal with the short wavelength gravity information.

The downward continuation of either airborne gravity anomaly or airborne geoid undulation for the airborne geoid mapping needs more investigation, particularly for the mountain area. If the airborne gravity measurements are combined with ground gravity data or other gravity data, the question of optimization of the gravity data with different spectral bandwidth should be investigated.

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REFERENCES

Bastos, L., S. Cunha, R. Forsberg, A.V. Olesen, A. Gidskehaug, U. Mayer, T. Boebel, L. Timmen, G. Xu, M. Nesemann, K. Hehl, An airborne geoid mapping system for regional sea-surface topography: applications to the Skagerrak and Azores areas, In Forsberg et al. (Eds.): *Geodesy on the Move*, IAG Symposia, Vol 119, pp. 30-36, Springer Verlag, 1997.

Boedeker, G, Airborne strapdown gravimetry – Study of the dynamic environment, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 597-604.

Boedecker, G., Configuration optimization of accelerometers for strapdown airborne gravimeters, International Workshop "*Airborne Gravity and the Polar Gravity Field*", Kangerlussuaq, Greenland, June 2-4, 1998.

Brozena, J.M., M.F. Peters, and R. Salman, Arctic airborne gravity measurement program, In: Sagawa, J., H. Fujimoto, and S. Okubo (eds), *Gravity, Geoid and Marine geodesy*, Proc. IAG Symposia GRAGEOMAR, Tokyo 1996, IAG Symposia, Vol 117, pp. 131-138, Springer Verlag, Heidelberg, 1997.

Brozena, J.M., M.F. Peters, and V.A. Childers, The NRL airborne gravimetry program, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 553-556.

Bruton, A.M., and K.P. Schwarz, Airborne gravity estimation using adaptive filters, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 605-612.

Bruton, A.M., C.L. Glennie and K.P. Schwarz, Differentiation for high precision GPS velocity and acceleration determination. Accepted for Publication by GPS Solutions, 1998.

Childers, V.A., M.F. Peters, and J.M. Brozena, Error analysis of the NRL airborne gravimetry system, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 625-632.

Cunha, S.R., On the INS and GPS data processing for airborne gravimetry applications, International Workshop "*Airborne Gravity and the Polar Gravity Field*", Kangerlussuaq, Greenland, June 2-4, 1998.

Forsberg, R., and J.M. Brozena, Airborne geoid measurements in the arctic ocean, In: Sagawa, J., H. Fujimoto, and S. Okubo (eds), *Gravity, Geoid and Marine Geodesy*, Proc. IAG Symposia GRAGEOMAR, Tokyo 1996, IAG Symposia, Vol 117, pp. 139-146, Springer Verlag, Heidelberg, 1997.

Forsberg, R., K. Hehl, L. Bastos, A. Gidskehaug, and U. Meyer, Development of an airborne geoid mapping system for coastal oceanographphy (AGMASCO), In: Sagawa, J., H. Fujimoto, and S. Okubo (eds), *Gravity, Geoid and Marine Geodesy*, Proc. IAG Symposia GRAGEOMAR, Tokyo 1996, IAG Symposia, Vol 117, pp. 163-170, Springer Verlag, Heidelberg, 1997.

Forsberg, R., Report of Workshop "Airborne Gravity and the Polar Gravity Field" - Greenland, June 1998, *IAG Newsletter*, Nov. 1998.

Forsberg, R., A.V. Olesen, and K. Keller, Airborne gravity survey of the north Greenland Shelf 1998, Technical Report, No. 10, National Survey and Cadastre, Denmark, 1999.

Glennie, C. and K.P. Schwarz, Airborne gravity by strapdown INS/DGPS in a 100 km by 100 km area of the Rocky Mountains, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 619-624.

Glennie, C.L., K.P. Schwarz, A.M. Bruton, J.K. Tennant, M. Wei, A combined DGPS/INS and synthetic aperture radar system for geoid-referenced elevation models and ortho-rectified image maps, *ION-GPS 1998*, Nashville, Ten. USA, Sept. 15-19, 1159-1164.

Glennie, C.L. and K.P. Schwarz, a comparison and analysis of airborne gravimetry results from two strapdown inertial/DGPS systems, accepted by *Journal of Geodesy*, 1999.

Glennie, C.L., An analysis of airborne gravity by strapdown INS/DGPS. Ph.D. thesis, University of Calgary, UCGE Report # 20125, Calgary, 1999.

Hammada, Y. and K.P. Schwarz, Airborne gravimetry, model-based versus frequency-domain filtering approaches, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 581-595.

Hehl, K., L.Bastos, S. Cunha, R. Forsberg, A.V. Olesen, A. Gidskehaug, U. Mayer, T. Boebel, L. Timmen, G. Xu, and M. Nesemann, Concepts and first results of the AGMASCO project, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 557-563.

Jekeli, C., and R. Garcia, GPS phase acceleration for moving-base vector gravimetry, *Journal of Geodesy*, Vol, 71, No. 10, pp. 630-639, 1997.

Jekeli, C., and J.H. Lwon, Results of airborne vector (3-D) gravimetry, Submitted to *Geophysical Research Letters*, 1999.

Jones, P., Towards a new free air anomaly map of the Antarctic Peninsula, In Forsberg et al. (Eds.): *Geodesy on the Move*, IAG Symposia, Vol 119, pp. 517-522, Springer Verlag, 1997.

Kearsley, A.H.W., R. Forsberg, A. Olesen, L.Bastos, K. Hehl, U. Mayer, and A. Gidskehaug, Airborne gravimetry used in precise geoid computations by ring integration, *Journal of Geodesy*, Vol, 73, No. 10, pp. 600-605, 1998.

Kenyon, S., The contribution of airborne and polar gravity to NIMA's global gravity modelling efforts, International Workshop "*Airborne Gravity and the Polar Gravity Field*", Kangerlussuaq, Greenland, June 2-4, 1998.

Klingelé, E.E., M. Cocard, M. Halliday and H.-G. Kahle, The airborne gravimetric survey of Switzerland, *Contribution to the Geology of Switzerland*, Geophysique., 31, Swiss Geophys. Comm., Switzerland, 1996.

Klingelé, E.E., M. Cocard, H.-G. Kahle and M. Halliday, Kinematic GPS as a source for airborne gravity reduction in the airborne gravity survey of Switzerland, *Journal of Geophysical Research*, Vol. 102, No. B4, pp. 7705-7715,April 10, 1997.

Lemoine, F.G., D.E. Smith, L. Kunz, R. Smith, E.C. Pavlis, N.K. Pavlis, S.M. Klosko, D.S. Chinn, M.H. Torrence, R.C. Williamson, C.M. Cox, K.E. Rachlin, Y.M. Wang, S.C. Kenyon, R. Salman, R. Trimmer, R.H. Rapp and R.S. Nerem, The development of NASA GSFC and NIMA joint geopotential model, In: Sagawa, J., H. Fujimoto, and S. Okubo (eds), *Gravity, Geoid and Marine Geodesy*, Proc. IAG Symposia GRAGEOMAR, Tokyo 1996, IAG Symposia, Vol 117, pp. 461-469, Springer Verlag, Heidelberg, 1997.

Lemoine, F.G., S.C. Kenyon, J. Factor, R. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S. Luthcke, M.H. Torrence, Y.M. Wang, R.C. Williamson, E. Pavlis, R.H. Rapp and T.Olson, The development of joint NASA GSFC and National Imagery and Mapping Agency (NIMA) geopotential model EGM96, NASA Technical Publication TP-1998-208261, 1998.

Moritz, H., *Advanced Physical Geodesy*, Herbert Wichmann Verlag, Karlsruhe, 1980.

Olesen, A.V., R. Forsberg, and A. Gidskehaug, Airborne gravimetry using the LaCoste & Romberg gravimeter – an error analysis, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 613-618.

Paik, H.J., E.R. Canavan, and M.V. Moody, Airborne/shipborne SGG survey system, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 565-570.

Salychev, O.S., Airborne gravimetry with high precision resolution, Technical Report, Department of Geomatics Engineering, The University of Calgary, 1995.

Schwarz, K.P, Airborne gravimetry - an assessment of the current state and future potential of the technology. *Proc. of the Int. Symp. Geoinformatics '96*, Wuhan, PRC, October 16-19, 1996, pp. 367-376.

Schwarz, K.P. and Y.C. Li, What can airborne gravimatry contribute to geoid determination?, *Journal of Geophysical Research*, Vol. 101, No. B8, pp. 17873-17881, August 10, 1996.

Schwarz, K.P. and Z. Li, An introduction to airborne gravimetry and its boundary value problems. *IAG Int. Summer School on Boundary Value Problems in Geodesy*, Como, May 1996. Published by Springer Verlag in 1997, pp. 312-358.

Schwarz, K.P. and C. Glennie, Improveing accuracy and relibility of airborne gravimetry by multiple sensor configurations, In Forsberg et al. (Eds.): *Geodesy on the Move*, IAG Symposia, Vol 119, pp. 11-17, Springer Verlag, 1997.

Sideris, M.G., On the use of heterogeneous noisy data in spectral gravity field modeling methods, *Journal of Geodesy*, 70, pp. 470-479, 1995.

Torge, W., *Gravimetry*, Walter de Gruyter, Berlin-New York, 1989.

Tennant, J.K., M Wei, K.P. Schwarz and C. Glennie, STAR-3i Gravity Mapping – California Test Results, Submitted to *Canadian Journal for Remote Sensing*, 1998.

Tscherning C.C, F. Rubek and R. Forsberg, Combining airborne and ground gravity using collocation, In Forsberg et al. (Eds.): *Geodesy on the Move*, IAG Symposia, Vol. 119, pp. 18-23, Springer Verlag, 1997.

Wang, J., F. Dwaik and C. Jekeli, INS, GPS and photogrammetry integration for vector gravimetry, In: M.E. Cannon, and G. Lachapelle (eds.), *Proc. International Symposium on Kinematic System in Geodesy, Geomatics and Navigation*, Banff, Canada, June 3-6, 1997, pp. 571-580.

Wei, M. and K.P. Schwarz, Comparison of different approaches to airborne gravimetry by strapdown INS/DGPS, In: Sagawa, J., H. Fujimoto, and S. Okubo (eds), *Gravity, Geoid and Marine Geodesy*, Proc. IAG Symposia GRAGEOMAR, Tokyo 1996, IAG Symposia, Vol 117, pp. 155-162, Springer Verlag, Heidelberg, 1997.

Wei, M. and K.P. Schwarz, Flight test results from a strapdown airborne gravity system, *Journal of Geodesy*, Vol, 72, No. 6, pp. 323-332, 1998.

Wei, M. J.K. Tennant and K.P. Schwarz, Star-3i Airborne Geoid Mapping, Paper present at AGU 1998 Western Pacific Meeting, Taipei, Taiwan, July 21-24, 1998.

Wu, L. and M.G. Sideris, Accuracy improvement of airborne vector gravimetry with and without noise PSDs, In: Sagawa, J., H. Fujimoto, and S. Okubo (eds), *Gravity, Geoid and Marine geodesy*, Proc. IAG Symposia GRAGEOMAR, Tokyo 1996, IAG Symposia, Vol 117, pp. 147-154, Springer Verlag, Heidelberg, 1997.

IAG SPECIAL STUDY GROUP 3.165:
GLOBAL GRAVITY FIELD DETERMINATION AND EVALUATION

REPORT FOR THE PERIOD: JULY 1995 – JULY 1999

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This Special Study Group was established by the International Association of Geodesy (IAG) during the XXI General Assembly of the International Union of Geodesy and Geophysics (IUGG) held in Boulder, Colorado, in July 1995. Its program of activities and its members are given next.

Program of Activities

The proposed list of activities and research topics is as follows:

1. Modeling and estimation techniques. This includes:
   - functional representation of various data types
   - consideration of systematic effects
   - efficient techniques for high degree harmonic analysis/synthesis
   - alternative techniques for the development of high degree combination solutions
   - alternative forms of gravity field representation

2. Improvement on the consideration of the error properties of large data sets used in the development of global gravity models (e.g., consideration of correlated errors among the gravity anomalies in global 30'x30' data bases).

3. Design and setup of a data base that may include:
   - published global gravitational models
   - independent data which may be used for evaluation of existing and future gravity models (e.g., GPS/Leveling-derived geoid undulations)

The SSG, in close cooperation with other bodies of the IAG such as the International Geoid Service (IGeS), should decide the content and format and consider the logistics involved in establishing and maintaining such a database.

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Members of SSG 3.165, as well as other interested colleagues, made a significant effort towards accomplishing the program of activities of this SSG. Progress has been made in three major areas of research as it is discussed next.

1. Global geopotential model development and evaluation

During this reporting period several new models were developed. These include EGM96 [Lemoine et al., 1997; 1998a], TEG-3 [Tapley et al., 1997], GRIM4-S4/C4 [Schwintzer et al., 1997], GFZ96 [Gruber et al., 1997]. EGM96 represents a significant milestone in global gravity field modeling. Its development incorporated a plethora of satellite tracking data, satellite altimetry, and the most up to date surface gravity information that was available at that time. The performance of EGM96 on a wide variety of applications (orbit determination, land and marine geoid modeling) was tested both by its development team, and by an independent, international group of researchers, chaired by M. Sideris and operating under the auspices of IGeS. The findings of this group were published in Bulletin No. 6 of the IGeS [Sansò, 1997].

In addition to the above models Wenzel [1998] presented ultra-high degree solutions (GPM98A, B and C) obtained from orthogonality relations applied on global grids of gravity anomalies. These anomalies result from the merging of terrestrial and altimetry-implied data. Chambers et al. [1998] presented an accuracy assessment of recent global geoid models. Results from the intercomparison and evaluation of five contemporary global geopotential models (JGM-3 [Tapley et al., 1996], GRIM4-C4, TEG-3, EGM96, and GPM98A) were presented by Pavlis et al. [1998a]. Jekeli [1999] presented an analysis of vertical deflections derived from high-degree spherical harmonic models.

Gravity model improvement activities continue within several groups (e.g., GFZ/GRGS, NASA/GSFC, UT/CSR). Such activities include reprocessing of historic tracking data using improved models and analysis techniques, addition of new tracking data types (such as high-low satellite-to-satellite tracking (SST) data from the TDRSS and GPS constellations), and the possible incorporation of Ocean Circulation Model (OCM) information into the development of global geopotential solutions. The German-French team that produced the GRIM series of models is currently working on the development of GRIM5 [Schwintzer et al., 1999]. This model aims to provide the basis for inclusion of tracking data to be acquired from the CHAMP mission [Reigber et al., 1996]. Lemoine et al. [1998b; 1998c] discussed ongoing efforts towards gravity field model improvements within NASA/GSFC. Preliminary results from the introduction of OCM information into global geopotential solutions were presented by Pavlis et al. [1998b; 1998c] and by Tapley et al. [1998].

During this reporting period two missions have been approved for launch, which will have a direct impact on the determination of the global gravity field. The CHAMP mission will carry a GPS receiver and an accelerometer in low Earth orbit, and the GRACE mission which is a low-low SST configuration [NRC, 1997]. CHAMP is currently scheduled for launch in early 2000, and GRACE in 2001. In addition, the GOCE mission has been proposed to the European Space Agency, to carry a gradiometer in low Earth orbit [Balmino et al., 1998]. Both GRACE and GOCE will also include on board GPS receivers, whose tracking data are sensitive to the long wavelength gravitational signal, and thus complement the low-low SST observations (GRACE) and the gradiometer observations (GOCE). The realization of these missions (especially GRACE and GOCE) is expected to enable a “quantum leap” in our global gravity field determination capability. A review of past and future developments in geopotential modeling was presented by Rapp [1998].

2. Modeling and estimation techniques

Numerous contributions were made in this area. Those mentioned next represent just a sample that covers some of the specific topics within the SSG’s program of activities. Investigations related to harmonic analysis and the issues of aliasing and filtering were reported by Jekeli [1996]. Sneeuw and Bun [1996] presented a method for performing global spherical harmonic computations using 2-D Fourier transformation methods. Several papers related to estimation problems can be found in the DEOS Progress Letters 97.1 and 98.1, published by the Delft University of Technology. Bouman [1998] presented a report on the quality of regularization methods. Schuh [1996] presented tailored numerical solution strategies for global gravity field determination, addressing specifically the future missions mentioned above. Kim et al. [1999] presented a simulation study for the GRACE mission. Strakhov et al. [1997] investigated a numerical approach (SNAP-approach) applicable to the solution of very large linear systems that are encountered in high-degree spherical harmonic modeling. Freeden and Windheuser [1997] discussed combined spherical harmonic and wavelet expansions.

Rapp [1997] revisited the use of potential coefficients for geoid undulation determination, demonstrated the significance of the systematic difference between height anomalies and geoid undulations, and developed appropriate corrections to account for this difference. Rapp [1999] also investigated some artifacts that are introduced when truncated spherical harmonic series of functions (to degree 360) are used for point function evaluations. Pavlis [1998d] considered the inconsistencies that are (still) observed between satellite-only and surface gravity-only geopotential models. Pavlis [1998e] presented an approach for the

modeling and the estimation of long wavelength systematic errors in surface gravimetric data, along with preliminary results from this method.
A relatively new area of investigation is related to the use of oceanographic information in the development of global geopotential solutions. Naturally, this approach requires the inter-disciplinary cooperation between geodesists and oceanographers, and offers the opportunity for inter-comparison of models that are developed by the respective groups. Pavlis et al. [1999] reported results from such an inter-comparison between models developed at NASA/GSFC and corresponding models developed at MIT [Stammer et al., 1997].

3. Collection of Relevant Data Sets

Two types of relevant information were collected: 1) published sets of spherical harmonic coefficients of the geopotential, and, 2) geoid undulation and height anomaly files obtained from GPS positioning and leveling observations. Additional work needs to be done in order to re-format some of the collected data sets into a consistent format, and to construct user-friendly electronic means for their distribution (e.g., through a web page).
The potential coefficient files were collected from three primary sources: the archives of R.H. Rapp, files provided by H.-G. Wenzel, and files retrieved from the NASA Goddard Space Flight Center's archives. Bouman [1997] presented a survey of global gravity models, where several of the models that were collected here are referenced and briefly described in terms of their development strategy, data used, etc..
Several colleagues provided GPS/leveling data upon request. Unfortunately some of these files were provided with restrictions imposed on their distribution. It is highly desirable that systematic collection and documentation of such data becomes a longer-term activity under the auspices of some IAG body (such as IGeS), which may also ensure their unrestricted distribution. Such a data collection should preferably include data for other functionals of the field (e.g., deflections of the vertical), in addition to geoid undulation information obtained from space positioning (GPS, SLR) and leveling, which is currently the most widely used data type for gravity model evaluations over land areas. It is also important that GPS/leveling data collections are accurately documented, so that model evaluations can be carried out with due care of appropriate corrections. Accurate and complete documentation of these data could also permit their use for investigations related to vertical datum connections.

Conclusions and Recommendations

During the past four years members of this SSG and other colleagues made significant contributions that enabled addressing most of this SSG's objectives and goals. Global gravity field determination and evaluation is an endeavor that is expected to continue into the foreseeable future. The new missions that are currently in preparation promise a wealth of highly precise data that could enable "quantum leap" improvements in our knowledge of both the static (time-averaged) and the time-varying components of the global gravity field. Analysis, validation, and geophysical interpretation of the data from these new missions will present new challenges both for theoretical and for applied/numerical investigations. The combination of these new data with existing, complementary data is another aspect that may play a prominent role in the future. The need for accurate, independent data and information that can be used to calibrate and validate the results from new missions is expected to become ever more critical. It is recommended here that the evolution of this

SSG into a new body (SSG or other) should take into account these developments and address these future challenges.

References

Balmino, G., et al., European Views on Dedicated Gravity Field Missions: GRACE and GOCE, ESA, ESD-MAG-REP-CON-001, May 1998.
Bouman, J., A survey of global gravity models, DEOS Report 97.1, Delft Inst. for Earth-Oriented Space Research, Delft University of Technology, July 1997.
Bouman, J., Quality of regularization methods, DEOS Report 98.2, Delft University Press, 1998.
Chambers, D.P., M.C. Kim, J.C. Ries, and B.D. Tapley, Accuracy assessment of recent global geoid models, presentation at the 1998 Spring AGU Meeting, Boston, May 26-29, 1998.
Freeden, W. and U. Windheuser, Combined spherical harmonic and wavelet expansion – a future concept in Earth’s Gravitational determination, Applied and Computational Harmonic Analysis, 4, 1-37, 1997.
Gruber, T., et al., Improvements in high resolution gravity field modeling at GFZ, in: *Gravity, Geoid and Marine Geodesy*, J. Segawa, H. Fujimoto, and S. Okubo (eds.), IAG Symposia, Vol. 117, Springer-Verlag, Berlin, Heidelberg, 1997.
Jekeli, C., Spherical harmonic analysis, aliasing, and filtering, *J. Geod.*, *70*, 214-223, 1996.
Jekeli, C., An analysis of vertical deflections derived from high-degree spherical harmonic models, *J. Geod.*, *73*, 10-22, 1999.
Kim, J.-R., P.J. Roesset, S.V. Bettadpur, and B.D. Tapley, Simulation of the Gravity Recovery and Climate Experiment (GRACE) mission, Paper AAS 99-144, presented at the AAS/AIAA Space Flight Mechanics Meeting, Breckenridge, Colorado, February, 1999.
Lemoine, F.G., et al., The development of the NASA GSFC and NIMA joint geopotential model, in: *Gravity, Geoid and Marine Geodesy*, J. Segawa, H. Fujimoto, and S. Okubo (eds.), IAG Symposia, Vol. 117, Springer-Verlag, Berlin, Heidelberg, 1997.
Lemoine, F.G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M. Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp, and T.R. Olson, The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, NASA/TP-1998-206861, Goddard Space Flight Center, Greenbelt, MD, July, 1998a.
Lemoine, F.G., E.C. Pavlis, N.K. Pavlis, C.M. Cox , D.S. Chinn, M.H. Torrence, R.G. Williamson, and Y.M. Wang, Gravity Field Improvement Activities at NASA GSFC, International Association of Geodesy Symposia, Vol. 119, Forsberg et al. (eds), Geodesy on the Move, Springer-Verlag, Berlin, Heidelberg, 1998b.
Lemoine, F.G., C.M. Cox, D.S. Chinn, N.K. Pavlis, Y.M. Wang, M.H. Torrence, R.G. Williamson, and E.C. Pavlis, Improved Earth Gravity Solutions Derived From TDRSS, presentation at European Geophysical Society XXIII EGS98, Nice France, April 20-24, 1998c.
NRC (National Research Council), Satellite Gravity and the Geosphere, National Academy Press, Washington D.C., 1997.
Pavlis, N.K., C.M. Cox , E.C. Pavlis, and F.G. Lemoine, Intercomparison and evaluation of some contemporary global geopotential models, presentation at the 2nd Joint Meeting of the International Gravity Commission (IGC) and the International Geoid Commission (IGeC), Trieste, Italy, September 7-12, 1998a.

Pavlis, N.K., Y.M. Wang, D.S. Chinn, C.M. Cox, and F.G. Lemoine, Introduction of Ocean Circulation Model Information in Global Geopotential Solutions: Preliminary Results, presentation at European Geophysical Society XXIII EGS98, Nice France, April 20-24, 1998b.
Pavlis, N.K., C.M. Cox , Y.M. Wang, and F.G. Lemoine, Further analyses towards the introduction of ocean circulation model information into geopotential solutions, presentation at the 2nd Joint Meeting of the International Gravity Commission (IGC) and the International Geoid Commission (IGeC), Trieste, Italy, September 7-12, 1998c.
Pavlis, N.K., Observed Inconsistencies Between Satellite-only and Surface Gravity-Only Geopotential Models, International Association of Geodesy Symposia, Vol. 119, Forsberg et al. (eds.), Geodesy on the Move, Springer-Verlag, Berlin, Heidelberg, 1998d.
Pavlis, N.K., Modeling of Long Wavelength Systematic Errors in Surface Gravimetric Data, presentation at European Geophysical Society XXIII EGS98, Nice France, April 20-24, 1998e.
Pavlis, N.K., C.M. Cox, and F.G. Lemoine, Comparison of dynamic ocean topography solutions combining geodetic and oceanographic information, *Eos Trans.*, AGU, Vol. 80, No. 17, 1999.
Rapp R.H., Use of potential coefficient models for geoid undulation determinations using a spherical harmonic representation of the height anomaly/geoid undulation difference. *J. Geod*., 71, 282-289, 1997.
Rapp, R.H., Past and future developments in geopotential modeling, International Association of Geodesy Symposia, Vol. 119, Forsberg et al. (eds.), Geodesy on the Move, Springer-Verlag, Berlin, Heidelberg, 1998.
Rapp, R.H., Artifacts introduced in the point evaluation of functions expanded into a degree 360 spherical harmonic series, NASA/CR-1999-209229, Goddard Space Flight Center, Greenbelt, MD, May, 1999 (in press).
Reigber, Ch., et al., CHAMP Phase-B Executive Summary, GFZ, STR96/13, 1996.
Sansò, F., The Earth Gravity Model EGM96: Testing Procedures at IGeS, in *International Geoid Service Bulletin No. 6*, Politecnico di Milano, Milano, Italy, 1997.
Schuh, W.-D., Tailored numerical solution strategies for the global determination of the Earth's gravity field, technical report, Inst. of Theor. Geod., Tech. Univ. of Graz, Austria, 1996.
Schwintzer, P., et al., Long-wavelength global gravity field models: GRIM4-S4, GRIM4-C4, *J. Geod.*, *71*, 189-208, 1997.
Schwintzer, P., et al., Status of the GRIM-5 Gravitational Model Development, *Eos Trans.*, AGU, Vol. 80, No. 17, 1999.
Sneeuw, N. and R. Bun, Global spherical harmonic computation by two-dimensional Fourier methods, *J. Geod., 70*, 224-232, 1996.
Stammer, D., C. Wunsch, R. Giering, Q. Zhang, J. Marotzke, J. Marshall, and C. Hill, The global ocean circulation estimated from TOPEX/POSEIDON altimetry and the MIT general circulation model, Rep. No. 49, Center for Global Change Science, Dept. of Earth, Atmospheric and Planetary Sciences, Massachusetts Inst. of Technology, Cambridge, MA, July 1997.
Strakhov, V.N., U. Schäfer, A.V. Strakhov, D.E. Teterin, Ein neuer Ansatz zur Approximation des Gravitationsfeldes der Erde, Interim-Report zum Projekt INTAS-93-1779, IfAG, Potsdam, 1997.
Tapley, B.D., et al., The Joint Gravity Model 3, *J. Geophys. Res., 101 (B12)*, 28029-28049, 1996.

Tapley, B.D., et al., The TEG-3 geopotential model, in: *Gravity, Geoid and Marine Geodesy*, J. Segawa, H. Fujimoto, and S. Okubo (eds.), IAG Symposia, Vol. 117, Springer-Verlag, Berlin, Heidelberg, 1997.
Tapley, B.D., D.P. Chambers, M.C. Kim, S. Poole, and J.C. Ries, Improvement in Global Geoid Models by Including Ocean General Circulation Model Data, presentation at the 2nd Joint Meeting of the International Gravity Commission (IGC) and the International Geoid Commission (IGeC), Trieste, Italy, September 7-12, 1998.
Wenzel G.; 1998: Ultra hochauflösende Kugelfunktionsmodelle GPM98A und GPM98B des Erdschwerefeldes. In: Progress in Geodetic Science. W. Freeden (Ed.). Proceedings Geodäticshe Woche 1998, October 12-17 1998, Kaiserslautern. Shaker Verlag.

REGIONAL LAND AND MARINE GEOID MODELLING 1995 - 1999 REPORT OF SSG 3.167

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Abstract

This paper summarizes the activities and achievements of the IAG Special Study Group (SSG) 3.167: "Regional Land and Marine Geoid Modelling", which was established by the XXIth General Assembly of IAG held in Boulder, Colorado, USA, July 3-14, 1995. The objectives of the SSG 3.167 reflects the duality between past and future and it consolidates what it has already been achieved, and works towards addressing open and new questions. The current state of knowledge in regional geoid modelling refers to: (a) theoretical models related to Boundary Value Problem (BVP) (e.g., how to include terrain and non-linear effects); (b) data reductions and data preparations; (c) modelling procedures for land and marine geoids; (d) accurate regional-scale marine geoid solution and their contribution to sea surface topography and other related oceanographic studies; and (e) validation procedures regarding the quality of the geoid product. Looking to open issues we could mention: (a) new efficient ways of working with heterogeneous data; (b) the impact of GPS - heights not only to validation procedures but also to common adjustments with geoid heights; (c) the study of compatibility of neighbouring datums through geoid determination; (d) the contribution of oceanography to synthetic geoid modelling and (e) new solutions of the global BVP, which can lead to better theoretical geoid models.

In terms of applications, and in the frame of the above mentioned main tasks, considerable work has been carried out in regional land and marine geoid modelling applying successfully efficient spectral and stochastic algorithms, as well as several new alternatives, and using large amounts of terrestrial and airborne gravity data, satellite altimetry data from recent and most accurate missions, and new global reference models.

1. INTRODUCTION AND BACKGROUND

The modelling of the geoid in a regional scale is a traditional part of the activities of Section III (Determination of the gravity field) of IAG, and much has been achieved in this area, both as regards approximation and numerical methods and in results. That the interest of geoid modelling continues is due not only to its significance to practical geodetic surveying tasks and the needs of scientific investigations in other fields, but also because

there remain unmet and new challenges within the topic itself, arising from new theoretical methods, new data sources, and new computational possibilities.
One of the reasons for the establishment of SSG 3.167 was, between others, the need of theoretical research in the frame of the BVPs in the direction of computing regional-scale geoid solutions of high accuracy and resolution. Significant research was carried out in this topic during the life of our Study Group by some of its members and other individuals and since this research is still going on interesting results are expected both in terms of methodological procedures and in results as well. The open part of this kind of research is one of the major reasons that we strongly suggest the continuation of this SSG for the next four years.

The availability of vast amounts of terrestrial, airborne and satellite data sets, related to the gravity field, has also substantially contributed to the precise geoid determinations in different scales. Although there are difficulties in working across the land/sea divide (see paragraph 3), these data sets, e.g., from satellite altimetry and sea and land gravimetry gave the possibility to elaborate large data grids in the computers and to compute in one run geoid heights and other gravity field quantities over land/sea areas. This was also one of the main tasks of our group and many of its members concentrated their efforts on this target. More details for related specific accomplishments are given in paragraph 3.

During the past decade, spectral methods have been competing very favourably against the classical ones, showing almost the same level of accuracy but much higher efficiency. These methods and the fast algorithms (e.g., Fast Fourier Transform - FFT, Fast Hartley Transform - FHT) developed for computations using large gridded data sets, were improved in terms of three-dimensional computations, spherical approximation procedures, spectral computations in non-uniform grids. On the other hand, multiple-input output spectral relationships were developed to combine heterogeneous terrestrial, airborne and satellite altimetry data. Based on these methods significant progress was made in the study of isotropic and non-isotropic power spectral density functions, and the introduction of parametric models, especially for power spectrum estimation. Other methodologies were also developed for gravity field modelling, like wavelets and spectral algorithms in inverse problems, but these mainly belong to IAG Section IV and only some review papers will be referenced in paragraph 3. The traditional stochastic methods based on least-squares collocation procedures, were mainly used, the last years, to the common adjustment of different height sets and to the treatment of the residuals between gravimetric geoid heights and GPS-derived corresponding heights.

2. SSG 3.167 - MEMBERS, TASKS AND GOALS

SSG 3.167 had twenty one regular members, including the president and eight corresponding members. The SSG started its activities after Boulder (July 3-14, 1995) under the chairmanship of Herman van Gysen. After the sad circumstance of Herman's death (February 19, 1998) I took over the chair of the SSG according to the relevant decision of the IAG Executive Committee. The names of the members of the SSG and countries are given on the following list:

PRESIDENT:
Herman van Gysen (Canada) from July 1995 to February 1998

Ilias N. Tziavos (Greece) from February 1998 - today
MEMBERS:
O. Andersen (Denmark)
M. Kuhn (Germany)
R. Barzaghi (Italy)
J. Li (Canada)
D. Behrend (Germany)
C. Merry (South Africa)
W. Featherstone (Australia)
D. Milbert (USA)
R. Hipkin (United Kingdom)
E. de Min (The Netherlands)
Z. Jiang (France)
G. Papp (Hungary)
A.H.W. Kearsley (Australia)
B. Shaofeng (China)
P. Knudsen (Denmark)
G.C. Tsuei (Taiwan)
J. Krynski (Poland)
M. Vermeer (Finland)
CORRESPONDING MEMBERS:
D. Blitzkow (Brazil)
M. Pearse (N. Zealand)
M. Bouziane (Algeria)
M. Satomura (Japan)
H. Denker (Germany)
M.Sideris (Canada)
R. Forsberg (Denmark)
W. Wiezak (Poland)

After the meeting in Trieste (September 7-12, 1998) the following colleagues started to be informed on the activities of the SSG 3.167, acting, unofficially, as corresponding members: R. Haagmans (The Netherlands), Y. Fukuda (Japan) and V.D. Andritsanos (Greece).
The input of most of the above members in the frame of a "position paper" sent to the first President of the SSG together with the recommendations for further research resulted in the formation of the tasks and goals of SSG 3.167 which are outlined in the Objectives and Programme (http://tziavos@olimpia.topo.auth.gr) and are given below:

1. Extent of the various elements on regional geoid modelling; data reductions and data preparation (including data gridding and block averaging).
2. The use of theoretical models in regional geoid modelling with respect to terrain and non-linear effects.
3.The use of numerical techniques and the possibilities to prescribe or recommend the extent of a standard procedure.
4. Substantive differences between the modelling procedures for land and marine geoids and the difficulties in working across the land/sea divide.
5. Validation procedures and measures of quality of the geoid product.

6. Availability of regional geoids (maps, gridded heights, function coefficients, data compression techniques).

Looking to open questions the following questions present themselves:
1. What is the best way of working with heterogeneous data?
2. Are GPS-derived geoid heights forever to be relegated to a validation-only role? Are there new techniques for a common adjustment of GPS and geoid heights? What is the impact of GPS in studying the compatibility of neighbouring datums through geoid determination?
3. Are there new solutions of the GBVP that hold the promise of better theoretical geoid models?
4. Are there new approximation and numerical techniques that hold the promise of a closer representation or more efficient computation?
5. What is the contribution of an accurate regional-scale marine geoid solution on sea surface topography studies?
6. Are there lessons that geodesists can learn from the oceanographers' technique of 'synthetic' geoid modelling?

Specific accomplishments and suggestions for future research work related, mainly, to the above mentioned open questions are given in the next section. The members of the SSG 3.167 met informally during several international symposia held in the period of 1995 to 1999. More specifically, during the last one and half year we had two informal meetings in Budapest (March 1998) and Trieste (September 1998) in the frame of IAG Symposia. Although the Study Group, as a unit, was not engaged in any service activity, various members served or are still serving on national and international committees. Several members also have contributed to national and international geodetic agencies, industry and universities by providing them with softwares and different data sets.

3. SPECIFIC ACCOMPLISHMENTS

The members of the Study Group concentrated their efforts mainly on tasks 1, 3, 4, 5, 6 tabulated in paragraph 2. Significant research work has been also carried out in the frame of the so called "open questions" (see paragraph 2) defined when establishing the main objectives of the Study Group. Although much progress has been made answering almost all of these questions, significant research is necessary to be done in the future in the frame of some of these topics, mentioned in the sequel as question 1, 2, etc. Some work was also done on theoretical problems (see Task 2) related to regional geoid or quasi-geoid modelling not only by members of the SSG 3.167 but also from colleagues who had a good connection with the group or have been acted as corresponding members of it. BVPs in different scales and the mixed altimetry-gravimetry problem investigating the choice of the best norm and the linearization of errors inherent in standard procedures were studied in the frame of gravity field modelling in general and in regional land and marine geoid approximation in particular (see, e.g., Sanso, 1997; Sanso and Rummel, 1997; Martinec and Grafarend, 1997; Martinec, 1998; Lehman, 1999; Holota, 1996, 1998, 1999; Vanicek et al., 1995; Vanicek and Featherstone, 1998; Zhang and Featherstone, 1997).

For Task 1, progress was made by the optimization of techniques for computing direct and indirect effects of the topography on geoid and gravity. Formulas in spherical approximations and in the frequency domain were developed and techniques were proposed based on kernels' modification in order to overcome singularity problems apparent in computations in very dense and mountainous terrains (Petrovic, 1996; Liu et al., 1997; Rosza, 1998; Toth, 1998; Tziavos and Andritsanos, 1998; Tsoulis, 1998; Dahl and Forsberg, 1999; Nahavandchi and Sjoberg, 1998a; Nahavandchi, 1999); very promising results were reported recently by Tsoulis (1999). The effects of density variations on terrain corrections and geoid determinations were studies by Tziavos et al. (1996), Kuhtreiber (1998), Martinec (1998). Denker and Tziavos (1998) studied the Molodensky correction terms, with emphasis on the use of different terrain reduction techniques. Maximum effects of the Molodensky series terms are 10 cm in mountainous areas and 1 cm for highland areas. The theory of height systems is discussed in several publications with regard to the combination with GPS ellipsoidal heights (Grafarend et al., 1996; Lelgemann and Petrovic, 1997; Grafarend and Okeke, 1998; Nahavandchi and Sjoberg, 1998b). The unification of different neighbouring or local height system is also investigated by several authors, as well as the contribution of gravimetric geoid solutions and GPS in the connection of neighbouring datums (Khafid, 1998; Pan and Sjoberg, 1998).

Several objectives of SSG 3.167 (see tasks 3, 4, 5, 6), which cover also the topics of Questions 1, 2, 4, 5 are directly connected with the analysis, processing and combination of large data sets available from (a) satellite altimetry of the high resolution geodetic missions of Geosat and ERS-1 and the most recent and accurate missions of TOPEX/Poseidon and ERS-2, (b) airborne gravimetry, (c) sea and terrestrial gravimetry, (d) GPS, (e) gravity gradients, (f) deflections of the vertical and (g) high resolution Digital Terrain Models (DTMs) and Digital Depth Models (DDMs). The optimal combinations of one or more of these data sources with a high degree and order geopotential model according to the well known remove-restore technique contribute to the high resolution and accuracy regional-scale geoid or quasi-geoid determinations (see, e.g., Denker and Torge, 1998; Torge and Denker, 1998; Ihde et al., 1998; Vermeer, 1998). Denker and Torge (1998) were evaluated the new revised version of the European Geoid EGG97 by a number of GPS/levelling data sets. The residuals showed medium to long wavelength features of a few cm/100 km and a few dm/1000 km. The long wavelength errors can be modelled by a trend and signal component using least squares collocation with an appropriate covariance function, as it is proposed by Denker (1998), Forsberg (1998), Kotsakis and Sideris (1998) and Duquenne (1999), while results from a combination of gravimetric geoid heights with heights from GPS/levelling and a geopotential model were carried out by Seeber and Torge (1997), Seeber et al. (1997), Duquenne (1996, 1999), Ihde et al. (1998). Interesting results were also reported by Milbert (1995), Sideris and She (1995), Pagiatakis (1996), Blitzkow et al. (1995, 1997) and Veronneau (1997a) with regard to the improvement of continental-scale and high resolution geoid height models. Various tests on geoid/quasi-geoid on GPS benchmarks confirmed the above mentioned accuracy levels and some authors, within the residuals, studied additionally, several systematic effects (Behrend et al., 1995; Verhoef et al., 1996; Jiang, 1996; Barbarella et al., 1998; Toth et al., 1998; Tsuei et al., 1998; Fukuda et al., 1997; Kenyeres, 1997; Duquenne, 1998; Ollikainen, 1998; Tziavos et al., 1998; Veronneau, 1997b; Basic et al., 1999). In Featherstone et al. (1998), Featherstone and Sideris (1998), Forsberg and Featherstone (1998), Vanicek and Featherstone (1998), Tziavos et al. (1998), Toth et al. (1998) the effects of different kernels modification and the limited cap-size on geoid height determination were extensively discussed.

Much progress was also made in terms of the improvement of methods widely used in physical geodesy during the last decade, as, e.g., the spectral techniques and the fast algorithms (FFT, FHT) developed for computing efficiently geoid and other components related to the gravity field, as well as terrain effects, on the surface of the earth and on level surfaces (Sideris, 1995; Tziavos, 1995; Denker et al., 1997; Forsberg, 1998;). The outperformance of the 1D-FFT over the other spectral techniques in local and regional-scale geoid/quasi-geoid computations has been discussed by several authors (see, e.g., Sideris, 1995; Tziavos, 1995; Sideris and She, 1995; Li, 1996; Li and Sideris, 1997; Min, 1996a; 1996b). The use of Input/Output system theory (IOST) algorithms in the frequency domain were also used the last few years to combine heterogeneous data for regional geoid modelling in the frequency domain such overcoming one of the main advantages of the spectral methods (e.g., Sanso and Sideris, 1997; Sideris, 1995a; 1995b; Li, 1996; Tziavos et al., 1998b; 1998c; 1998d; 1998e; Kotsakis and Sideris, 1998). The IOST methods, very similar to least squares collocation method in the frequency domain, contributed also to error propagation studies and to the optimal treatment of noise-to-signal ratios of the different input data sets to the combination procedures, as was pointed out by Sideris (1995b), Tziavos et al. (1997), Tziavos et al. (1998c, 1998d). Refinements were performed by several authors in classical integral, least-squares collocation based methods, point mass representation algorithms and combinations of them, and the modified algorithms heve been used in geoid computation exapmles (see, e.g., Arabelos and Tscherning, 1998; Min, 1995; Tscherning et al., 1998; Vermeer, 1998).

Special emphasis was put on the combination of marine gravity data with altimeter sea surface heights, either using spectral or stochastic methods. The implication of altimeter derived gravity anomalies in such procedures available from global data bases (Andersen and Knudsen, 1998; Andersen et al., 1998; Sandwell and Smith, 1997) helped to fill gaps in sea areas, and contributed substantially to high accuracy and resolution marine geoid modelling. Hwang and Parsons (1997), Hwang (1998), Zhang (1998) were carried out promising results as regards of marine geoid and gravity computations over extended test areas using multi-resolution satellite altimetry and shipborne gravimetry. Kirby (1996) proposed a new spectral method for the optimal combination of altimeter heights with sea gravimetry and Behrend (1999) documented the above mentioned combination strategy based on the remove restore technique. Relevant results and marine geoid solutions on a regional scale were published by different authors (see, e.g., Hipkin, 1995; Olgiati et al., 1995; Li, 1996; Tziavos et al., 1996b; 1998b, 1998c, 1998d, 1998e; Rodriguez and Sevilla, 1999). Andersen and Knudsen (1999) discussed the role of satellite altimetry in gravity field modelling in coastal areas, combining marine, land, satellite and airborne observations. They also discussed the computation problems at the boundary (see/land) and proposed the use of an appropriate covariance function to enhance the spatial resolution. Hipkin (1999) performed an interesting analysis on the modelling of gravity, geoid and sea surface topography in coastal and self areas pointing out problems and possibilities.

Regional-scale geoid computations were presented by Milbert (1995), Milbert and Smith (1996), Smith and Milbert (1997), Smith and Small (1999), who gave also promising comparison results on GPS/levelling/tide benchmarks. Merry (1998) has been presented an interesting paper on a regional quasi-geoid determination for the South-Western Cape in South Africa and discussed the crucial role of such a geoid solution in transforming GPS-derived heights to normal heights. Papp et al. (1998) studied the geophysical dimension of a regional geoid approximation determining a lithospheric geoid solution for Hungary, Strykowski (1996) studied interesting inverse gravity models related to geophysical fields, Toth (1998), Toth et al. (1998) investigated correlations of regional gravimetric geoids with upper crust densities and other geophysical parameters.

National-scale geoid computations have been published by many authors and almost all these contributions are included in the Proceeding issues of IGeS (Bulletins No 4 and No 7) and Finnish Geodetic Institute and in the IAG and EGS Proceedings edited by (Tziavos and Vermeer, 1996; Sanso and Rummel, 1997; Segawa et al., 1997; Vermeer and Adam, 1998; Forsberg et al., 1998). Last, but definitely not least, it is worth mentioning here the interesting review paper by Vermeer (1998), who thoroughly studied the geoid/quasi-geoid as a final product and gave several other dimensions of it related to economic and ideological arguments.

4. CONCLUSIONS AND FUTURE RESEARCH

As it is apparent from the analysis given in section 3, Members of the SSG and other colleagues, during the last four years, worked towards to address in its different targets and to identify the key issues of the open problems that remain to be tackled. Many important refinements have been made to the methods used to regional land and marine geoid modelling, and interesting results were reported in different publications. It is expected that further improvements and new applications will develop as a result of the research already done. It is suggested that special attention be paid and further investigation be done with respect to some of the open questions mentioned before:

- Theoretical and numerical work in land/sea regional geoid/quasi-geoid computations and mainly in applications at the boundary and self seas taking advantage from oceanographic information.
- The impact of GPS in studying the compatibility of neighbouring datums through regional geoid/quasi-geoid determination.
- Modelling of medium and long wavelength errors in regional geoid computations by the future dedicated gravity field missions (CHAMP, GRACE, GOCE, etc.).
- More accurate sea surface topography determinations by marine combined geoid solutions.

On the whole, it is recommended the work of SSG 3.167 to be continued for the next four years. The rich bibliography given below will provide the basis for tackling the new goals outlined above.

BIBLIOGRAPHY AND REFERENCES PROCEEDINGS

New geoids in the world. Special Issue of the International Association Geodesy, International Geoid Service (IGeS) Bulletin No 4, Bureau Gravimetrique International Bulletin d' Information No 77, 1995.

Techniques for local geoid determination. Proceedings, (Ilias N. Tziavos and Martin Vermeer eds.), Session G7 European Geophysical Society, XXI General Assembly, The Hague, The Netherlands, 6-10 May, 1996, publ. 96:2, Finnish Geodetic Institute, 1996.

Geodetic boundary value problems in view of the one centimeter geoid., (Fernando Sanso and Reiner Rummel eds.), Lecture Notes, 592 pp, Springer, 1997.

Gravity, Geoid and Marine Geodesy. Proceedings, (J. Segawa, H. Fujimoto and S. Okubo eds.), Tokyo, Japan, September 30 - October 5, 1996, IAG Symposia vol. 117, publ. Springer, 1997.
The Earth Gravity Model EGM96: Testing procedures at IGeS. International Geoid Service (IGeS) Bulletin No 7, 1997.
Second Continental Workshop on the Geoid in Europe. Proceedings (Martin Vermeer and Jozsef Adam eds.), Budapest, Hungary, March 10-14, 1998, publ. 98:4, Finnish Geodetic Institute, 1998.
Geodesy on the Move - Gravity, Geoid, Geodynamics, and Antarctica, Proceedings (R. Forsberg, M. Feissel, R. Dietrich eds.), IAG Scientific Assembly, Rio de Janeiro, Sept. 3-9, 1997, IAG Symposia vol. 119, Springer, 1998.

INDIVIDUAL PUBLICATIONS

Abd-Elmotaal, H.A. and M. El-Tokhey: Effect of spherical approximation on datum transformation. Manuscripta Geodaetica, 20(6), 469-474, 1995.
Abd-Elmotaal, H. A.: Detailed gravimetric geoid for the Egyptian south-western desert. Phys. Chem. Earth, 23(1), 77-80, 1998.
Abd-Elmotaal, H. A.: Gravity reduction techniques and their comparisons applied to the gravity field in Egypt. Finnish Geodetic Institute Report 98:4, pp. 177-183. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Abd-Elmotaal, H.A.: An efficient technique for the computation of the gravimetric quantities from geopotential earth models. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 182-187, Springer, 1998.
Abd-Elmotaal, H.A., N. Kuhtreiber: Improving the geoid by adapting the reference field. Phys. Chem. Earth (A), 24(1), 53-60, 1999.
Adjaout, A., M. Sarrailh: A new gravity map, a new marine geoid around Japan and the detection of the Kuroshio current. Journal of Geodesy, 71(12), 725-735, 1997.
Ahmad-Berger, Z., A.H.W. Kearsley: Geoid height optimization via sequential least squares method. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 629-636, Springer, 1997.
Al Bayari, O., G. Bitelli, C. Bonini, A. Capra, D. Dominici, E. Ercolani, S. Gandolfi, A. Pellegrinelli, M. Unguendoli, L. Vittuari: A local geoid in the south-eastern Po Valley (ITALY). Finnish Geodetic Institute Report 96:2, pp. 157-164. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Albertella, A., R. Barzaghi, F. Sanso, G.Sona: Geopotential models validation at EGS. IGeS Bulletin no 6, pp. 135-150, 1997.
Albertella, A., F. Sacerdote: Spectral analysis of block averaged data in geopotential global model determination. Journal of Geodesy, 70(3), 166-175, 1995.
Andersen, O., P. Knudsen: Global marine gravity field from the ERS-1 and Geosat geodetic mission altimetry. JGR, 103(C4), 8129-8137, 1998.
Andersen, O., P. Knudsen, S. Kenyon, R. Trimmer: Recent improvements in the KMS global marine gravity field. Proceed. 2nd Joint Meeting of the Int. Gravity Commission and the Int. Geoid Commission, Trieste, 7-12 Sept. 1998, in print.
Andersen, O., P. Knudsen: The role of satellite altimetry in gravity field modelling in coastal areas. Proceed. XXIV EGS Gen. Assembly, The Hague, 19-23 April, 1999, in print.
Andritsanos, V.D., D. Arabelos, S.D. Spatalas, I.N. Tziavos: Mean sea level studies in the Aegean Sea. Proceed. XXIV EGS Gen. Assembly, The Hague, 19-23 April, 1999, in print.

Arabelos, D., C. C. Tscherning: Gravity field recovery from airborne gradiometer data using collocation and taking into account correlated errors. Phys. Chem. Earth (A), 24(1), 19-26, 1999.
Arabelos, D., C.C. Tscherning: Calibration of satellite gradiometer data aided by ground gravity data. Journal of Geodesy, 72(11), 617-625, 1998.
Arabelos, D., C.C. Tscherning: Comparison of recent geopotential models with surface, airborne and satellite data in different areas of the earth.
Arabelos, D., C.C. Tscherning: The use of least square collocation method in the global gravity field modelling. Phys. Chem. Earth, 23(1), 1-12, 1998.
Arabelos, D., I.N. Tziavos (1996). Combination of ERS-1 and TOPEX altimetry for precise geoid and gravity recovery in the Mediterranean Sea. Geophys. J. Int., 125, 285-302.
Arabelos, D., I.N. Tziavos: Gravity-field improvement in the Mediterranean Sea by estimating the bottom topography using collocation. Journal of Geodesy, 72(3), 136-143, 1998.
Arabelos, D., C.C. Tscherning: Collocation with finite covariance functions. IGeS Bulletin no 5, pp. 117-135, 1996.
Arabelos, D., S. Spatalas, I. N. Tziavos, M. Sevilla, J. Catalao: Geoid and tidal studies in the Mediterranean Sea. Finnish Geodetic Institute Report 96:2, pp. 175-180. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Ayhan, M.E.: Updating and computing the geoid using two dimensional fast Hartley transform and fast T transform. Journal of Geodesy, 71(6), 362-369, 1997.
Auzinger, T., W.-D. Schuh: High-degree spherical harmonic analysis combining gridded and random distributed data sets. Phys. Chem. Earth, 23(1), 19-24, 1998.
Banerjee, P., G.R. Foulger, Satyaprakash, C.P. Dabrai: Geoid undulation modelling and interpretation at Ladak, NW Himalaya using GPS and levelling data. Journal of Geodesy, 73(2), 79-86, 1999.
Barbarela, M., R. Barzaghi, D. Dominici, M. Fiani, S. Gandolfi, G. Sona: A comparison between Italgeo '95 and GPS/Levelling data along the coasts of Italy. Phys. Chem. Earth, 23(1), 81-86, 1998.
Barzaghi, R., A. Borghi: The definition of a regional geopotential model for precise gravity field modelling. IGeS Bulletin no 7, pp. 52-67, 1995.
Barzaghi, R., M. A. Brovelli, G. Sona, A. Manzino, D. Sguerso: The new Italian quasigeoid: ITALGEO95. Finnish Geodetic Institute Report 96:2, pp. 111-120. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Barzaghi, R., M.A. Brovelli, G. Sona, A. Manzino, D. Sguerso: The new Italian quasigeoid: ITALGEO95. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 137-152, 1995.
Basic, T., M. Brkic, H. Sunkel: A new, more accurate geoid for Croatia. Phys. Chem. Earth (A), 24(1), 67-72, 1999.
Behrend, D., H. Denker, W. Torge: Gravity field determination in the German Bight (North Sea). Pres. Paper, XXI IUGG General Assembly, Boulder, Colorado, U.S.A., July 2-14, 1995.
Behrend, D.: Untersuchungen zur Schwerefeldbestimmung in den europ_ischen Randmeeren. Wiss. Arb. D. Fachr. Verm.wesen d. Univ. Hannover (Diss.), Nr. 229, 1999.
Belikov, M.V., E. Groten: An attempt to construct the precise gravimetric geoid in Germany. Allg. Verm.nachr., 305-309, 1995.
Benaim, E. H., A. M. Swassi, M. Sevilla: The first Northern Moroccan gravimetric geoid. Phys. Chem. Earth, 23(1), 65-70, 1998.

Berrocoso, M., J. Garate, J. Martin, A. Fernandez, G. Moreu, B. Jigena: Improving the local geoid with GPS. Finish Geodetic Institute Report 96:2, pp. 91-96. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.

Birardi, G., D. Santarsiero, D. Tufillaro, L. Surace: Setting-up local "mapping geoids" with the aid of GPS/LEV traverses. Applications to the geoids of Sardinia and Calabria. Journal of Geodesy, 70(1-2), 98-109, 1995.

Blais, J.A.R.: Spectrum estimation using maximum entropy and multiresolution considerations. Journal of Geodesy, 70(6), 349-356, 1995.

Blitzkov, D.: NASA(GSFC) / NIMA Model evaluation. IGeS Bulletin no 6, pp. 47-70, 1997.

Blitzkow, D., J.D. Fairhead, M.C. Lobianco: A preliminary gravimetric geoid for South America. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 53-66, 1995.

Blitzkow, D., M.C.B. Lobianco, J.D. Fairhead: Data coverage improvement for geoid computation in South America. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 523-531, Springer, 1997.

Biltzkow, D.: Toward 10' resolution geoid for South America: a comparison study. Phys. Chem. Earth (A), 24(1), 33-40, 1999.

Bouman, J., R. Koop: Regularization in gradiometric analysis. Phys. Chem. Earth, 23(1), 41-46, 1998.

Bouziane, M.: The new Algerian quasi-geoid 96 computed using spherical FFT. IGeS Bulletin no 5, pp. 40-56, 1996.

Bursa, M., J. Kouba, A. Muller, K. Radej, S. A. True, V. Vatrt, M. Vojtiskova: Accuracy estimates of EGM96 geoid with emphasis on central Europe, Scandinavia and Baltic region. Finnish Geodetic Institute Report 98:4, pp. 81-85. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Bursa, M., K. Radej, Z. Sima, S.A. True, V. Vatrt: Tests for accuracy of recent geopotential models. IGeS Bulletin no 6, pp. 167-188, 1997.

Catalao, J.C., M.J. Sevilla: Geoid studies in the north-east Atlantic. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 269-274, Springer, 1998.

Chen, J., J. Li, J. Ning, D. Chao: testing and evaluation of the GSFC/DMA EGM in China. IGeS Bulletin no 6, pp. 189-202, 1997.

Chen, Junyong: Accuracy evaluation of the height anomaly prediction by means of gravity data in a height anomaly control network. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 67-76, 1995.

Chuanding, Z., L. Zhonglian, W. Xiaoping: Truncation error formulae for the disturbing gravity vector. Journal of Geodesy, 72(3), 119-123, 1998.

Colic, K., B. Pribicevic, D. Svehla: First cm-geoid in the Republic of Croatia- the capital city Zagreb pilot project. Finnish Geodetic Institute Report 98:4, pp. 245-249. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Dahl, O. C., R. Forsberg: Different ways to handle topography in practical geoid determination. Phys. Chem. Earth (A), 24(1), 41-46, 1999.

Dahl, O.C., R. Forsberg: Geoid models around Sognefjord using depth data. Journal of Geodesy, 72(9), 547-556, 1998.

Daho, S.A.B., S. Kahlouche: The gravimetric geoid in Algeria: first results. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 262-268, Springer, 1998.

De Santis, A., J.M. Torta: Spherical cap harmonic analysis: a comment on its proper use for local gravity field representation. Journal of Geodesy, 71(9), 526-532, 1997.

Denker, H., D. Beherend, W. Torge: The European gravimetric quasigeoid EGG95. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 3-12, 1995.
Denker, H., D. Behrend, W. Torge: A new European gravimetric geoid model (EGG95). pres. paper, XXI IUGG General Assembly, Boulder, Colorado, U.S.A., July 2-14, 1995.
Denker, H., D. Behrend, W. Torge: The European gravimetric quasigeoid. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 532-539, Springer, 1997.
Denker, H., I.N. Tziavos: Investigation of the Molodensky series terms for terrain reduced gravity field data. Proceed. 2nd Joint Meeting of the Int. Gravity Commission and the Int. Geoid Commission, Trieste, 7-12 Sept. 1998, in print.
Denker, H., W. Torge: The European gravimetric quasigeoid EGG97 - an IAG supported continental enterprise. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 249-254, Springer, 1998.
Denker, H.: Evaluation and improvement of the EGG97 quasigeoid model for Europe by GPS and levelling data. Finnish Geodetic Institute Report 98:4, pp. 53-61. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Denker, H.: Evaluation of the NASA/GSFC and NIMA joint geopotential models for Europe. IGeS Bulletin no 6, pp. 83-102, 1997.
Denker, H.: Stand und Aussichten der Geoidmodellierung in Europa. Zeitschrift f_r Vermessungswesen 121, 264-277, 1996.
Dermanis, A.: Generalized inverses of nonlinear mappings and the nonlinear geodetic datum problem. Journal of Geodesy, 72(2), 71-100, 1998.
Doerflinger, E., Z. Jiang, H. Duquenne, R. Bayer: Determination of the quasi-geoid in a mountainous area example of the Eastern Pyrenees (France). In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 643-650, Springer, 1997.
Doufexopoulou, M.G., V. N. Pagounis: Investigation of tectonic traces upon the regional geoid without the use of gravity. Finnish Geodetic Institute Report 98:4, pp. 153-159. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Doufexopoulou, M.G., R. Korakitis: On the gravimetric inverse problem in geodetic gravity field estimation. Journal of Geodesy, 71(6), 311-319, 1997.
Duquenne, H., Z. Jiang: The geoid in the Southern Alps of France. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 115-130, 1995.
Duquenne, H., M. Sarrailh: Improvement of gravimetric geoid determination in the French Alps. Finnish Geodetic Institute Report 96:2, pp. 71-76. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Duquenne, H.: Comparison and combination of a gravimetric quasigeoid with a levelled GPS data set by statistical analysis. Phys. Chem. Earth (A), 24(1), 79-83, 1999.
Duquenne, H.: QGF98, a new solution for the quasigeoid in France. Finnish Geodetic Institute Report 98:4, pp. 251-255. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Dusatko, D., P. Koppecki, V. Vatrt: Quasigeoid of the central Europe from the multinational data. IGeS Bulletin no 6, pp. 165-166, 1997.
Eissfeller, B.: Upward continuation of Markov type anomalous gravity potential models. Journal of Geodesy, 70(9), 539-545, 1995.
Erker, E.: The geoid in Austria- one decade of application. Finnish Geodetic Institute Report 98:4, pp. 239-240. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Fan, H.: On an Earth ellipsoid best-fitted to the Earth surface. Journal of Geodesy, 72(9), 511-515, 1998.
Featherstone, W., J. Olliver: Evaluation of the DMA/GSFC geopotential models over the British isles. IGeS Bulletin no 6, pp. 131-134, 1997.
Featherstone, W.E., J.D. Evans, J.G. Olliver: A Meissl-modified Vanicek and Kleusberg kernel to reduce the truncation error in gravimetric geoid computations. Journal of Geodesy, 72(3), 154-160, 1998.
Featherstone, W.E., J.F. Kirby, K.F. Zhang, A.H.W. Kearsley, J.R. Gilliland: The quest for a new Australian gravimetric geoid. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 581-588, Springer, 1997.
Featherstone, W.E., J.G. Olliver: A method to validate gravimetric-geoid computation software based on Stokes's integral formula. Journal of Geodesy, 71(9), 571-576, 1997.
Featherstone, W.E., M.G. Sideris: Modified kernels in spectral geoid determination - first results from Western Australia. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 188-193, Springer, 1998.
Fenoglio, L., E. Groten: Mean sea level determination in small ocean basins from altimetry and tide gauge data. Manuscripta Geodaetica, 20(6), 394-407, 1995.
Font, G., M.C. Pacino, D. Blitzkow, C. Tocho: A preliminary geoid model for Argentina. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 255-261, Springer, 1998.
Forsberg, R., J. Kaminskis, D. Solheim: Geoid of the Nordic and Baltic region from gravimetry and satellite altimetry. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 540-547, Springer, 1997.
Forsberg, R., J.M. Brozena: Airborne geoid measurements in the arctic ocean. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 139-146, Springer, 1997.
Forsberg, R., K. Hehl, L. Bastos, A. Giskehaug, U. Meyer: Development of an airborne geoid mapping system for coastal oceanography (AGMASCO). In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 163-170, Springer, 1997.
Forsberg, R.: Comparison of EGM models in the nordic region and Greenland. IGeS Bulletin no 6, pp. 115-120, 1997.
Forsberg, R.: Geoid computations in the Nordic and Baltic area. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 105-114, 1995.
Forsberg, R., W. Featherstone.: Geoid and cap. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 18-23, Springer, 1998.
Forsberg, R.: Geoid tailoring to GPS - with examples of a 1-cm geoid of Denmark. Finish Geodetic Institute Report 98:4, pp. 191-197. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Forsberg, R.: The use of spectral techniques in gravity field modelling: trends and perspectives. Phys. Chem. Earth, 23(1), 31-40, 1998.
Fukuda, Y., J. Kuroda, Y. Takabatake, J. Itoh, M. Murakami: Improvement of JGEOID93 by the geoidal heights derived from GPS/levelling survey. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 589-596, Springer, 1997.
Grafarend, E.W., A.A. Ardalan: Wo-an estimate in the Finnish height Datum N60, epoch 1993.4, from twenty five GPS points of the Baltic Sea level project. Journal of Geodesy, 71, 673-679, 1996.

Grafarend, E.W., F. Okeke: Transformation of conformal coordinates of type mercator from a global datum (WGS 84) to a Local Datum (Regional, National). Marine Geodesy, 21(3), 169-180, 1998.
Groten, E.: High precision geoid evaluation for Germany - geoid and quasigeoid. Acta Geod. Geoph. Hung. 31, 293-303, 1996.
Groten, E.: New altimetric results obtained for Baltic and Mediterranean Sea. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 392-399, Springer, 1997.
Heck, B.: Formulation and linearization of boundary value problems: from observables to a mathematical model. In F. Sanso and R. Rummel (Eds.), Geodetic boundary value problems in view of the one centimeter geoid., Lecture Notes, pp 121-160, Springer, 1997.
Hefty, J., L. Husar, J. Melicher, M. Mojzes, J. B. Rogowski, A. Pachuta: Application of astronomical positioning for local geoid determination. Finnish Geodetic Institute Report 96:2, pp. 145-148. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Heiland, R., B. Hofmann-Wellenhof, G. Kienast, N. Kuhtreiber: Recomputation of the Austrian astrogeodetic geoid. Finnish Geodetic Institute Report 98:4, pp. 235-238. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Higgins, M., R. Forsberg, A.H.W. Kearsley: The effects of varying cap-sizes on geoid computation - experiences with fft and ring integration. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 201-206, Springer, 1998.
Hipkin, R.: Geoid models for Great Britain and the North Sea. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 131-136, 1995.
Hipkin, R.: Modelling gravity and sea surface topography in coastal areas. Proceed. XXIV EGS Gen. Assembly, The Hague, 19-23 April, 1999, in print.
Holota, P.: Geoid, Cauchy's problem and displacement. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 368-375, Springer, 1997.
Holota, P.: Variational methods and subsidiary conditions for geoid determination. Finnish Geodetic Institute Report 98:4, pp. 99-105. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Holota, P.: Variational methods for quasigeoid determination. Finish Geodetic Institute Report 96:2, pp. 9-22. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Holota, P.: Variational methods in geoid determination and function bases. Phys. Chem. Earth (A), 24(1), 3-14, 1999.
Hwang, C. and B. Parsons: Gravity anomalies derived from Seasat, Geosat, ERS-1 and TOPEX/POSEIDON altimetry and ship gravity: a case study over the Reykjanes Ridge. Geophys. Geophys. J. Int., 122, 551-568, 1995.
Hwang, C.: A method for computing the coefficients in the product-sum formula of associated Legendre functions. Journal of Geodesy, 70(1-2), 110-116, 1995.
Hwang, C.: Analysis of some systematic errors affecting altimeter-derived sea surface gradient with application to geoid determination over Taiwan. Journal of Geodesy, 71(2), 113-130, 1997.
Hwang, C.: Inverse Vening Meinesz formula and deflection-geoid formula: applications to the predictions of gravity and geoid over the south China Sea. Journal of Geodesy, 72(5), 304-312, 1998.

Ihde, J., U. Schirmer, F. Toppe: Geoid modelling without point masses. Finnish Geodetic Institute Report 98:4, pp. 199-204. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Ivan, M., M. J. Sevilla: Local Quasi-geoid and downward continuation by integrated harmonic series. Application to Dobrudja area-Romania. Finnish Geodetic Institute Report 98:4, pp. 128-136. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Jekeli, C.: An analysis of vertical deflections derived from high-degree spherical harmonic models. Journal of Geodesy, 73(1), 1-22, 1999.
Jekeli, C.: Spherical harmonic analysis, aliasing, and filtering. Journal of Geodesy, 70(4), 214-223, 1995.
Jiancheng, L., C. Dingbo, N. Jinsheng: Spherical cap harmonic expansion for local gravity field representation. Manuscripta Geodaetica, 20(4), 265-277, 1995.
Jiang Z., H. Duquenne: On the combined adjustment of a gravimetrically determined geoid and GPS levelling stations. Journal of Geodesy, 70(8), 505-514, 1995.
Jiang, Z., G. Balmino, H. Duquenne: On the numerical approximation of the errors in a GPS aided gravimetric geoid determination. Finnish Geodetic Institute Report 96:2, pp. 57-66. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Jiang, Z., H. Duquenne: On fast integration in geoid determination. Journal of Geodesy, 71(2), 59-69, 1997.
Jiang, Z.: Geoid determination in France. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 486-493, Springer, 1997.
Jiang, Z.: Geoid prediction using GPS levelling points and digital terrain model- a new French geoid determination G96-01. Finnish Geodetic Institute Report 96:2, pp. 121-128. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Kahar, J., A. Kasenda, K. Prijatna: The Indonesian geoid model 1996. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 613-620, Springer, 1997.
Kahlouche, S., M.I. Kariche, S.A.B. Daho: Comparison between altimetric and gravimetric geoid in the south-west Mediterranean basin. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 281-287, Springer, 1998.
Kakkuri, J.: Discussion on geodetic measuring techniques to determine the sea surface topography for unification of European Vertical Datums. Finnish Geodetic Institute Report 98:4, pp. 41-46. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Kaminskis, J., R. Forsberg: A new detailed geoid for Latvia. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 621-628, Springer, 1997.
Kaminskis, J., R. Forsberg: The geoid determination in Latvia from gravity and satellite altimetry. Finnish Geodetic Institute Report 96:2, pp. 149-156. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Kearsley, A.H.W., R. Forsberg, A. Olesen, L. Bastos, K. Hehl, U. Meyer: Airborne gravimetry used in precise geoid computations by ring integration. Journal of Geodesy, 72(10), 600-605, 1998.
Keller, W.: Collocation in reproducing Kernel Hilbert spaces of a multiscale analysis. Phys. Chem. Earth, 23(1), 25-30, 1998.

Keller, W.: Geoid computation by collocation in scaling spaces. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 176-181, Springer, 1998.
Keller, W.: On a scalar fixed altimetry-gravimetry boundary value problem. Journal of Geodesy, 70(8), 459-469, 1995.
Keller, W.: Wavelet-vaguelette decomposition as a tool in local geoid determination. Phys. Chem. Earth (A), 24(1), 15-18, 1999.
Kenyeres, A., G. Virag: Testing of recent geoid models with GPS/levelling in Hungary. Finnish Geodetic Institute Report 98:4, pp. 217-223. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Kenyeres, A.: A strategy for GPS heighting: the Hungarian solution. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 651-658, Springer, 1997.
Kenyeres, A.: Completion of the nationwide GPS-gravimetric geoid solution for Hungary. Phys. Chem. Earth (A), 24(1), 85-90, 1999.
Kenyeres, S.: Determination and use of the geoid in Hungary. Finnish Geodetic Institute Report 96:2, pp. 81-90. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Kirby, J.F., R. Forsberg: A comparison of techniques for the integration of satellite altimeter and surface gravity data for geoid determination. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 207-212, Springer, 1998.
Kirby, J.F.: The development and application of a new algorithm for ocean geoid recovery. Ph. D. Thesis, University of Edinburgh, 1996.
Klees, R.: Boundary value problems and approximation of integral equations by finite elements. Manuscripta Geodaetica, 20(5), 345-361, 1995.
Knudsen, P., O. Andersen: Improved recovery of the global marine gravity field from the GEOSAT and the ERS-1 Geodetic Mission altimetry. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 429-436, Springer, 1997.
Korth, K., R. Dietrich, G. Reitmayr, V. Damm: Regional geoid improvement based on surface gravity data. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 523-528, Springer, 1998.
Kotsakis, C., M.G. Sideris: Application of multiresolution filtering in geoid determination. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 170-175, Springer, 1998.
Kotsakis, C., M.G. Sideris: On the adjustment of combined GPS/Levelling/Geoid networks. Presented at the IV Hotine-Marussi Symposium on Mathematical Geodesy, Trento, Italy, Sept. 14-17, 1998. Accepted for publication in Journal of Geodesy.
Kuhtreiber, N.: Precise geoid determination using a density variation model. Phys. Chem. Earth, 23(1), 59-64, 1998.
Kuhtreiber, N.: Using different digital terrain models for a precise Austrian geoid. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 597-604, Springer, 1997.
Kuhtreiber, N.: Improved gravimetric geoid AGG97 of Austria. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 306-311, Springer, 1998.
Kumar, M., K. Burke: Realizing a global vertical datum with the use of geoid. Finnish Geodetic Institute Report 98:4, pp. 87-94. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Kusche, J., K.H. Ilk, S. Rudolph, M. Thalhammar: Application of spherical wavelets for regional gravity field recovery-a comparative study. In: R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 213-218, Springer, 1998.

Lacy de, M.C., C. Rodriguez Cadero, A.J. Jil, R. Barzaghi, F. Sanso: Quasigeoid computation in Jaen. IGeS Bulletin no 7, pp. 30-37, 1995.
Lehman, R.: Fast space-domain evaluation of geodetic surface integrals. Journal of Geodesy, 71(9), 533-540, 1997.
Lehman, R.: Information measures for global geopotential models. Journal of Geodesy, 70(6), 110-116, 1995.
Lehmann, R.: Studies on the altimetry-gravimetry problems for geoid determination. Phys. Chem. Earth (A), 24(1), 47-52, 1999.
Lelgeman, D., S. Petrovic: Bemerkungen ueber den Hoehenbegriff in der Geodaesie. Zeitschrift fuer Verm.wesen, 122, 503-509, 1997.
Li, Z., K.-P. Schwarz: Approximation of regional gravity fields from multi-scale data. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 548-556, Springer, 1997.
Li, J., M.G. Sideris: Marine gravity and geoid determination by optimal combination of satellite altimetry and shipborne gravimetry data. Journal of Geodesy, 71(4), 209-216, 1997.
Li, J.: Detailed marine gravity field determination by combination of heterogeneous data. UCGE Report No 20102, M. Sc. Thesis, Dept. of Geomatics Eng., The Univ. of Calgary, Canada, 1996.
Li, Y.C., M.G. Sideris and K.-P. Schwarz: A numerical investigation on height anomaly prediction in mountainous areas. Bull. Geod., 69(3), 143-156, 1995.
Liu, Q.M., Y.C. Li, M.G. Sideris: Evaluation of deflections of the vertical on the sphere and the plane: a comparison of FFT techniques. Journal of Geodesy, 71(8), 461-468, 1997.
Lyszkowicz, A.: Tests of a new gravimetric geoid in GPS network. Finnish Geodetic Institute Report 96:2, pp. 77-80. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Lyszkowicz, A.: The Polish gravimetric quasigeoid QUASI97b versus vertical reference system Kronstadt 86. Finnish Geodetic Institute Report 98:4, pp. 271-276. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Lyszkowicz, A., R. Forsberg: Gravimetric geoid for Poland area using spherical fft. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 153-162, 1995.
Lyszkowicz, A., A.A. Wahiba: The gravimetric geoid for Libya. In R. Forsberg et al. (Eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 275-280, Springer, 1998.
Marson, I., M. Stoka, I. Velicogna, F. Coren, C. Zanolla: Gravity, geoid, isostasy and Moho depth in the Ross Sea, Antarctica. In J. Segawa et al. (Eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 351-359, Springer, 1997.
Marti, U., B. B_rki, H.-G. Kahle: National investigation in Switzerland. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 181-190 , 1995.
Marti, U.: The new geoid CHGEO97 of Switzerland. Finnish Geodetic Institute Report 98:4, pp. 281-287. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Martinec, Z., C. Matyska: On the solvability of the Stokes pseudo-boundary-value problem for geoid determination. Journal of Geodesy, 71(2), 103-112, 1997.
Martinec, Z., E.W. Grafarend: Construction of Green's function to the external Dirichlet boundary-value problem for the Laplace equation on an ellipsoid of revolution. Journal of Geodesy, 71(9), 562-570, 1997.
Martinec, Z., P. Vanicek, A. Mainville, M. Veronneau: The effect of lake water on geoidal height. Manuscripta Geodaetica, 20(3), 193-203, 1995.

Martinec, Z.: Boundary-value problems for gravimetric geoid determination of a precise geoid. Lecture notes in earth sciences, vol. 73, 223 pp., Springer, 1998.
Martinec, Z.: Construction of Green's function for the Stokes boundary-value problem with ellipsoidal corrections in the boundary condition. Journal of Geodesy, 72(7-8), 460-472, 1998.
Milbert, D.G.: Improvements of a high resolution geoid height model in the United States by GPS height on NAVD 88 benchmarks. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 13-36, 1995.
Milbert, D.G., D.A. Smith: Converting GPS height into NAVD88 elevation with the GEOID96 geoid height model. Proceedings, GIS/LIS '96 Annual Conference, Denver, 1997.
Min, Erik de: A comparison of Stokes' numerical integration and collocation, and a new combination technique. Bull. Geod., 69(4), 223-232, 1995.
Min, Erik de: The Netherlands geoid computation procedure. Finnish Geodetic Institute Report 96:2, pp. 35-40. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996a.
Min, Erik de: The new Netherlands geoid. Finnish Geodetic Institute Report 96:2, pp. 139-144. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996b.
Minchev, M., P. Gabenski: A note on the contemporary geoid investigations in Bulgaria. Finnish Geodetic Institute Report 98:4, pp. 241-244. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Mojzes, M., J. Janak: Gravimetric model of Slovak quasigeoid. Finnish Geodetic Institute Report 98:4, pp. 277-280. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Nahavandchi, H., L.E. Sjoberg: Terrain corrections to power H3 in gravimetric geoid determination. Journal of Geodesy, 72(3), 124-135, 1998a.
Nahavandchi, H., L.E. Sjoberg: Unification of vertical datums by GPS and gravimetric geoid models using modified Stokes formula. Marine Geodesy, 21(4), 261-274, 1998b.
Nahavandchi, H.: Terrain correction computations by spherical harmonics and integral formulas. Phys. Chem. Earth (A), 24(1), 73-78, 1999.
Nakane, K., Y. Kuroishi: Combined adjustment of GPS observations and geoid heights in Japan. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 637-642, Springer, 1997.
Neuman, M. Yu., J. Li, Q. Liu: Modification of Stokes and Vening-Meinesz formulas for the inner zone of arbitrary shape by minimization of upper bound truncation errors. Journal of Geodesy, 70(7), 410-418, 1995.
Nsombo, P.: Preliminary geoid over Zambia. Journal of Geodesy, 72(3), 144-153, 1998.
Olgiati, A., G. Balmino, M. Sarrailh: Gravity anomalies from satellite altimetry: comparison between computation via geoid heights and via deflections of the vertical. Bull. Geod., 69(4), 252-260, 1995.
Ollikainen, M.: GPS levelling results obtained in Finland. Finnish Geodetic Institute Report 98:4, pp. 205-210. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Pacino, M.C., G. Font, D. Blitzkow: Data processing for a geoid in Argentina. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 288-293, Springer, 1998.
Pagiatakis, S.D.: Towards a refined gravimetric geoid for Canada 1996-1999. IGeS Bulletin no 5, pp. 31-39, 1996.

Pan, M., L.E. Sjoberg: Unification of vertical datums by GPS and gravimetric geoid models with application to Fennoscandia. Journal of Geodesy, 72(2), 51-63, 1998.
Papp, G., J. Kalmaz, J. Juhasz: Determination and evaluation of the lithospheric geoid in the Pannonian basin, Hungary. Project report, 1998.
Paquet, P., Z. Jiang, M. Everaerts: A new Belgian geoid determination: BG96. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 605-612, Springer, 1997.
Parsons, B. A.: Strategy for the creation of a local geoidal model for the Sultanate of Oman. Finnish Geodetic Institute Report 96:2, pp. 169-174. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Paunescu, C., C. Dina: Fitting of Romanian airport to the ETRF89 network on the WGS-84 ellipsoid. Finnish Geodetic Institute Report 98:4, pp. 211-215. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Pavlis, E. C.: On the Reference Frames Inherent in the Recent Geopotential Models. Finnish Geodetic Institute Report 98:4, pp. 29-40, 1998.
Pearse, M.B., A.H.W. Kearsley: Analysis of EGM models in New Zealand. IGeS Bulletin no 6, pp. 203-212, 1997.
Peng, M., Y. Cai Li, M.G. Sideris: First results on the computation of terrain corrections by the 3D FFT method. Manuscripta Geodaetica, 20(6), 475-488, 1995.
Perdomo, R., C. Mondinally, D. Del Cogliano: Decimetric geoid for Buenos Aires province based on GPS and global models. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 294-299, Springer, 1998.
Petrovic, S.: Determination of the potential of homogeneous polyhedral bodies using line integrals. Journal of Geodesy, 71(1), 44-58 , 1996.
Petrovskaya, M. S., J. B. Zielinski: Application of spatial gradiometry for constructing quasigeoid models. Finnish Geodetic Institute Report 98:4, pp. 107-112. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Poitevin, Z. Jiang, M. Everaert: Le geoide gravim_trique en B_lgique: premiers resultats. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 77-104, 1995.
Rapp, R.H.: Separation between reference surfaces of selected vertical datums. Bull. Geod., 69(1), 26-31, 1995.
Rapp, R.H.: Global models for the 1cm geoid-Present status and near term prospects. In F. Sanso and R. Rummel (eds.), Geodetic boundary value problems in view of the one centimeter geoid. Lecture Notes, pp. 273-308, Springer, 1997.
Rapp, R.H.: Comparison of altimeter-derived and shipgravity anomalies in the vicinity of the gulf of California. Marine Geodesy, 21(4), 245-260, 1998.
Reinhart, E., B. Richter, H. Wilmes, E. Erker, D. Ruess, J. Kakkuri, J. Makinen, I. Marson, J. Sledzinski: UNIGRACE - A project for the unification of gravity systems in central Europe. Finnish Geodetic Institute Report 98:4, pp. 95-98. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Rentsch, M., M. Anzenhofer, Th. Gruber, K.-H. Neumayer: Maps of altimetric gravity based on ERS-1 geodetic phase data. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 408-414, Springer, 1997.
Ritter, S.: The nullfield method for the ellipsoidal Stokes problem. Journal of Geodesy, 72(2), 101-106, 1998.
Rozsa, Sz.: Determination of terrain correction in Hungary and the surrounding area. Finnish Geodetic Institute Report 98:4, pp. 185-189. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Romaides, A.J., R.W. Sands: Elevation determination using GPS and GEOID93: Getting the topography out of gravimetry. IGeS Bulletin no 5, pp. 88-106, 1996.
Rodriguez, G., M.J. Sevilla: Geoid model in the western Mediterranean Sea. Proceed. XXIV EGS Gen. Assembly, The Hague, 19-23 April, 1999, in print.
Rummel, R., M. van Gelderen: Meissl scheme-spectral characteristics of physical geodesy. Manuscripta Geodaetica, 20(5), 379-385, 1995.
Rummel, R.: Spherical spectral properties of the earth's gravitational potential and its first and second derivatives. In F. Sanso and R. Rummel (Eds.), Geodetic boundary value problems in view of the one centimeter geoid., Lecture Notes, pp 359-401, Springer, 1997.
Sandwell, D.T., W.H.F. Smith: Marine gravity anomaly from Geosat and ERS-1 satellite altimetry. JGR, 102(B5), 10039-10054, 1997.
Sanso, F., G. Sona: The theory of optimal linear estimation for continuous fields of measurements. Manuscripta Geodaetica, 20(3), 204-230, 1995.
Sanso, F., C. Sciarretta, F. Vespe. New IGeS formulas for the terrain corrections. IGeS Bulletin no 7, pp. 68-83, 1995.
Sanso, F.: The long road from measurements to boundary value problems in physical geodesy. Manuscripta Geodaetica, 20(5), 326-344, 1995.
Sanso, F. and M.G. Sideris: On the similarities and differences between system theory and least-squares collocation in physical geodesy. Bollettino di Geodesia e Scienze Affini, 2, 174-206, 1997.
Santis, A. de , J. M. Torta: Spherical cap harmonic analysis of local gravity field. Finnish Geodetic Institute Report 96:2, pp. 67-70. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Schrama, E.J.O.: Satellite altimetry, ocean dynamics and the marine geoid. In F. Sanso and R. Rummel (eds.), Geodetic boundary value problems in view of the one centimeter geoid., Lecture Notes, pp. 405-452, Springer, 1997.
Schwarz, K.-P., Z. Li: An introduction to airborne gravimetry and its boundary value problems. In F. Sanso and R. Rummel (Eds.), Geodetic boundary value problems in view of the one centimeter geoid. Lecture Notes, pp. 312-355, Springer, 1997.
Seeber, G., W. Torge: Eine GPS/Geoid-Hoehenuebertragung zum Meerespegel in Helgoland. Z. F. Verm.wesen, 122, 445-457, 1997.
Seeber, G., W. Torge, H. Denker, H.-J. Goldan: Praezise Hoehenbestimmung des Helgolaender Pegels. Die Kueste, 59/97, 39-61, 1997.
Sevilla, M.: A new gravimetric geoid in the Iberian Peninsula. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 163-180, 1995.
Sevilla, M.J.: A high-resolution gravimetric geoid in the Strait of Gibraltar. Journal of Geodesy, 71(7), 402-410, 1997.
Shaofeng, B., W. Xiaoping: An improved prism integration for gravimetric terrain correction. Manuscripta Geodaetica, 20(6), 515-518, 1995.
Sharni, D., H. Papo, Y. Forrai: The geoid in Israel: Haifa pilot. Finnish Geodetic Institute Report 98:4, pp. 263-270. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Sideris, M.G.: FFT geoid computations in Canada. IAG, Bulletin d' Information no 77, IGeS Bulletin no 4, pp. 37-52, 1995.
Sideris, M.G.: Fourier geoid determination with irregular data. Journal of Geodesy, 70(1-2), 2-12, 1995.
Sideris, M.G.: On the use of heterogeneous noisy data in spectral gravity field modelling methods. Journal of Geodesy, 70(8), 470-479, 1995.

Sideris, M.G., B.B. She: A new, high-resolution geoid for Canada and part of the U.S. by the 1D-FFT method. Bull. Geod., 69(2), 92-108, 1995.
Sjoberg, L. E.: The atmospheric geoid and gravity corrections. Finnish Geodetic Institute Report 98:4, pp. 161-167. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Sjoberg, L.E., H. Nahavandchi: On the indirect effect in the Stokes-Helmert method of geoid determination. Journal of Geodesy, 73(1), 87-93, 1999.
Sjoberg, L.E.: On the quasigeoid to geoid separation. Manuscripta Geodaetica, 20(3), 182-192, 1995.
Sjoberg, L.E.: The exterior Airy/Heiskanen topographic-isostatic gravity potential anomaly and the effect of analytical continuation in Stokes' formula. Journal of Geodesy, 72(11), 654-662, 1998.
Smith, D.A., D.G. Milbert: Evaluation of preliminary models of the geopotential in the united states (Addendum: Evaluation of EGM96 model of the geopotential in the United States). IGeS Bulletin no 6, pp. 7-46, 1997.
Smith, D.A., H.J. Small: The CARIB97 high-resolution geoid height model for the Caribbean Sea. Journal of geodesy, 73(1), 1-9, 1999.
Sneeuw, N., R. Sun: Global spherical harmonic computation by two-dimensional Fourier methods. Journal of Geodesy, 70(4), 224-232, 1995.
Stewart, M.P., W.E. Featherstone, J.F. Kirby, M. Dumville: Comparison of Geosat and gravimetric geoid profiles in the North Sea. Marine Geodesy, 21(4), 319-330, 1998.
Strykowski, G., O. C. Dahl: The geoid as an equipotential surface in a sense of Newton's integral - ideas and examples. Finnish Geodetic Institute Report 98:4, pp. 113-116. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Strykowski, G., R. Forsberg: Operational merging of satellite, airborne and surface gravity data by draping techniques. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 243-248, Springer, 1998.
Strykowski, G.: Geoid and mass density-why and how? In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 237-242, Springer, 1998.
Strykowski, G.: Borehole data and stochastic gravimetric inversion. Dissertation, Kort & Matrikelstyrelsen, Denmark, 1996.
Sun, W., L. E. Sjoberg: A new global topographic-isostatic model. Phys. Chem. Earth (A), 24(1), 27-32, 1999.
Sun, W., L. E. Sjoberg: Gravitational potential changes of a spherically symmetric earth model caused by a surface load. Phys. Chem. Earth, 23(1), 47-52, 1998.
Sun, W., P. Vanicek: On the discrete problem on downward continuation of Helmert's gravity. Finnish Geodetic Institute Report 96:2, pp. 29-34. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Sun, W., P. Vanicek: On some problems of the downward continuation of the 5'x5' mean Helmert gravity anomalies. Journal of Geodesy, 72(7-8), 411-420, 1998.
S_nkel, H.: GBVP-Classical solutions and implementation. In F. Sanso and R. Rummel (eds.), Geodetic boundary value problems in view of the one centimeter geoid. Lecture Notes, pp. 219-237, Springer, 1997.
Thong, N.C.: Explicit expression and regularization of the harmonic reproducing kernels for the earth's ellipsoid. Journal of Geodesy, 70(9), 553-538, 1995.
Torge, W., H. Denker: The European Geoid-Development over more than 100 years and present status. Finish Geodetic Institute Report 98:4, pp. 47-52. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Toth, J.: Topographic-isostatic models fitted to the geopotential. Finnish Geodetic Institute Report 98:4, pp. 117-123. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Toth, J., J. Adam, Sz. Rozsa, I.N. Tziavos and V. Andritsanos: Gravimetric geoid computations in Hungary and the surrounding area. Paper presented at the 2nd joint meeting of the Int. Gravity Commission (IGC) and the Int. Geoid Commission (IGeC), Trieste, Sept. 7-12, 1998.

Tscherning, C.C., F. Rubek, R. Forsberg: Combining airborne and ground gravity using collocation. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 18-23, Springer, 1998.

Tsuei, G.-C., D. Arabelos, I.N. Tziavos: Recent geoid computations in Taiwan. Geomatrics Research Australasia, 65, 43-58, 1996.

Tsoulis, D.V.: A combination method for computing terrain corrections. Phys. Chem. Earth, 23(1), 53-58, 1998.

Tsoulis, D.V.: Analytical and numerical methods in gravity field modelling of ideal and real masses. Dissertation, in print, 124 pp., Munich, 1999.

Tziavos, I. N., M. G. Sideris, H. Sunkel: The effect of surface density variations on terrain modelling- A case study in Austria. Finnish Geodetic Institute Report 96:2, pp. 99-110. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996a.

Tziavos, I. N., M. G. Sideris, J. Li: Optimal spectral combination of satellite altimetry and marine gravity data. Finnish Geodetic Institute Report 96:2, pp. 41-56. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996b.

Tziavos, I. N., V. D. Andritsanos: improvements in the computation of deflections of the vertical by FFT. Phys. Chem. Earth, 23(1), 71-76, 1998.

Tziavos, I. N., V. D. Andritsanos: Recent advances in terrain correction computations. Finnish Geodetic Institute Report 98:4, pp. 169-175. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.

Tziavos, I. N., V. D. Andritsanos: Recent geoid computations for the Hellenic area. Phys. Chem. Earth (A), 24(1), 91-95, 1999.

Tziavos, I.N., Jinwen Li, M.G. Sideris: A comparison of marine gravity field modelling methods using non-isotropic information. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 400-407, Springer, 1997.

Tziavos, I.N., J. Adam, Gy. Toth, V. D. Andritsanos, Sz. Rozsa: Recent geoid computations in Hungary and the surrounding area. Finish Geodetic Institute Report 98:4, pp. 257-262. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998a.

Tziavos, I.N., M.G. Sideris and R. Forsberg: Combined satellite altimetry and shipborne gravimetry data processing. Marine Geodesy, 21, 299-317, 1998b.

Tziavos, I.N., R. Forsberg, M.G. Sideris: Marine gravity field modelling using shipborne gravity and geodetic mission altimetry data. Geomatrics Research Australasia, 69, 1-18, 1998c.

Tziavos, I.N., R. Forsberg, M.G. Sideris: Marine gravity field recovery by combining satellite altimetry and shipborne gravimetry. Paper presented at the 2nd joint meeting of the Int. Gravity Commission (IGC) and the Int. Geoid Commission (IGeC), Trieste, Sept. 7-12, 1998d.

Tziavos, I.N., R. Forsberg, M.G. Sideris, V.D. Andritsanos: A comparison of satellite altimetry methods for the recovery of gravity field quantities. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 150-155, Springer, 1998e.

Tziavos, I.N.: Comparisons of spectral techniques for geoid computations over large regions. Journal of Geodesy, 70(6), 357-373, 1995.
Tziavos, I.N.: Evaluation of the new GSFC/DMA geopotential models in the Hellenic area and the Mediterranean Sea. IGeS Bulletin no 6, pp. 151-164, 1997.
Yu, Z.C.: A universal formula of maximum likelihood estimation of variance-covariance components. Journal of Geodesy, 70(4), 233-240, 1995.
Vajda, P., P. Vanicek: Truncated geoid and gravity inversion for one point-mass anomaly. Journal of Geodesy, 73(2), 58-66, 1999.
Vanicek, P., M. Najafi, Z. Martinec, L. Harrie, L.E. Sjoberg: Higher-degree reference field in the generalised Stokes-Helmert scheme for geoid computation. Journal of Geodesy, 70(3), 176-182, 1995.
Vanicek, P., W.E. Featherstone: Performance of three types of Stokes's kernel in the combined solution for the geoid. Journal of Geodesy, 72(12), 684-697, 1998.
Vanicek, P., W. Sun, P. Ong, Z. Martinec, M. Najafi, P. Vajda, B. Ter Horst: Downward continuation of Helmert's gravity. Journal of Geodesy, 71(1), 21-34 , 1996.
Varga, P.: Temporal variation of second degree geopotential. Finnish Geodetic Institute Report 98:4, pp. 125-128. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Verhoef, H. M. E., H. M. de Heus: Subsidence analysis from integrated GPS- and precise levelling data. Finnish Geodetic Institute Report 96:2, pp. 129-136. Proceedings, Session G7, EGS XXI Gen. Assembly, The Hague, The Netherlands, 6-10 May, 1996.
Vermeer, M.: Mass point geopotential modelling using fast spectral techniques; historical overview, toolbox description, numerical experiment. Manuscripta Geodaetica, 20(5), 362-378, 1995.
Vermeer, M.: Regularization constraints in mass point grids and their relation to gravity field stochastics. Phys. Chem. Earth, 23(1), 13-18, 1998.
Vermeer, M.: The geoid as a product. Finnish Geodetic Institute Report 98:4, pp. 63-69. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Veronneau, M.: The GSD95 geoid model for Canada. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 573-580, Springer, 1997a.
Veronneau, M.: Evaluation of NASA/NIMA earth geopotential model (EGM96) over Canada. IGeS Bulletin no 6, pp. 47-70, 1997b.
Volgyesi, L.: Geoid computations based on torsion balance measurements. Finnish Geodetic Institute Report 98:4, pp. 145-151. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Wang Y.M.: On the error of analytical downward continuation of the earth's external gravitational potential on and inside the earth's surface. Journal of Geodesy, 71(2), 70-82, 1997.
Wang, Y.M.: On the ellipsoidal corrections to gravity anomalies computed using the inverse Stokes integral. Journal of Geodesy, 73(1), 29-34, 1999.
Wenzel, G.: Ultra high degree geopotential model GPM3E97A to degree 1800 tailored to Europe. Finnish Geodetic Institute Report 98:4, pp. 71-80. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Wildermann E., M. Hoyer, G. Acuna: Towards a regional geoid determination in western Venezuela. In R. Forsberg et al. (eds.), Geodesy on the Move. IAG Symp. Proceed. vol. 119, pp. 300-305, Springer, 1998.

Zhang, C.: A general formula and its inverse formula for gravimetric transformations by use of convolution and deconvolution techniques, Journal of Geodesy, 70(1-2), 51-64, 1995.
Zhang, C.: Estimation of dynamic ocean topography in the Gulf Stream area using Hotine formula and altimetry data. Journal of Geodesy, 72(9), 499-510, 1998.
Zhang, C., J.A.R. Blais: Comparison of methods for marine gravity determination from satellite altimetry data in Labrador Sea. Bull. Geod., 69(3), 173-180, 1995.
Zhang, K, W. Featherstone, M. Stewart, A. Dodson: A new gravimetric geoid of Australia. Finnish Geodetic Institute Report 98:4, pp. 225-233. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Zhang, K., S. Bian, W. Shen: The singular integration of physical geodesy in the frequency domain. Manuscripta Geodaetica, 20(4), 241-247, 1995.
Zhang, K.: Altimetric gravity anomalies, their assessment and combination with local gravity field. Finnish Geodetic Institute Report 98:4, pp. 137-144. Proceedings of the 2nd Continental Workshop on the Geoid in Europe, Budapest, March 10-14, 1998.
Zhang, K.: On the determination of new Australian Geoid. Phys. Chem. Earth (A), 24(1), 61-66, 1999.
Zhang, K.F., W.E. Featherstone: A preliminary evaluation of the terrain effects of gravimetric geoid determination in Australia. In J. Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy IAG Symp. Proceed. vol. 117, pp. 565-572, Springer, 1997.
Zhong, D.: Robust estimation and optimal selection of polynomial parameters for the interpolation of GPS geoid heights. Journal of Geodesy, 71(9), 552-561, 1997.

REPORT OF IAG SPECIAL STUDY GROUP 3.177 SYNTHETIC MODELLING OF THE EARTH'S GRAVITY FIELD (1996-1999)

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INTRODUCTION

In April 1996, the Executive Committee of IAG Section III (Determination of the Gravity Field) endorsed the out-of-cycle creation of SSG 3.177 "Synthetic Modelling of the Earth's Gravity Field". This can be interpreted as a logical continuation and extension of the work undertaken by Sub-Commission 2 (Numerical Approximation and Methods) of IAG Section IV (General Theory and Methodology), which is summarised by Klees (1995) and Vermeer (1995). The primary objective of IAG SSG 3.177 is to develop the theoretical basis and computational methods necessary to construct a synthetic model of the Earth's gravity field for use in geodesy.

At present, gravity field researchers often rely on empirical error estimates to validate their results, which are generally based on observed data. A classical example can be seen in gravimetric geoid determination, where the computed models are often compared with GPS and geodetic levelling data that have their own error budgets. In addition, these data types have different physical and geometrical interpretations. The availability of a synthetic gravity field model would avoid this somewhat undesirable scenario and give a more independent validation of the procedures presently used. However, a synthetic gravity field model is not widely available to the geodetic research community, which is at odds with other areas of the geosciences. The most notable example of this is the Preliminary Reference Earth Model or PREM (Dziewonski & Anderson 1981), which has made tremendous contributions to seismology. An additional rationale for the activities of SSG 3.177 can be found in the preface of Moritz (1990), who argues that the emphasis of physical geodesy should change from the treatment of only the external gravity field to that of both the internal and external gravity field. Since the Earth's internal structure generates the (interior and exterior) gravity field, this should be considered in gravity field modelling.

This report gives the Chair's perspective of the work undertaken by SSG 3.177 since its creation and the future problems to be addressed, assuming that the tenure of the group will be extended for a further four years. It is important to acknowledge that, due to time constraints, not all members' activities have been included in this report; for this I apologise. It is expected that the final outcome of SSG 3.177 will be the theories, methodologies/software and a synthetic model, which will probably be distributed via the International Geoid Service (IGeS) and the Bureau Gravimetrique International (BGI). It is anticipated that the synthetic model will allow for an objective test of the various theories and methodologies in use and may contribute to the resolution of some of the procedural differences currently encountered between gravity field researchers around the world.

SOME PREVIOUS WORK (pre-1996)

An elementary synthetic model of the Earth's gravity field is generated by the normal ellipsoid (Moritz 1968a,b) which is often (incorrectly) assumed to be error-free. However, as can be concluded from the magnitude of gravity anomalies and geoid undulations, this model is far too simplistic. Moreover, it does not allow for the testing of modern gravity field determination techniques. Refined models of the global gravity field, usually based on spherical harmonics, have been developed with increasing degree and now reach degree 1800 (eg. Wenzel 1998). However, neither are these spherical harmonic models error-free, because of the quality and treatment of the observed data used in their construction. Accordingly, a synthetic gravity field model is also desired to calibrate and test the construction of these models. Nevertheless, spherical harmonic models can be assumed to generate an error-free synthetic gravity field and therefore used to test, for example, residual geoid determination techniques (Tziavos, 1996), which will be discussed later.

In addition to the normal ellipsoid and spherical harmonic models, the external gravity fields generated by point-mass models have been used for a number of years. Vermeer (1995) gives a useful review of these approaches. Essentially, point masses of various magnitudes are placed at points inside the Earth, such that the superposition of their gravitational acceleration and potential (computed using Newton's integrals) replicate the external gravity field (eg. Vermeer 1982, Barthelmes *et al*. 1991, Vermeer 1992, Lehmann 1993a, Sünkel 1982). Point-mass models have also been used to generate gravity gradients (Vermeer 1989a,b, Balmino *et al*. 1991, Vermeer 1994) and gravity disturbances (Zhang & Blais 1993). Logically, the use of point-mass models has been extended to the use of digital density models (eg Heikkinen 1981, Martinec & Pec 1987, Marussi 1980, Moritz 1989, Tscherning & Sünkel 1981) to better replicate the continuous nature of Earth's density distribution.

Similar to point-mass and digital density modelling is forward modelling, which involves the generation of a synthetic gravity field from geophysical structures that are chosen to be as realistic as possible. Analytic solutions for simple figures, such as cylinders or prisms, are available in many of the geophysical or potential theory textbooks (eg. Blakely 1995). However, in order to achieve these analytic solutions, the models used are very restrictive because they almost always rely on simple geometric figures of constant density (cf. Tscherning 1981). Arguably more sophisticated alternatives use topographic-isostatic models of the Earth (eg. Sünkel 1985, 1986, Grafarend & Engels 1993, Martinec 1993, 1994a,b, Grafarend *et al*. 1995, 1996).

WORK OF THE SSG (1996-1999)

It is important to state that this section summarises only **some** of the work undertaken by a few of the members of SSG 3.177; apologies are extended to those whose results have been omitted.

Members
Georges Balmino (BGI, France), Will Featherstone (Australia), Yoichi Fukada (Japan), Erik Grafarend (Germany), Chris Jekeli (USA), Ruediger Lehman (Germany), Zdenek Martinec (Czech Republic), Yuri Neyman (Russia), Edward Osada (Poland), Gabor Papp (Hungary), Doug Robertson (USA), Walter Schuh (Austria), Michael Sideris (Canada),

Gabriel Strykowski (Denmark), Gyula Toth (Hungary), Ilias Tziavos (Greece), Petr Vanicek (Canada), Peter Vajda (Slovak Republic), Giovanna Venuti (IGeS, Italy), Martin Vermeer (Finland)

Corresponding Members

Fabio Boschetti (Australia), Hans Engels (Germany), Heiner Denker (Germany), Rene Forsberg (Denmark), Simon Holmes (Australia), Jonathan Evans (UK), Adam Dziewonski (USA), Marcel Mojzes (Slovak Republic), Spiros Pagiatakis (Canada), Roland Pail (Austria), Dru Smith (USA), Hans Sünkel (Austria)

Synthetic Gravity Fields Based on Spherical Harmonics

As an extension of the work of Tziavos (1996), a high-degree spherical harmonic model can be used to construct a synthetic gravity field. Assuming harmonicity, this can be used to investigate some of the errors associated with gravity field modelling. Members, and some non-members, of SSG 3.177 have constructed two such models as follows.

Curtin/UNB models

An Australian Research Council-funded project between Curtin University of Technology (Australia) and The University of New Brunswick (Canada) has led to a synthetic spherical harmonic model, which extends to degree 5400. This high degree has been achieved by artificially scaling the coefficients and fully normalised associated Legendre functions to avoid numerical instabilities in the latter. The higher degree terms have been constructed by scaling and recycling the EGM96 coefficients. The degree-variance of this synthetic model has been constrained to follow that of the degree 1800 model of Wenzel (1998) and the Tscherning-Rapp model beyond 1800.

This synthetic field has been used to construct self-consistent and assumed error-free geoid heights and gravity anomalies at the geoid. These have been used to investigate the performance of modified kernels in regional gravimetric geoid determination. Table 1 summarises the results of preliminary studies in western Canada (Novak *et al*., 1999) and Western Australia (Featherstone, 1999) and indicates that modified kernels offer a slightly more preferable approach.

area	*kernel*	*max.*	*min.*	*mean*	*std.*
western Canada	unmodified	0.058	-0.041	0.008	0.011
	modified	0.035	-0.035	0.000	0.008
Western Australia	unmodified	0.033	-0.026	0.003	0.009
	modified	0.026	-0.017	0.003	0.008

Table 1. Statistics of the differences between the synthetic geoid heights and geoid heights computed using unmodified and modified kernels (units in metres).

European Space Agency/GOCE models

As part of a collaborative project "Refinement of Observation requirements for GOCE" for the European Space Agency (ESA), a consortium of investigators has also generated a synthetic gravity field model based on spherical harmonics. This model extends to degree

1800 through the use of the coefficients and numerical algorithms of Wenzel (1998). A FORTRAN program `harmexg.f` is available at http://www.gfy.ku.dk/~cct/goce-study.htm. and can be used to generate point and grid values of the gravity field.

This synthetic gravity field is consistent with *a-priori* statistical information using a simple random-number generator. The values of the spherical harmonic coefficients, or perturbations of these, are calculated corresponding to a normal distribution with a given variance and zero mean. Global gravity fields can be generated from the existing GPM98 coefficients (Wenzel, 1998) using the degree-variances as variances in the distribution, or for the GOCE study, the error-degree-variances are used to generate perturbed fields. Local gravity field models are also generated using the global coefficients, where the variances are scaled by the ratio between the local and the global variance. Some problems were encountered when using the error estimates of existing spherical harmonic models, because the coefficient errors do not depend on the local gravity field variation. Therefore, the synthetic model is now being designed to use error models that take into account the variability of the gravity field, the terrain and the spatial availability of these data.

Point Mass Modelling

Point-mass models (eg. Lehmann 1993, Vermeer 1995) continue to be used as a useful means of determining the external gravity field. These have been used in the determination of the geoid (eg. Ihde *et al*., 1998). Through the numerical or analytic integration of Newton’s integrals, self-consistent values of the gravitational potential and acceleration can be generated. However, it can be argued that these approaches become limited when one attempts to generate gravity field quantities inside the Earth, because the gravity field is not harmonic in this region. Nevertheless, these models will probably continue to attract attention because of their ease of use and conceptual simplicity.

Vajda and Vanicek (1997, 1998a, 1999a) seek point masses that are neither fixed or free, which is an alternative to the two existing approaches. Their strategy is as follows:

1. Compute the sequence of surfaces of the truncated geoid with systematically decreasing values of the truncation parameter (the TG sequence) and the sequence of surfaces of the first derivative of the TG sequence, with respect to the truncation parameter, with systematically increasing values of the truncation parameter (the DTG sequence) from a geopotential model on or above the boundary.
2. Construct a set of mass points: At the smallest numerically achievable value of the TG sequence, the positions of the maxima and minima of the truncated geoid are assigned as the horizontal positions of the sought mass points.
3. The sought set of mass points is completed by finding their depths. In the DTG sequence, dimple events are observed and the depths of the sought point masses are determined from the instants of the dimple onsets.
4. From this, a preliminary set of point masses is formed, with the number of point masses being equal to the number of horizontal positions determined in step 2. If the number of clearly observed dimple onsets is less than the number of highs and lows from step 2, the depth of the remaining point masses (those in horizontal positions from step 2 that do not display a clear dimple onset in step 3) may be estimated or assumed. Another option is to reject the remaining point masses and exclude them from the preliminary set of point masses.

The Reference Earth Model (REM)

Following the success of PREM (Dziewonski & Anderson 1981), a new project is being led by the seismological community (http://www.mahi.ucsd.edu/Gabi/rem.html) to generate an extension called REM. The primary aim of this project is to construct a reference model of the Earth that fits a greater variety of geophysical constraints than PREM, which only considered the seismic properties of the Earth. Of importance to SSG 3.177, the instigators of REM seek the input of other earth scientists, and one of the stated objectives of REM is a model that will generate gravity and geoid values. Accordingly, the two groups' activities are complementary and formal links were established in 1997.

At this stage of SSG 3.177, possibly the most useful aspect of the REM project is through the links to other geoscientists and recent global datasets that can be used in the construction of a synthetic gravity field. These are given at the REM web-site, with the most notable being a global topographic/bathymetric model and a global model of the crust (Mooney *et al*. 1998). Complementary data that are not linked to the REM web-site include the compensation depth of topographic masses (eg. Sünkel 1985, 1986, Grafarend & Engels 1993, Martinec 1993, 1994a,b, Grafarend *et al*. 1995, 1996) and the position of the Mohorovicic discontinuity (Martinec 1994b). However, it should be bourn in mind that the boundaries of different physical properties inside the Earth do not necessarily coincide, so the construction of the synthetic field does not have to be rigidly constrained to all these boundaries.

Forward Modelling Using *a-priori* Geophysical Data

As part of the aim to make the synthetic gravity model as realistic as possible, complementary geophysical data can be used to place constraints on the density distribution in a forward modelling process (eg. Strykowski 1996, 1997a,b 1998a,b, 1999a,b, Toth 1996, 1998, Papp 1996b, Tziavos *et al*. 1996; Kakkuri & Wang, 1998; Wang, 1998). A study by Papp *et al*. (http://www.ggki.hu/a/gravity/geoid1.html) concentrates on the determination and evaluation of the lithospheric geoid in the Pannonian Basin, Hungary. This used geological and geophysical data concerning the structure of the lithosphere in the region, which were used to construct a volume element model of the crustal structure and density distribution. This was supplemented by a simple model of the lower crust derived from deep seismic sounding data and gravity inversion. The resulting geoid undulations were compared to an existing gravimetric quasi-geoid solution. Preliminary results showed agreements of ±0.22m. By fine-tuning the method and completing the geophysical model with the surface topography, the agreement was improved to ±0.10m. The latest version of the model of the lithosphere consists of 180,000 rectangular prisms of differing dimensions. It extends from the eastern Carpathians to the eastern Alps and from the western Carpathians to the Dinarides.

Pail (1999) has constructed a global synthetic gravity field from a spherical body with a realistic three-dimensional density structure. This synthetic body consists of PREM as a radial background model, superposed by a mantle density distribution based on seismic tomography data and an isostatically compensated (local Airy/Heiskanen and Vening-Meinesz smoothing) crustal layer. A topography function of arbitrary roughness is generated by means of a fractal approach. This structure has been to generate synthetic test fields predominantly for global applications. As an example, a satellite gravity gradiometry mission is simulated in order to compare 'inner' (statistical) and 'outer' (absolute) error estimates and the influence of a variety of orbit configurations, noisy and band-limited observations and inhomogeneous data coverage on harmonic coefficient recovery. An abstract and overview are given at: http://www.cis.tu-graz.ac.at/mggi/pail_diss.html.

SUGGESTED FUTURE WORK (1999-onwards)

In order not be too prescriptive over the future activities of SSG 3.177, the following are **suggested** directions to the Group. Firstly, it is important to recognise that different authors are investigating different, yet complementary, approaches to the construction of the synthetic gravity field. This in itself is essential so that there is cross fertilisation of ideas and, moreover, tests on the synthetic field(s) that may eventually be used as control. With all this in mind, the following are offered as a list of functions that a complete synthetic gravity field model could have to make it as realistic as possible and, more importantly, useable to a wide range of ‘customers’.

Input

Assuming that the synthetic gravity field model will be constructed from geophysical forward modelling, the following should be considered:

- Realistic models of the Earth’s topography by the densest available digital elevation models, which can be artificially extended to higher resolutions, perhaps by fractals.
- Realistic models of the bulk density distribution within the deep earth, crust and mantle, possibly from *a-priori* geophysical models from other disciplines.
- Realistic models of the modes and depths of isostatic compensation and other boundaries that are characterised by bulk density changes.
- Realistic models of noise and systematic errors (correlated and un-correlated), which can be varied by the user for sensitivity analyses.

Most importantly, the model should rely on as few assumptions as possible so that it can be used to test the assumptions currently in use. In addition, the use of realistic and accepted models of the Earth should guarantee that the results from the synthetic field can be applied to the real Earth.

Ouput

It is envisaged that the synthetic gravity field should at least offer the following features:

- Generation of the synthetic gravity field in different formats; these being point, grid or mean values of geoid, gravity anomalies, gravity gradients and vertical deflections.
- A spherical harmonic series expansion with various spectral error characteristics.
- Generation of point, grid and mean gravity data with various error characteristics.
- Generation of gravity data above and within the Earth’s physical surfaces.

Ideally, the model will generate gravity to <1microGal and the geoid to <1mm at all frequencies, though this aim may prove to be over optimistic; but let’s try!

REFERENCES AND BIBLIOGRAPHY

Ballani L, Engelis J, Grafarend, EW (1993) Global base functions for the mass density in the interior of a massive body (Earth), manuscripta geodaetica, 18: 99-114.

Balmino G, Barriot J, Koop R, Middel B, Thong N, Vermeer M (1991) Simulation of gravity gradients: a comparison study, Bulletin Géodésique, 65: 218-229.
Barthelmes F (1986) Untersuchungen zur Approximation des ausseren Gravitationsfeldes der Erde durch Punktmassen mit optimierten Positionen. Veroff. d. Zentr. Inst. f. Phys. d Erde, Nr. 92, Potsdam, Germany.
Barthelmes F, Dietrich R, Lehmann R (1991) Use of point masses on optimised positions for the approximation of the gravity field, in: Rapp RH, Sanso F (eds) Determination of the Geoid, Springer, Berlin, 484-493.
Blakely RJ (1995) Potential Theory in Gravity and Magnetic Applications, Cambridge University Press.
Bullen KE (1975) The Earth's Density, Chapman-Hall.
Crank J (1984) Free and moving boundary problems, Oxford University Press.
Dampney CNG (1969) The equivalent source technique, Geophysics, 34: 39-53.
Dziewonski AM, Anderson DL (1981) Preliminary reference Earth model. Physics of the Earth Planetary Interiors, 25: 297-356.
Engels J (1991) Eine approximative Loesung der fixen geodaetischen Randwert-aufgabe im Innen- und Aussenraum der Erde. Deutsche Geodaetische Kommission Reihe C Nr. 379, Bayerische Akademie der Wissenschaften, Germany.
Engels J, Grafarend E, Keller W, Martinec Z, Sanso F, Vanicek P (1993) The geoid as an inverse problem to be regularised. in: Inverse Problems: Principles and Applications to Geophysics, Technology and Medicine, Anger et al., (eds), Akademie Verlag, Berlin, 122-167.
Featherstone WE, Olliver JG (1997) A method to validate gravimetric geoid computation software based on Stokes's integral, Journal of Geodesy, 72(3): 154-160.
Featherstone WE (1999) Tests of two forms of Stokes's integral using a synthetic gravity field based on spherical harmonics, in: Festschrift Erik Grafarend, University of Stuttgart, Germany.
Feistritzer M (1998) Geoidbestimmung mit geopotentiellen Koten. Deutsche Geodaetische Kommission Reihe C Nr. 486, Bayerische Akademie der Wissenschaften, Germany.
Grafarend E, Engels J (1993) The gravitational field of topographic-isostatic masses and the hypothesis of mass condensation, Surveys in Geophysics, 14: 495-524.
Grafarend EW, Keller W (1995) Setup of observational functionals in gravity space as well as in geometry space, manuscripta geodaetica, 20: 301-325
Grafarend E, Engels J, Sorcik P (1995) The gravitational field of topographic-isostatic masses and the hypothesis of mass condensation - part I and II. Technical Report 1995.1 Schriftenreihe der Institut des Fachbereichs Vermessungswesen, Department of Geodesy, Stuttgart, Germany.
Grafarend E, Engels J, Sorcik P (1996) The gravitational field of topographic-isostatic masses and the hypothesis of mass condensation II - the topographic-isostatic geoid, Surveys in Geophysics, 17: 41-66.
Grafarend E, Engels J, Varga P (1997) The spacetime gravitational field of a deformable body, Journal of Geodesy, 72(1): 11-30.
Heikkinen M (1981) Solving the shape of the Earth by using digital density models, Report 81, Finnish Geodetic Institute, Masala, Finland.
Holota P (1995) Two branches of the Newton potential and geoid, In: Sünkel H, Marson I (eds) Gravity and Geoid, Springer, Berlin, 92-101.
Ihde J, Schirmer U, Stefani F, Toeppe F (1998) Geoid modelling with point masses, Proc Second Continental Workshop on the Geoid in Europe, Budapest, 199-204.

Jordan SK (1978) Statistical model for gravity, topography, and density contrasts in the Earth, Journal of Geophysical Research, 83(B4): 1816-1824.
Kakkuri J, Wang Z (1998) Structural effects of the crust on the geoid modelled using deep seismic sounding interpretation. Geophysical Journal International 135: 495-504.
Katsambolos, KE (1981) Simulation studies on the computation of the gravity vector in space from surface data considering the topography of the Earth, Report 314, Department of Geodetic Science and Surveying, Ohio State University, Columbus.
Keller W (1998) On a scalar fixed gravimetry-altimetry boundary value problem, Journal of Geodesy, 70(8): 459-469.
Klees R (1995) Report SC2-project: comparison of several techniques for solving geodetic boundary value problems by means of numerical experiments in Willis p (ed) Travaux de l'association internationale de geodesie, paris.
Lambeck K (1988) Geophysical Geodesy, Oxford University Press, Oxford, 718p
Lehmann R (1993a) The method of free-positioned point masses - geoid studies on the Gulf of Bothnia, Bulletin Geodesique, 67: 31-40.
Lehmann R (1993b) Nonlinear gravity field inversion using point masses – diagnosing non-linearity, in: Montag H, Reigber C (eds) Geodesy and Physics of the Earth, Springer, Berlin, 256-260.
Lehmann R (1996) Information measures for global geopotential models, Journal of Geodesy, 70: 342-348.
Martinec Z, Pec K (1987) Three-dimensional density distribution generating the observed gravity field of planets – Part 1, The Earth, Proc Figure of the Earth Moon and other planets, Research Institute of Geodesy, Prague.
Martinec Z (1993) A model of compensation of topographic masses, Surveys in Geophysics, 14: 525-535.
Martinec Z (1994a) The minimum depth of compensation of topographic masses, Geophysical Journal International, 117: 545-554.
Martinec Z (1994b) The density contrast at the Mohorovicic discontinuity, Geophysical Journal International, 117: 539-544.
Marussi A (1980) On the density distribution in bodies of assigned outer Newtonian attraction, Bolletino di Geofisica Teorica ed Applicata, XXII(86): 83-94.
Mooney WD, Laske G, Masters G (1998) CRUST 5.1: A global crustal model at 5°x5°, Journal of Geophysical Research, 103: 727-747.
Moritz H (1968a) Density distributions for the equipotential ellipsoid, Report 115, Department of Geodetic Science and Surveying, Ohio State University, Columbus.
Moritz H (1968b) Mass distributions for the equipotential ellipsoid, Bolletino di Geofisica Teorica ed Applicata, 10: 59-65.
Moritz H (1989) A set of continuous density distributions within a sphere compatible with a given external gravitational potential, Gerlands Beitr. Geophysik, 98: 185-192.
Moritz H (1990) The Figure of the Earth: Theoretical Geodesy of the Earth's Interior, Wichman.
Novak P, Vanicek P, Veronneau M, Holmes S, Featherstone WE (1999) On the accuracy of Stokes's integration in the precise high-frequency geoid determination, poster presented to the AGU spring meeting, Boston, USA, June.
Okubo S (1991) Potential and gravity changes raised by point dislocations, Geophysical Journal International, 105: 573-586.
Pail R. (1999): Synthetic Global Gravity Model for Planetary Bodies and Applications in Satellite Gravity Gradiometry, Ph.D. Thesis, Technical University of Graz, Austria.

Papp G, Wang, ZT (1996) Truncation effects in using spherical harmonic expansions for forward local gravity field modelling. Acta Geodaetica et Geophysica Hungarica, 31(1-2): 47-66.
Papp G (1996a) On the application of physical filtering in 3-D forward gravity modelling. Meurers, B. (ed.) Proceedings of the 7 th International Meeting on Alpine Gravimetry. In: Österreichische Beiträge zu Meteorologie und Geophysik, Heft 14: 145-154.
Papp G (1996b) Gravity field approximation based on volume element model of the density distribution. Acta Geod. Geoph. Hung., 31: 339-358.
Papp G, Kalmar, J (1996) Toward the physical interpretation of the geoid in the Pannonian Basin using 3-D model of the lithosphere. IGeS Bulletin 5: 63-87.
Robertson DS (1996) Treating absolute gravity data as a space-craft tracking problem. Metrologia, 33: 545-548
Sanso F, Barzaghi R, Tscherning CC (1986) Choice of norm for the density distribution of the Earth, Geophysical Journal of the Royal Astronomical Society, 87:123-141.
Sanso F, Rummel R (eds) (1997) Geodetic Boundary Value Problems in View of the One Centimeter Geoid, Springer-Verlag.
Strakov VN Schaefer U, Strakhov AV, Luchitsky AI, Teterin DE (1995) A new approach to approximate the Earth’s gravity field, in Sünkel H, Marson I (eds) Gravity and Geoid, Springer, Berlin, 225-237.
Strykowski G (1995) Geodetic and geophysical inverse gravimetric problem, the most adequate solution and the information content. In: Sünkel and Marson (eds) Gravity and Geoid, Springer, Berlin, 215-224.
Strykowski G (1996) Borehole data and stochastic gravimetric inversion. PhD-thesis, University of Copenhagen. Publ. 4 series, vol. 3, National Survey and Cadastre - Denmark, ISBN 87-7866-013-0.
Strykowski G (1997) Formulation of the mathematical frame of the joint inverse gravimetric-seismic modelling problem based on the analysis of regionally distributed borehole data, In: Segawa, Fujimoto and Okubo (eds) Gravity, Geoid and Marine Geodesy, Springer, Berlin, 360-367.
Strykowski G (1998a) Geoid and mass density - why and how? In: Forsberg, Feissl and Deitrich (eds) Geodesy on the Move, Springer, Berlin, 237-242.
Strykowski G (1998b) Experiences with a detailed estimation of the mass density contrasts and of the regional gravity field using geometrical information from seismograms, Proc. XXII General Assembly of the European Geophysical Society, Vienna, 1997, Phys. Chem. Earth, 23, 845-856.
Strykowski G, Dahl OC (1998c) The geoid as an equipotential surface in a sense of Newton's integral - ideas and examples, Proc. 2nd Continental Workshop on the Geoid in Europe, Budapest, Hungary, Report 98.4, Finnish Geodetic Institute, 113-116.
Strykowski G (1999a) Some technical details concerning a new method of gravimetric-seismic inversion, Proc. XXIII General Assembly of the European Geophysical Society, Nice, France, 1998, Phys. Chem. Earth, 24, 207-214.
Strykowski G (1999b) Silkeborg gravity high revisited: horizontal extension of the source and its uniqueness. Proc. XXIV General Assembly of the European Geophysical Society, The Hague, The Netherlands.
Sünkel H (1982) Point mass models and the anomalous gravitational field, Report 327, Department of Geodetic Science and Surveying, Ohio State University, Columbus.
Sünkel H (1985) An isostatic earth model, Report 367, Department of Geodetic Science and Surveying, Ohio State University, Columbus.

Sünkel H (1986) Global topographic-isostatic models, in Mathematical and Numerical Techniques in Physical Geodesy, Sunkel H (ed), Springer, Berlin, Germany: 417-462.
Toth G (1996) Topographic-isostatic models fitting to the global gravity field, Acta Geodaetica et Geophysica Hungarica, 31(3-4): 411-421.
Toth G (1998) Topographic isostatic models fitted to geopotential, Proc. 2nd Continental Workshop on the Geoid in Europe, March, Budapest, Hungary.
Timmen L, Wenzel H-G (1995) Worldwide synthetic gravity tide parameters, in Sünkel and Marson (eds) Gravity and Geoid, Springer, Berlin, 92-101.
Tscherning CC, Sünkel H (1981) A method for the construction of spheroidal mass distributions consistent with the harmonic part of the Earth's gravity potential, manuscripta geodaetica, 6: 131-156.
Tscherning CC (1985) On the use and abuse of Molodensky's mountain, In: Schwarz K-P, Lachapelle G (eds) Geodesy in Transition, University of Calgary, 133-147.
Tziavos IN (1996) Comparisons of spectral techniques for geoid computations over large regions, Journal of Geodesy, 70: 357-373.
Tziavos IN, Sideris MG, Sünkel H (1996) The effect of surface density variations terrain modelling - a case study in Austria. Report 96.2, Finnish Geodetic Institute, 99-110.
Vajda P, Vanicek P (1997) On gravity inversion for point mass anomalies by means of the truncated geoid. Studia Geophysica et Geodaetica, 41: 329-344.
Vajda P, Vanicek P (1998a) On the numerical evaluation of the truncated geoid. Contributions to Geophysics and Geodesy, 28(1): 15-27.
Vajda P, Vanicek P (1998b) A note on spectral filtering of the truncated geoid. Contributions to Geophysics and Geodesy, 28(4): 253-262.
Vajda P, Vanicek P (1999a) Truncated geoid and gravity inversion for one point-mass anomaly. Journal of Geodesy, 73: 58-66.
Vajda P, Vanicek P (1999b) The instant of the dimple onset for the high degree truncated geoid. submitted to Contributions to Geophysics and Geodesy.
Vanicek P, Christou N (eds) (1993) Geoid and its Geophysical Interpretations, CRC Press, Boca Raton.
Vanicek P, Kleusberg A (1985) What an external gravitational potential can really tell us about mass distribution. Bolletino Geofisica Teoretica et Applicata, XXCII(108): 243-250.
Vermeer M (1982) The use of point mass models for describing the Finnish gravity field, Proc. Ninth Nordic Geodetic Commission, Sept. 13-17, Gavle, Sweden.
Vermeer M (1989a) Modelling of gravity gradient tensor observations using buried shells of mass quadrupoles, In: Andersen OB (ed) Modern Techniques in Geodesy and Surveying, Kort-og Matrikelstyrelsen, Copenhagen, 461-478.
Vermeer M (1989b) Global geopotential inversion from satellite gradiometry using mass point grid techniques. In: Sacerdote F, Sansó F (eds) Proc. II Hotine-Marussi Symposium on Mathematical Geodesy, June 5-8, Pisa, 325-368.
Vermeer M (1989c) FGI studies on satellite gravity gradiometry. 1. Experiments with a 5-degree buried masses grid representation, Report 89:3, Finnish Geodetic Institute, Helsinki.
Vermeer M (1992) Geoid determination with mass point frequency domain inversion in the Mediterranean, Mare Nostrum 2, GEOMED report, Madrid, 109-119.
Vermeer M (1994) STEP inversion simulations by a spectral domain, buried masses method. In: Rummel R, Schwinzler P (eds) A major STEP for Geodesy. Report 1994, STEP Geodesy Working Group, 75-83.
Vermeer M (1995) Mass point geopotential modelling using fast spectral techniques; historical overview, toolbox description, numerical experiment, manuscripta geodaetica, 20: 362-378.

Wang Z (1998) Geoid and crustal structure in Fennoscandia. Report 126, Finnish Geodetic Insitute. PhD thesis, 118 pp.
Werner RA (1997) Spherical harmonic coefficients for the potential of a constant-density polyhedron, Computers and Geosciences, 23(10): 1071-1077
Xia J, Sprowl DR (1991) Correction of topographic distortions in gravity data, Geophysics, 56: 537-541.
Xia J, Sprowl DR, Adkins-Heljeson (1993) Correction of topographic distortions in potential-field data: A fast and accurate approach, Geophysics, 58: 515-523.
Zhang C, Blais JAR (1993) Recovery of gravity disturbances from satellite altimetry by FFT techniques: a synthetic study, manuscripta geodaetica, 18: 158-170.

Report of ARCTIC GRAVITY PROJECT - IAG SSG 3.178

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There is currently a great need to compile a uniform gravity grid of the Arctic region, for use in both geophysics/geology and geodesy/orbit determination. Recent advances in data collection technology, notably the advent of airborne gravimetry, the development of satellite altimetry over ice-covered regions, and availability of gravity data from scientific cruises with nuclear submarines, have meant that a large part of the Arctic is covered by substantial, accessible gravity field information.

The ArcGP will provide a detailed insight into the tectonics of the region, and allowing for the first time an accurate geoid model to be established. Recent presentations make it clear that monumental efforts have been made by Russia in mapping major parts of the gravity field of the Arctic Ocean, and make the formation of the ArcGP timely. The establishment of a freely available uniform gravity grid of the Arctic follows ongoing activities to develop an Arctic bathymetric map and database under the auspices of the International Hydrographic Office (IHO).

The Arctic Gravity Project (AGP) is a new international effort dedicated to the compilation of a public-domain gravity grid of the Arctic gravity field north of 64° N. The focus of the gravity grid will be the Arctic Ocean, Greenland, and the continental margins of the Asian and North American continents. The initiative for the project was taken after two international meetings in 1998 ("Airborne Gravity Measurements and the Polar Gravity Field", Greenland, June 1999, and the "International Conference on Arctic Margins (ICAM-III)" held in Celle, Germany, October 1999). The project proposal was inspired by presentations of Russian scientists, and by the success of the ongoing IHO project on Arctic Bathymetry. Ron McNabb, Canada, and B. Coakley, USA, were originally proposing a formal working group on gravity, for which the undersigned was subsequently proposed as chairman.

The primary interest is the compilation of state-of-the-art detailed free-air and Bouguer anomaly grids that will be made available to the general public in the year 2001. Additional tasks for the Arctic Gravity Project working group is to compare and calibrate different gravity sources, e.g. comparison of airborne, satellite, surface and submarine data, and the computation of an arctic-wide geoid model.

At the ICAM-III meeting National Imagery and Mapping Agency (NIMA) offered the future ArcGP to assist in the compilation of the final gravity grid products, using the extensive personnel and computer resources available at NIMA for this kind of work, and to release all data for the compilation of the grid product (the original data will not be made available, only the grids), including recent data acquired by the Naval Research Laboratory airborne gravity programmes plus other surface gravity data from its Point Gravity Anomaly file which contains over 35 million data values.

The target date for final 5' x 10' free-air and bouguer gravity grids to be released to BGI and the general public is December 2000 with preliminary grids released in 1999 to AGP Working Group Members. It is also planned to publish a CD-ROM.

Activities up to July 1999

Following the call for participation in the ArcGP group's activities, positive responses were obtained from all circum-arctic countries and some other major major data-active countries, cf. the list of members below. It was also agreed that the goal of the project is to produce a 5' grid (10' in longitude) covering the area north of 64N, with the exception of Iceland, where 62 N will be used as southern limit.

The National Imagery and Mapping Agency (NIMA) has designated an ftp box for data collection, and has set up a ArcGP web site (http://www.nima.mil/GandG/arctic.htm).

The International Association of Geodesy has approved the ArcGP as a "Special Study Group" belonging to Section III - Gravity Field Determination. An application has also been made to the International Arctic Science Committee (IASC) the have ArcGP recognized as an official IASC project.

Numerous countries and investigators have allready contributed significant data sets, which has allowed a first-cut compilation of available data, to be presented in the IUGG symposium on "Polar Geophysics".

The following data sources have been contributed as of July 1999, and used for the initial compilations of data, to be presented at IUGG. Some of these providers have provided national data base extracts including commercial data. We thank all the data providers who have allready committed data for the project at this early stage.

Agency/investigator	***Data***
National Land Survey (LMV) - Sweden	*Swedish point gravity data (2.5' resolution)*
Geodettinen Laitos – Finland	*Finnish point gravity data (do)*
Statens Kartverk (SK) – Norway	*Svalbard/Norway available land and marine gravity data*
Orkustofnum - Iceland	*Icelandic land and marine gravity data*
National Survey and Cadastre -Denmark	*Greenland land, marine and airborne gravity data*
Tsniigaik - Russia	*European Russia 10' gravity grid*
NIMA –USA	*North American point and NRL airborne data*
B. Coakley – Lamont/USA	*SCICEX Arctic Ocean submarine gravity*
Geomatics Canada (EMR) - Canada	*Canadian data, incl. new Ellesmere Island data*
Alfred Wegener Institute - Germany	*Fram Strait/Greenland airborne and marine gravity data*
Bureau Gravimetrique - France	*Marine gravity from satellite altimetry over sea-ice*

We hope in the future especially to expand this list with more Russian data, more oil company data (e.g., north of Alaska) and to incorporate data from ongoing 1999 field activies by airborne and submarine surveys.

Arctic Gravity Project Membership list

Chairman: R. Forsberg - National Survey and Cadastre (KMS), Denmark

Co-chairman: S. Kenyon - National Imagery and Mapping Agency (NIMA), USA
Georges Balmino -Bureau Gravimetrique International, France
John Brozena - Naval Research Lab,
Bernard J Coakley – Tulane University, USA
Gleb Demianov – TSNIIGAIK, Russia
Lars Ake Haller - National Land Survey (LMV) - Sweden
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Jussi Kääriäinen - Geodeettinen Laitos, Finland
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Report of International Association of Geodesy Section IV

GENERAL THEORY AND METHODOLOGY
for the period 1995-1999

by

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Section IV has primarily a methodological character. It was given its present title at the 18th General Assembly of the IUGG in Hamburg, 1983. The scope of the Section is not confined to one particular topic in geodesy which would be peculiar to this section only, but rather all topics are shared in one way or another with other IAG sections, with the accent of the research pointing towards the systematic mathematical treatment of geodetic problems. In particular the by-laws of the IAG put emphasis on the following tasks of the Section: general mathematical models for geodesy, statistical and numerical analysis, data processing and management, optimization methods, least squares methods, differential and integral theories of the gravity field.

The past four years have been a productive period with advances on many fronts. It has certainly seen a strong involvement of Section IV into most of the activities of the IAG. The structure which made it possible for this Section to fulfill its mandate consists of one special commission and five special study groups. It is as follows:

Special Commission SC1: *Mathematical and Physical Foundations of Geodesy*
President: E.W. Grafarend (Germany)

SSG 4.168: *Inversion of Altimetric Data*
Chairman: P. Knudsen (Denmark)

SSG 4.169: *Wavelets in Geodesy*
Chairman: B. Benciolini (Italy)

SSG 4.170: *Integrated Inverse Gravity Modelling*
Chairman: L. Ballani (Germany)

SSG 4.171: *Dynamic Isostasy*
Chairman: L.E. Sjöberg (Sweden)

SSG 4.176: *Temporal Variations of the Gravity Field*
Chairman: D. Wolf (Germany)

The above structure of the Section is described with all details, terms of references and a full list of members in the Geodesist's Handbook, pp. 940-948, which is a special issue of the Journal of Geodesy, Vol. 70, Number 12, 1996. In addition the development of the Section IV structure in the period 1979-1995 can be seen from an *Appendix* of this report.

Within the present structure of the Section Special Commission SC1 followed the standing concern to collect specialists on the mathematical treatment of various geodetic problems and to study those of them that are of a long term character. Special Commission SC1 was established on the basis of the decision taken by the IAG at the 20th General Assembly of the IUGG in Vienna, 1991. In the period 1995-1999 the research programme of the Special Commission was subdivided into specific tasks which were assigned to the following subcommissions of SC1:

Subcommission 1 - *Statistics*
Chairman: A. Dermanis (Greece)

Subcommission 2 - *Numerical and Approximation Methods*
Chairman: W. Freeden (Germany)

and its Working Group - *Comparison of several techniques for solving geodetic boundary value problems by means of numerical experiments*
Chairman: R. Klees (The Netherlands)

Subcommission 3 - *Boundary Value Problems*
Chairman: E.W. Grafarend (Germany)

Subcommission 4 - *Geometry, Relativity, Cartography*
Chairman: J. Zund (USA)

Subcommission 5 - *Theory of Orbits and Dynamics of Systems*
Chairman: R.J. You (Taiwan)

The task of the section president, P. Holota, and the section secretaries, B. Heck (Germany) and C. Jekeli (USA), was to coordinate and facilitate research in Section IV.

In the reported period Section IV and its accent on systematic theoretical and methodological treatment of geodetic problems were clearly visible and well represented at a number of IAG sponsored symposia and schools. For space limitation, we will only highlight the following events:

– The International Summer School of Theoretical Geodesy on "Boundary Value Problems and the Modelling of the Earth's Gravity Filed in View of the One Centimeter Geoid", Como, 1996, was an important meeting attended not only by young scientists, but also by a broader community of geodesists, mathematicians, geophysicists and representatives of other branches of related sciences. A number of key lectures and seminars at this summer school was given by members of Section IV.

- The International Symposium on Gravity, Geoid, and Marine Geodesy (GraGeoMar96), Tokyo, 1996. Scientific discussions at this meeting put an emphasis on practical as well as theoretical problems. In Tokyo there were 15 scientific sessions and 7 of them were convened by colleagues intimately associated with Section IV as its active members or as its officers.
- Scientific Assembly of the International Association of Geodesy (IAG97), Rio de Janeiro, 1997. The broad range of the programme of this meeting gave a considerable space to discussions of special interest to Section IV. In Rio the Section held also its *Business Meeting* and within the official programme of the scientific assembly the session "The Geoid - Theory and Methods" was entrusted to the Section IV care.
- Second Continental Workshop on the Geoid in Europe, Budapest, 1998, organized by the IAG Sub-commission for the Geoid in Europe in co-operation with the Technical University of Budapest. Here again Section IV took a very active part and *was also a sponsor of this workshop.*
- IAG School on Wavelets in the Geosciences. Delft, 1998.

From the above it is also clear that in the reported period the activities of Section IV followed the principle of *equal geographical distribution*. Moreover, in a sense through its contributions the Section was "an ambassador" participating in the work of other scientific bodies of IUGG as well as in the work of EGS (European Geophysical Society), ECGS (European Center for Geodynamnics and Seismology), ESA and others. In this way it helped to make contacts with other scientific organizations real. Members and officers of Section IV were also entrusted to act as conveners of a number of EGS Symposia. Let us mention at least:

- Joint Inversion as a General Problem in Earth Sciences. 22nd General Assembly of the EGS, Vienna, 1997;
- Modelling Techniques and Joint Inversion in Earth Sciences,
- Ocean Modelling from Altimetry and Remote Sensing

both held on the occasion of the XXII General Assembly of the EGS, Nice, 1998, and three symposia convened at the 24th General Assembly of the EGS in The Hague, 1999:

- Topography and Bathymetry in Geodetic and Geophysical Applications,
- Potential Fileds in Geodesy, Geophysics and Geology,
- Mathematical Modelling and Adjustment Theory.

All the merits of the success of actions of Section IV go to its special commission, sub-commissions and its SSG's which were active and productive. Limiting now ourselves to those only that can be considered specific of Section IV, we for sure have to recall as a minimum the success of the:

- Meeting of SSG 4.170 (Integrated Inverse Gravity Modelling), Walferdange, Luxembourg, 1996;
- Meetings of SSG 4.176 (Temporal Variations of the Gravity Filed), Walferdange, Luxembourg, 1997 and Potsdam, 1998;
- International Summer School "Data Analysis and the Statistical Foundations of Geomatics", Chania, Crete, 1998 (organized by IAG SC 1);
- IV Hotine-Marussi Symposium on Mathematical Geodesy, Trento, 1998.

Traditionally, Hotine-Marussi symposia are events which offer an exceptional opportunity to discuss research done within Section IV. In Trento the discussion concentrated upon boundary value problems, gravity field modelling, orbital dynamics, differential geometry in geodesy, relativity, upon the theory of cartographic projections, estimation theory, approximation theory and numerical methods, inverse problems and also problems in geodynamics with emphasis on geodetic aspects. In addition in Trento Section IV had also a broad and thorough discussion concerning its work and future plans, especially those for the period after the 22nd General Assembly of the IUGG. Special thanks go to the organizers of the IV Hotine-Marussi symposium who made it possible to devote one of the programme blocks of the symposium to the *Business Meeting of Section IV.*

The profile of Section IV research activities and the nature of results achieved was completed by a very successful Symposium G4 "General Theory and Methodology" organized by Section IV within the programme of the 22nd General Assembly of the IUGG, Birmingham, 1999. First part of this symposium was organized as a *Business Meeting of the Section*, were the president of the Section, the president of SC1 and the Chairmen of individual SSG's presented their reports.

It was clear from this symposium that functional-analytic aspects were strongly pronounced in the majority of mathematical studies carried out in the Section. This concerns not only the use of methods of mathematical analysis or the use of the theory of boundary value problems, but also the use of numerical methods and a great variety of other applications. The results achieved speak about the mathematical properties of the geodetic problems discussed in a way which is more transparent, more complete and more general. We believe that these are the properties that will do geodesy good service in its future tasks.

In Birmingham in addition some of the contributions resulting from the research carried out in Section IV were presented within inter-association symposia. Section IV was also represented in the team of conveners of an inter-association symposium on Solid-Earth Geophysical Data Fusion and Analysis Method. Moreover, in Birmingham representative achievements resulting from the research in Section IV were then also presented in Symposium G6 "Geodesy Beyond 2000 - The Challenges of the First Decade". This important symposium mainly oriented to future tasks gave the Section a space to discuss topics that cover problems related: to the World Geodetic Datum 2000, to studies associated with the representation of the time-varying gravity filed, to applications of the so-called direct methods for the solution of boundary value problems in physical geodesy with their tie to the minimization of a quadratic functional and the famous Lax-Milgram theorem, to studies concerning the use of wavelets in geodesy, then also to coordinate systems in four-dimensional space-time geodesy and to the recovery of the gravity filed form gravity gradient measurements.

Finally, the author would like to refer the reader of this report to detailed reports of the Special Commission and the Special Study Groups of Section IV that follow in the sequel and where the information given above are further amplified. Another important source of information are the individual issues of the SC1-Bulletin regularly published in the period 1995-1999.

Acknowledgements. Concluding this brief report, I wish to express my sincere thanks to all my colleagues from Section IV and to all officers of this Section for excellent cooperation and all the results achieved that often are associated with months or years of a great endeavor and a devoted work. My sincere thanks go also to many scientists in geodesy, in mathematics and other branches of science that have been contributing to this success and helped the Section to accomplish its mission. Honestly, in a considerable measure it is exactly the work of all these people and distinguished scientists that created a springboard for the activity of the Section in the next period. Much success and good fortune for Section IV in its further work!

Appendix:
DEVELOPMENT OF THE SECTION IV STRUCTURE IN THE PERIOD 1979-1999

Period 1979-1983
Title of the Section:

THEORY AND EVALUATION
THÉORIE ET TRAITEMENT DES DONNÉES

President: L.P. Pellinen (USSR)
Secretaries: E.W. Grafarend (Fed. Rep. of Germany)
F. Halmos (Hungary)

Special Study Group 4.56
Differential Geometry of the Gravity Field
Chairman: E.W. Grafarend (Fed. Rep. of Germany)

Sub-Group: **Relativistic Aspects of Differential Geodesy**
Chairman: C. Boucher (France)

Special Study Group 4.57
Boundary Value and Convergence Problems in Physical Geodesy
Chairman: F. Sanso (Italy)

Sub-Group: **Improperly Posed Problems**
Chairman: P. Holota (Czechoslovakia)

Special Study Group 4.58
Representation of the Gravity Field
Chairman: H.M. Dufour (France)

Special Study Group 4.60
Statistical Methods for Estimation and Testing of Geodetic Data
Chairman: K.R. Koch (Germany)

Special Study Group 4.65

Force Function of Two or More General Bodies: Application for Geodynamics
Chairman: E. Tengström (Sweden)

Special Study Group 4.66
Management of Geodetic Data
Chairman: C.C.Tscherming (Denmark)

Special Study Group 4.70
Gravity Field Approximation Techniques
Chairman: K.P. Schwarz (Canada)

Special Study Group 4.71
Optimization of Geodetic Networks
Chairman: G. Schmitt (Germany)

Period 1983-1987
Title of the Section:

GENERAL THEORY AND METHODOLOGY
THEORIE GENERALE ET METHODOLOGIE

President: E.W. Grafarend (Fed. Rep. of Germany)
Secretaries: K.-P. Schwarz (Canada)
F. Sanso (Italy)

Special Study Group 4.56
Differential Geometry of the Gravity Field
Chairman: E. Livieratos (Greece)

Special Study Group 4.57
Boundary Value and Convergence Problems in Physical Geodesy
Chairman: P. Holota (Czechoslovakia)

Special Study Group 4.60
Statistical Methods for Estimation and Testing of Geodetic Data
Chairman: D. Fritsch (Fed. Rep. of Germany)

Special Study Group 4.66
Geodetic Data Base Management
Chairman: A.U. Frank (USA)

Special Study Group 4.71
Optimal Design Problems
Chairman: G. Schmitt (Germany)

Special Study Group 4.91
Local Gravity Field Approximation
Chairman: H. Sünkel (Austria)

Special Study Group 4.92
Global Gravity Field Approximation
Chairman: L. Sjöberg (Sweden)

Special Study Group 4.93
Wave Propagation in Refractive Media
Chairman: P. Forsyth (Canada)

Special Study Group 4.94
Theory of Geodetic Reference Frames
Chairman: J. Wahr (USA)

Special Study Group 4.95
Multi Force Function: Geodetic Aspects of Astrodynamics
Chairman: K.H. Ilk (Fed. Rep. of Germany)

Special Study Group 4.96
Models for Time-Dependent Geodetic Positioning
Chairman: P. Vanicek (Canada)

Period 1987-1991
Title of the Section:

GENERAL THEORY AND METHODOLOGY
THEORIE GENERALE ET METHODOLOGIE

President: K.-P. Schwarz (Canada)
Secretaries: F. Sanso (Italy)
P. Holota (Czech Republic)

Special Study Group 4.91
Local Gravity Field Approximation
Chairman: R. Forsberg (Denmark)

Special Study Group 4.92
Global Gravity Field Approximation
Chairman: H.-G. Wenzel (Germany)

Special Study Group 4.93
Wave Propagation in Refractive Media
Chairman: F.K. Brunner (Austria)

Special Study Group 4.115
Mathematical Analysis of Geodetic Boundary Value Problems
Chairman: F. Sacerdote (Italy)

Special Study Group 4.116

Kinematic and Dynamic System Modelling in Geodesy
Chairman: K.-P. Schwarz (Canada)

Special Study Group 4.117
Optimization of Modern Positioning Techniques
Chairman: D. Delikaraoglu (Canada)

Special Study Group 4.118
Inverse Geodetic Problems
Chairman: K.H. Ilk (Germany)

Special Study Group 4.119
Relativistic Effects in Geodesy
Chairman: E.W. Grafarend (Germany)

Special Study Group 4.120
Non-Linear Adjustment
Chairman: P.J.G. Teunissen (The Netherlands)

Period 1991-1995
Title of the Section:

GENERAL THEORY AND METHODOLOGY
THEORIE GENERALE ET METHODOLOGIE

President: F. Sanso (Italy)
Secretaries: P. Holota (Czech Republic)
P.J.G. Teunissen (The Netherlands)

Special Commission SC1
Mathematical and Physical Foundations of Geodesy
President: E.W. Grafarend (Germany)

Subcommission 1: **Statistics**
Chairman: B. Schaffrin (USA)

Subcommission 2: **Numerical and Approximation Methods**
Chairman: R. Klees (Germany)

Subcommission 3: **Boundary Value Problems**
Chairman: F. Sacerdote (Italy)

Subcommission 4: **Differential Geometry**
Chairman: J. Zund (USA)

Subcommission 5: **Theory of Orbits and Dynamics of Systems**
Chairman: A. Drozyner (Poland)

Special Study Group 4.138
Modelling and Quality Control for Precise Integrated Navigation
Chairman: A. Kleusberg (Canada)

Special Study Group 4.139
The Role of Terrain in Gravity Field Modelling
Chairman: A. Geiger (Switzerland)

Special Study Group 4.140
Tomography of the Atmosphere by Geodetic Measurements
Chairman: T. Spoelstra (The Netherlands)

Special Study Group 4.141
Integrated Inverse Gravity Modelling
Chairman: R. Barzaghi (Italy)

Special Study Group 4.142
Application of the Boundary Value Problem Techniques to Space and Airborne Gravity Field Observations
Chairman: B. Heck (Germany)

Report of IAG Special Commission 1

MATHEMATICAL AND PHYSICAL FOUNDATIONS OF GEODESY
for the period 1995 - 1999

by

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The period of work within the years 1995 - 1999 was a very fruitful one. More than five hundred papers relating to the topics of SC#1 were published and documented in SC#1-Bulletins 1995.1, 1996.1, 1997.1, 1998.1 and 1999.1 (200 pages).

SC#1 operates in five subcommissions.

Subcommission 1 ("Statistics") is chaired by A. Dermanis, Aristoteles University Thessaloniki/Greece. The Subcommission Report highlights the IAG International Summer School "Data Analysis and the Statistical Foundations of Geomatics" (Ghania/Crete/Greece, 25-30 May 1998) as well as recent geodetic and non-geodetic work related to Subcommission 1. In addition B. Schaffrin and P. Xu (Kyoto University) presented an extension to this report completing the reviewing process of related literature. Highlights during the period of work have been (i) integer least-squares applied to GPS-double difference carrier phase observations, (ii) random tensor statistics for stress and strain, (iii) variance-covariance component estimation, (iv) Kalman-Bucy filtering of geodetic data, (v) robust estimations, (vi) Kolmogorov structure function/Krige variogram/variance-covariance functions of higher order increments, (vii) weak unbiasedness, (viii) Bayesian estimation and (ix) statistics of geodetic datum transformations.

Both quoted reports are published in SC#1-Bulletin 1999.2. Particularly, Lubomir and Ludmila Kubacek have to be mentioned, our liaison professors to Mathematical Statistics who supported Subcommission 1 ("Statistics") by book and paper reviews on non-linear regression.

Subcommission 2 ("Numerical and Approximations Methods") chaired by W. Freeden, The University of Kaiserslautern/Germany, presented a great review paper entitled "Constructive Approximation and Numerical Methods in Geodetic Research Today - An Attempt of a Categorization Based on an Uncertainty Principle" which has been accepted by Journal of Geodesy as a review paper on the topics of Subcommission 2. In addition the SC#1 president added an extensive literature list to SC#1-Bulletin 1999.1.

Subcommission 3 ("Boundary Value Problems") was chaired by SC#1 president. He presented three review papers entitled (i) The spheroidal fixed-free two-boundary value problem for geoid determination (The spheroidal Bruns transform) by E. Grafarend, A. Ardalan (Stuttgart University/Germany) and M.G. Sideris (University of Calgary/Canada), (ii) The form parameters of the Sonigliana-Pizzetti level ellipsoid from current best estimates of fundamental geodetic parameters based on a functional analytic review of the Sonigliana-Pizzetti gravitational field by E. Grafarend and A. Ardalan (Stuttgart University/Germany) and (III) Boundary value problems in the complex world of geodetic measurements by R. Lehmann (Dresden Polytechnion/Germany).

All three review papers will be published in the Journal of Geodesy on behalf of SC#1. The topics include two-boundary value problems, the Somigliana-Pizzetti level ellipsoid boundary value problem, altimetry-gravimetry boundary value problems, gravitational boundary value problems, pseudo-boundary value problems, overdetemined and constrained boundary value problems. The Subcommission Chairman has added an impressive list of reference papers. Particular mention has to be made to the Slepian problem on the sphere introduced by A. Albertella, N. Sueeuw and F. Sanso. In the report period with support from SC#1 two books appeared, namely (i) A. Marchenko: Parameterization of the Earth's gravity field and (ii) Z. Martinec: Boundary-value problems for gravimetric determination of a precise geoid.

Unfortunately from the Subcommission 4, chairman J. Zund/Las Cruces/USA, no report reached SC#1. A review of Subcommission 4 ("Geometry, relativity, cartography") activities has accordingly been given by SC#1 president. He gave an extensive update of extractive highlighting the following research items: (i) map projections of the reference ellipsoid of revolutions, (ii) boundary value problems of the Korn-Lichtenstein equations which generate conformal mapping, (iii) datum transformation of UTM and Gauss-Krueger coordinates, (iv) pseudo-Riemann geometry of 1-PN-space-time, (v) relativistic equations of multibody dynamics.

Finally Subcommission 5 ("Theory of orbits and dynamics of systems") under its chairman R.J. You/Tainan University/Taiwan focussed on (i) gravity field determination by dynamic satellite geodesy, (ii) precise orbit computation, (iii) relativistic orbit computation and (iv) modelling of non-gravitational forces on satellite motions. R.J. You presented an extensive review on the highlights of Subcommission 5 with an extensive reference list.

All quoted references and reports can be asked from SC#1/President 1991-1999/Erik W. Grafarend, Department of Geodesy and GeoInformatics, Stuttgart University, Geschwister-Scholl-Str. 24D, D-70174 Stuttgart, Germany, fax +49-711-121-3285,
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Report of IAG Special Study Group 4.168

INVERSION OF SATELLITE ALTIMETRY for the period 1995 - 1999

by

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Objectives

This Special Study Group was established to study various geodetic and oceanographic inversion methods and data assimilation techniques. Through a deeper understanding of such techniques new ideas may be brought in order to enhance the use of satellite altimetry.

Programme

1) The estimation of the marine gravity field has been highly improved with data from the geodetic missions of Geosat and ERS-1. However, most processing schemes leave parts of the medium and long wavelength parts of the gravity field unsolved. The SSG should study
a) The influence of ocean variability and on the data type (sea surface heights, slopes, or curvature data) on the recovery of the gravity field,
b) The use of TOPEX/POSEIDON altimetry as reference frame for GEOSAT and ERS-1 data,
c) The use a Global Circulation Models for elimination of the sea surface topography,
d) Procedures for processing altimeter data in a global gravity field mapping.

2) The inversion of altimetry into marine geoid and sea surface topography has been improved along with the increased accuracies of the altimeter data and the geopotential models. However, in many regions the gravity models are not adequately accurate. The SSG should study
a) The a-priori spectrum for the topography (homogeneous and isotropic),
b) The use of hydrodynamic flow mechanisms (geostrophy, friction, viscosity),
c) The use of hydrodynamic constraints (mass, salt, and heat balance),
d) The use of other data sources (ship gravimetry, hydrography, AVHRR/ATSR surface temperature, etc.).

3) The mapping of the ocean tides has been vastly improved in the deep ocean through the TOPEX/POSEIDON mission. However, in shelf regions major inconsistencies between the various models exist. The SSG should study
a) The trade-off between hydrodynamics and altimetry and the role of errors in the bathymetry,

b) Interpolation/extrapolation of ocean tides using empirical methods, assimilation techniques, or inversion techniques,
c) The smoothness and resolution of the ocean tides,
d) The use of other data sources (tide gauges, loadings, GPS, SAR).

Members

O.Ba. Andersen	(Denmark)
M. Brovelli	(Italy)
R. Coleman	(Australia)
G.D. Egbert	(U.S.A.)
G. Evensen	(Norway)
O. Francis	(Belgium)
Y. Fukuda	(Japan)
H. van Gysen	(South Africa)
R.H.N. Haagmans	(The Netherlands)
W. Keller	(Germany)
P.J. van Leeuwen	(The Netherlands)
F. Lyard	(England)
P.-Y. Le Traon	(France)
R.S. Nerem	(U.S.A.)
N. Pavlis	(U.S.A).
R. Ray	(U.S.A.)
D. Stammer	(U.S.A.)
C.C.Tscherning	(Denmark)
P.L. Woodworth	(England)
Changyou Zhang	(U.S.A.)

Progress

The field of satellite altimetry has been extremely active through the past four year period and important progress has been achieved in the area subject to this study group. Study group members were present at 2-3 meetings each year to present results.

The activities of the space agencies have been very important for the activities of this study group. Two satellites have been launched (ERS-2 and GFO) and the TOPEX/POSEIDON extended mission was initiated. Especially, the satellite mission associated science working teams (SWT) and the workshops that have been held for the SWT's have played an important role for the scientific work. The TOPEX/POSEIDON SWT has meet annually. Also, the annual EGS meetings have had session on altimetry jointly between geodesists and oceanographers.

The progress within the specific tasks of this study group are as follows:

1) The estimation of the marine gravity field has been highly improved with data from the geodetic missions of GEOSAT and ERS-1-2. The procedures for global processing of altimetry in a determination of the marine gravity field has been improved significantly. Especially, the improvement in the modelling of the covariance function has been

important. In estimates of the mean sea surface the use of TOPEX/POSEIDON was very valuable to define the reference frame.

2) The inversion of altimetry into marine geoid and sea surface topography has been improved along with the increased accuracies of the altimeter data and the geopotential models. Further improvements have been obtained by introducing dynamic constraints in the determination the sea surface topography. Through the period there has been put focus on long term changes in the sea surface topography to study Sea Level Rise and Global Change. Especially, issues related to calibration of the altimeter and atmospheric models used for corrections have been discussed.

3) The mapping of the ocean tides has been vastly improved in the deep ocean through the TOPEX/POSEIDON mission. Through the period the ocean tide modelling at shallow seas has been vastly improved. The improvements have been achieved by combining more data and by improving the estimation techniques. Furthermore, more tidal constituents have been included. The role of errors in the bathymetry models have been demonstrated to cause a trade-off between hydrodynamics and altimetry.

Conclusions and recommendations

Though the level of activities within the field of satellite altimetry is very high and many interesting results for geodesists are found, it became evident though the period that the role of the study group was unimportant. The members put much more effort into the collaboration that was supported by the space agencies. Hence, it is not recommended that SSG-4.168 is continued.

Additional information

Additional information on the activities within the field of satellite altimetry and information about publications may be found at http://topex-www.jpl.nasa.gov and http://www.esrin.esa.it

Report of IAG Special Study Group 4.169

WAVELETS IN GEODESY
for the period 1995-1999

by

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Some general remarks

Two ideas arise quite naturally at the end of this 4 years period: a lot of work has been done in field of interest of the SSG, but the way to a full exploitation of the application of wavelets and multiresolution analysis in geodesy is still quite long. It is also clear that the quite broad list of items in the program was very ambitious.

Report about activities and results.

Several of the members has developed an important activity in the field of the SSG or in fields that are strictly related. Some of the results are quite essentially reported here after.

Spherical wavelets. This field has been mainly treated by the Geomathematics Group of Kaiserlautern. Several papers have been published. It seams that, after several mathematical developments, we are approaching the possibility of practical applications.

Image analysis. This has been specially treated by Y. Pan and B. Schaffrin using a bayesian approach.

Wavelets and collocation. This is a field not originally mentioned in the terms of reference of the SSG. Some authors (Kostakis, Keller) treated the problem under different points of view. In fact the well known procedure of multi-step collocation is in some way a kind of multiresolution analysis.

Other treated fields include DTM analysis and transformation, the analysis of time series of INS measurements and the quite original development of Slepian functions for the sphere.

Publications

Albertella A., Sneeuw N., Sanso F. (1998). The Slepian Problem on the Sphere. IV Hotine-Marussi Symp. on Math. Geodesy. Trento.

Bayer M., Beth S., Freeden W. (1998). Geophysical Field Modelling by Multiresolution Analysis. Acta Geodaetica et Geophysica Hungarica 33, pp. 289-319.

Bayer M., Beth S., Maier T. (1998). Wavelet Modelling of Vectorial Components in Gravitational Field Determination. In: Freeden W. (ed.). Progress in Geodetic Science at GW98, pp. 208-217.

Benciolini B. (1997). Wavelets: An Introduction. International Archives of Phtogrammetry and Remote Sensing, Vol. XXXII, Part 6w1 - Proceedings of the workshop: International Cooperation and Technology Transfer, Padova, pp. 31-34.

Benciolini B., Zatelli P. (1997). Wavelets Applications in Local Geoid Computation. Scientific Assembly of IAG, Rio de Janeiro.

Blais J.A.R. (1996). Spectrum Considerations Using Maximum Entropy and Multiresolution Considerations. Journal of Geodesy, Vol. 70, No. 3, pp. 349-356.

Blais, J.A.R., He K., Larouche C. (1995). Multiresolution Analysis in Geomatics Applications. Canadian Geomatics CD-ROM, National Defence and Geomatics Canada.

Blais, J.A.R. (1996). Multiresolution Spatial Data Representation and Processing in GISs. Final Report submitted in February, 1996, to GIS and (Services Division, Natural Resources Canada, Ottawa, 41 pp.)

Bruton A.M., Skaloud J., Schwarz K.P. (1999). The Use of Wavelets for the Analysis and Denoising of Kinematic Geodetic Measurements. Poster presented in Symposium G4 at IUGG99 in Birmingham.

Chao B. F., Naito I. (1995). Wavelet Analysis Provides a new Tool for Studying Earth’s Rotation. EOS, Trans. Amer. Geophys. Union 76, pp. 161-165.

Kotsakis C., Sideris M.G. (1999) The Long Road from Deterministic Collocation to Multiresolution Approximation (Technical Report).

Freeden W. (1998). The Uncertainty Principle and Its Role in Physical Geodesy. In: Progress in Geodetic Science at GW98, pp. 225-236.

Freeden W., Schneider F. (1998). Wavelet Approximation on Closed Surfaces and Their Application to Boundary-Value Problems of Potential Theory. Math. Meth. in the Appl. Sci. 21, pp. 129-165.

Freeden W., Windheuser U. (1996). Spherical Wavelet Transform and Its Discretization. Advances in Computational Mathematics 5, pp. 51-94.

Freeden W., Windheuser U. (1997). Combined Spherical Harmonics and Wavelet Expansion - A Future Concept in Earth’s Gravitational Determination. Applied and Computational Harmonic Analysis (ACHA) 4, pp.1-37.

Freeden W. (1999). Multiscale Modelling of Spaceborne Geodata. 351 pp., ISBN 3-519-02600-7.

Freeden W., Gervens T., Schreiner M. (1998). Constructive Approximation on the Sphere. Oxford Science Publication, Oxford University Press, 427 pp., ISBN 0-19-853682-8.

Freeden W., Schneider F. (1998). An Integrated Wavelet Concept of Physical Geodesy. Journal of Geodesy 72, pp. 259-281.

Keller W. (1995). From Fourier Transform to Wavelet Transform - Similarities and Differences. International Lectures Series, Dept. of Geomathematics Engineering, Univ. of Calgary.

Keller W. (1996). Kontinueierliche Wavelet Transformation. Zeitschrift fur Vermessungswesen 121, pp. 563 - 572.

Keller W. (1997a). Collocation in Reproducing Kernel Hilbert Spaces of a Multi-Scale Analysis. 1997 Meeting of EGS.

Keller W. (1997b). Geoid Computation by Collocation in Wavelet Spaces. Scientific Assembly of IAG, Rio de Janeiro.
Kotsakis C. (1999a). The Multiresolution Character of Collocation (Paper submitted to Journal of Geodesy).
Kotsakis C. (1999b). Wavelets and Collocation: An Interesting Similarity. IUGG99, Symposium G6.
Liu H.S., Chao B.F. (1998). Wavelet Spectral Analysis of the Earth's Orbital Variations and Paleoclimatic Cycles. J. Atmos. Soc. 55, pp. 227-236.
Liu L.T., Hsu H.T., Gao B.X. (1998). A New Family of Orthonormal Wavelets Bases. Journal of Geodesy 72, pp. 294-303.
Michel V. (1998). Wavelet Based Method for the Gravimetry Problem. In: Freeden W. (ed.). Progress in Geodetic Science at GW98, pp. 283-298.
Michel V. (1999). A Multiscale Method for the Gravimetry Problem: Theoretical and Numerical Aspects of Harmonic and Anharmonic Modelling. PhD-thesis, University of Kaiserslautern.
Yanjun Pan, Schaffrin B. (1998a). Adaptive Wavelets for Multiscale DEM Transformation. AVN 105, pp. 101-104.
Yanjun Pan, Schaffrin B. (1998b). Bayesian Wavelet Analysis for Image De-noising and Image Fusion. 22nd. Europ. Meeting of Statisticians, Vilnius, Lithuania.
Yanjun Pan, Schaffrin B. (1999a). Bayesian Wavelet Analysis for Image De-noising. Photogr., Goinf. N2, pp. 95-100.
Yanjun Pan, Schaffrin B. (1999b). Image Fusion with Wavelets. (Accepted for publication on GIS August 1999).
Schreiner M. (1996). A Pyramid Scheme for Spherical Wavelets. Technical Report AGTM, Report No. 170, Geomathematics Group, University of Kaiserslautern.
Skaloud J., Bruton A.M., K.P. Schwarz K.P. (1999). Detection and Filtering of Short-Term (1/f) Noise in Inertial Sensors (Accepted for publication in ION Navigation.).
Windheuser U. (1995). Spherical Wavelet Packets and Its Application in Physical Geodesy. In: Neunzert H. (ed.). Progress in Industrial Mathematics - At the European Consortium of Mathematics in Industry'94.
Windheuser U. (1995). Spharische Wavelets: Theorie und Anwendung in der Physikalischen Geodasie. PhD-thesis, University of Kaiserslautern, Geomathematics Group.

Report of IAG Special Study Group 4.170

INTEGRATED INVERSE GRAVITY MODELLING
for the period 1995-1999

by

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1. Introduction

Special Study Group 4.170 "Integrated Inverse Gravity Modelling" continued the work of the former identically named SSG 4.141 (1991-1995) (Barzaghi 1995). The now traditional topic belonging to the inverse geodetic problems - Ilk (1992) has given a detailed overview - was slightly enlarged and adapted to new types of geodetic and geophysical techniques and theories which include gravity information. In addition to the classical joint inversion of gravity and seismic data, new combinations have been appeared: gravity data are successfully inverted jointly with stress and strain data, with magnetic and heat flow data, and also coupled to kinematic and rheologic information. The modelled structures under investigation vary widely in dimension, shape and depth, and in scale. A broad spectrum of mathematical and physical models is employed connected with a diversity of solving algorithms for the inversion procedure. The methods are of deterministic and stochastic type or embedded in the frames of information theory and artificial intelligence.

The membership in this group and in the topic of joint inversion was of high interest above all for geophysicists. The maximum number of registered persons (members and associate members – in most cases only a formal difference) was 36. There was also a slight fluctuation from different reasons over the time span. The following list shows the names and distribution over the countries:

Members:		Associate Members:	
U. Achauer	(France)	A. Buyanov	(Russia)
L. Ballani	(Chairman, Germany)	R.E. Chavez Segura	(Mexico)
R. Barzaghi	(Italy)	H. i kova	(Czech Republic)
O. adek	(Czech Republic)	M. Everaerts	(Belgium)
V.N. Glaznev	(Russia)	A. Geiger	(Switzerland)
R. Lehmann	(Germany)	E.E. Klingele	(Switzerland)
Z. Martinec	(Czech Republic)	O. Legostaeva	(Ukraine)
V.O. Mikhailov	(Russia)	H. Mikada	(Japan)
K. Mosegaard	(Denmark)	I.L. Prutkin	(Russia)
I. Nakanishi	(Japan)	A. Raevsky	(Russia)

M.K. Sen	(USA)	T.V. Romanyuk	(Russia)
P. Smilde	(Germany)	U. Schäfer	(Germany)
D. Stromeyer	(Germany)	V.N. Starostenko	(Ukraine)
G. Strykowski	(Denmark)	I.E. Stepanova	(Russia)
G. Toth	(Hungary)	V.N. Strakhov	(Russia)
I. Tziavos	(Greece)	D.W. Vasco	(USA)
Q. Wang	(P.R. China)		
T. Yegorova	(Ukraine)		
H. Zeyen	(Sweden)		
S. Zhao	(P.R. China)		

2. Activities

The main instrument for information and steering the group were the Circular Letters (No. 0 up to No. 4). The first letter (No. 0) at the beginning was a questioning to find out the very different setups, fields, data and strategies in inversion used. Two meetings to improve the personal contact within the group could be organized. The first meeting (28-30 Oct 1996 Walferdange/Luxembourg) was supported by the fund of the "Open Partial Agreement on Major Hazards" offered by the European Center for Geodynamics and Seismology (E.C.G.S.) in Luxembourg and Belgium (Prof. Bernard Ducarme), by the Executive Board of the GeoForschungsZentrum Potsdam (GFZ) and the International Association of Geodesy (IAG). The participants of the meeting were 20 members of the SSG and 3 guests. 21 papers were presented followed by intensive discussions. A second shorter meeting took place during the EGS General Assembly in Vienna/Austria 1997. The mainly discussed points referred to the structure and the contents of a possible monograph covering all the topics of the group as well as some open problems to give an orientation for the future work. A monograph and comparative tests with data between the algorithms used in the group, as were intended at the beginning of the time period and were prepared to a certain stage, could not be finally realized. A home page showing the basic facts of the group at the internet site of the IAG was created. Some of the members of the group were engaged in the organization of symposia and partly also in the edition of proceedings afterwards. Subsequently some significant meetings, symposia and sub-symposia are listed:

- Geodätische Woche (Geodetic Week), Session G12 "Geodätische Inverse Probleme/Geodetic Inverse Problems", Stuttgart, Germany, October 7-12, 1996.
- First Meeting of IAG-SSG 4.170 "Integrated Inverse Gravity Modelling", Walferdange, Luxembourg, October 28-30, 1996.
- EGS XXII General Assembly, Symposium EGS1 "oint Inversion as a General Problem in Earth Sciences", Vienna, Austria, 21-25 April 1997.
- EGS XXIII General Assembly, Symposium EGS3 "Modelling techniques and joint inversion in Earth sciences", Nice, France, 20-24, April, 1998.
- 2nd Joint Meeting of the International Gravity Commission and the International Geoid Commision, Session VII - Inverse gravimetric and related problems. Trieste, Italy, September 7-12, 1998,
- EGS XXIV General Assembly, Symposium G15 "Topography and bathymetry in geodetic and geophysical applications", Den Haag, The Netherlands, April 19-23, 1999.

– EGS XXIV General Assembly, Symposium SE46-02 "Inversion and interpretation of gravity and magnetic anomalies on all scales, case histories", Den Haag, The Netherlands, April 19-23, 1999.
– IUGG General Assembly, Inter-Association Symposium JSA40, "Solid-Earth Geophysical Data Fusion and Analysis Methods", Birmingham, UK, July 28, 1999

3. Results and Problems

As can be seen from the references (see below) a broad spectrum in inverse modelling is covered by the work of the group which can be, of course, summarized in different way. From the aspect of the aims and orientation of the SSG the following lines are important:
– ordinary ("single") inversion of gravity, magnetics, seismics and stress
– joint inversion of gravimetry and seismics or magnetics
– theoretical and computational aspects of joint inversion
– geodynamical inverse problems
– geophysical and geological applications

Only a few special points shall be stressed here: The inherent nonuniquenss and instability in the single inversion was investigated under different views (the structure of the null space and of parameter spaces, the evaluation of the a-priori and a-posteriori information, the application of the maximum entropy principle of the information theory). New algorithms reflecting diverse backgrounds and also non-linearity (simulated annealing, genetic algorithms, neural networks, Bayesian inference) were studied and applied. Optimization and regularization strategies (hybrid norms, sequential processing) were directly adapted to the inversion problem structure. There is a convergency between geodesy and geophysics in studying subjects as the downward continuation of the Earth's gravity field from the topography to the geoid. As an important aspect appears the study of mass density modelling and its different role in geodesy and geophysics. To overcome the known difficulties with the varying relationship between density and seismic velocity this relationship was included as unknown parameter in the joint gravito-seismic inversion procedure. Gravity information is more and more coupled in the inversion with numerous physical fields and geo-data. Then it often acts as a control to validate the geophysical model. The modelling situations comprehend not only regional and global layer models but also subducting plates and tectonic phenomena, e.g. collision zones. Dynamic inverse modelling relates e.g. the geoid with mantle viscosity and convection information or can give indications on rheological properties.

Future investigations in the field of integrated inverse gravity modelling should study
– the specific assumptions in the different seismic models and codes together with the investigated geophysical situation and the non-uniqueness of single inverse problems
– the different forms of coupling and correlation in the joint inversion, especially the role of geometry as a common quantity
– the connection of the mass density with the different geophysical fields and other geo-data, its role in topography, especially the study of the inverse gravimetric problem together with the geoid determination (boundary-value problem) making use of all types of geodetic measurements

4. References 1995 - 1999

A selection only of printed articles, with a few exceptions, can be given here (in alphabetical order related to the SSG members).

Sobolev, S.V.; **Zeyen, H.**; Granet, M.; **Achauer, U.**; Bauer, C.; Werling, F.; Altherr, R.; Fuchs, K.: Upper mantle temperatures and lithosphere-asthenosphere system beneath the French Massif Central constrained by seismic, gravity, petrologic and thermal observations. Tectonophysics, vol. 275 (1997) 1-3, 143-164.

Ballani, L.: Solving the Inverse Gravimetric Problem: On the Benefit of Wavelets. in: Sanso, F. (ed.), Geodetic Theory Today. IAG Symposia 114, Springer -Verlag Berlin etc., 1995, pp. 151-161.

Ballani, L.; Greiner-Mai, H.; **Stromeyer, D.**: Determining the Magnetic Field in the Earth's Deep Mantle by an Inverse Boundary Value Problem. Scientific Technical Report STR99/12, GeoForschungsZentrum Potsdam, Potsdam, Germany, 1999, 80 pages.

Barzaghi, R.: SSG 4.141 Integrated Inverse Gravity Modelling. in: Section IV Bulletin, General Theory and Methodology, IAG, IUGG, No.1, Delft, The Netherlands: The Office of the Netherlands Geodetic Commission, 1995, pp. 65-67.

Tondi, R.; De Franco, R.; **Barzaghi, R.**: Sequential integrated inversion of traveltimes and gravity data for 2D structures. Paper 2nd Joint Meeting of the International Gravity Commission and the International Geoid Commision, Session VII - Inverse gravimetric and related problems. September, 7 - 12, 1998, Trieste, Italy. (submitted to IGJ)

Buyanov, A.F.; **Glaznev, V.N.**; Mitrofanov, F.P.; **Raevsky, A.B.**: Three - dimensional modelling of the Lapland Granulite Belt and adjacent structures of the Baltic Shield from geophysical data. in: Nor. geol. unders. Special Publ. vol. 7, 1995, pp. 167-178.

adek, O.; **i kova, H.**; Yuen,D.A.: Mantle viscosity inferred by genetic algorithms from the geoid and seismic information. Phys. Chem. Earth (A), vol. 23 (1998) No. 9/10, 865-872.

Kido, M.; **adek, O.**: Inferences of viscosity from the oceanic geoid: indication of a low viscosity zone below the 660-km discontinuity. Earth Planet. Sci. Lett., vol. 151 (1997), 125-137.

i kova, H.; **adek, O.**; Yuen, D.A.; Hua-wei Zhou: Slope of the geoid spectrum and constraints on mantle viscosity stratification. Geophys. Res. Lett., vol. 23 (1996) 21, 3063-3066.

Kido, M.; Yuen, D.A.; **adek, O.**; Nakakuki, T.:Mantle viscosity derived by genetic algorithm using oceanic geoid and seismic tomography for whole-mantle versus blocked-flow situations. Phys. Earth Planet. Int., vol. 107 (1998) 4, 307-326.

Campos-Enriquez, J.O.; Delgado-Rodriguez, O.; **Chavez-Segura, R.**;Gomez-Contreras, P.; Flores-Marquez, E.L.; Birch, F.S.: The subsurface structure of the Chalco sub-basin (Mexico City) inferred from geophysical data. Geophysics, vol. 62 (1997) 1, 23-35.

Everaerts, M.; Poitevin, C.; De Vos, W.; Sterpin, M.: Integrated geophysical/geological modelling of the western Brabant Massif and structural implications. Bulletin de la Societe Belge de Geologie, vol.105 (1996) 1-2, 41-59.

Kahle, H.-G.; **Geiger, A.**; Buerki, B.; Gubler, E.; Marti, U.; Wirth, B.; Rothacher, M.; Gurtner, W.; Beutler, G.; Bauersima, I.; Pfiffner, O.A.: Recent crustal movements, geoid and density distribution; contribution from integrated satellite and terrestrial measurements. In: Pfiffner, O.A. et al (eds.), Results of NRP 20; Deep Structure of the Swiss Alps. Birkhaeuser, Basel, Switzerland. 1997, pp. 251-259.

Galichanina, L.D.; **Glaznev, V.N.**; Mitrofanov, F.P.; Olesen, O.; Henkel, H.: Surface density characteristics of the Baltic shield and adjacent territories. in: Nor. geol. unders. Special Publ. vol. 7, 1995, pp. 349-354.

Glaznev, V.N.; **Raevsky, A.B.**; Skopenko, G.B.: A three-dimensional integrated density and thermal model of the Fennoscandian lithosphere.Tectonophysics, vol. 258 (1996) 15-33.

Mints, M.V.; **Glaznev, V.N**.; Raevsky, A.B.: Three-dimensional geological model of the Earth's upper crust, the Kola ultradeep borehole and adjacent areas of the Kola Peninsula. Geotectonics, vol. 28 (1995) 6, 457-475.

Ilk, K.H.: Inverse Geodetic Problems. in: Travaux de l'Association Internationale de Géódésie, Paris, vol. 29 (1992) pp. 356 – 391.

Gret, A,; **Klingele, E.**: Application of Artifitial Neural Networks for Gravity Interpretation in Two Dimension. Geodäsie und Photogrammetrie ETH-Z. Bericht Nr.279. 1998. ISBN 3-906467-10-4. 88 pages.

Klingele, E.E.; Kahle, H.; Seismic Velocity-Density Relationship: A Critical Review. Paper Symposium EGS1 "Joint inversion as a general problem in Earth sciences", EGS XXII General Assembly, Vienna, Austria, April 21-25, 1997.

Lehmann, R.: The Integrated Inverse Gravimetric Problem - a Separated Minimum-Norm-Solution. Paper presented at the First Meeting of IAG - SSG 4.170 "Integrated Inverse Gravity Modelling", Walferdange, Luxembourg, October 28-30, 1996.

Lehmann, R.: Maximum entropy density determination for the earth and terrestrial planets. Studia geoghys. et geodaet., vol. 43 (1999) 1, 35-60.

Martinec, Z.: Stability investigations of a discrete downward continuation problem for geoid determination in the Canadian Rocky Mountains. J. Geod., Vol. 70 (1996) 805-828.

Martinec, Z.: Boundary-Value Problems for Gravimetric Determination of a Precise Geoid. Lecture Notes in Earth Sciences. Springer, Heidelberg, 1998, 223 pages.

Smolyaninova, E.I.; **Mikhailov, V.O.**; Lyakhovsky, V.A.: Numerical modelling of regional neotectonic movements in the northern Black Sea. Tectonophysics, vol. 266 (1996) 1-4, 221-231.

Mosegaard, K.; Tarantola,A.: Monte Carlo sampling of solutions to inverse problems. J. Geophys. Res. vol. 100 (1995) B7, 12431-12447.

Vasin, V.V.; **Prutkin, I.L**; Timerkhanova, L.Yu. : Retrieval of a Three-Dimensional Relief of Geological Boundary from Gravity Data. Izvestiya, Physics of the Solid Earth, vol. 32(1996) 901 - 905. (Russ.: Fizika Zemli, 1996, No.11, 58-62.)

Prutkin, I.L.: Determination of the 3D Topography for a Conductive Half-Space Boundary from Electromagnetic Data. Izvestiya, Physics of the Solid Earth (Russ.: Fizika Zemli, 1998, No.4, 62-66.).

Romanyuk, T.V.: Seismic and density modeling of the crust and upper mantle along the Quartz traverse. Izvestiya, Physics of the Solid Earth, vol. 31 (1996) 9, 735-747.

Chunduru, R.K.; **Sen,M.K.**; Stoffa, P.L.: Hybrid optimization methods for geophysical inversion. Geophysics, vol.62 (1997) 4, 1196-1207.

Zhao Lian She; **Sen, M.K.**; Stoffa, P.L.; Frohlich, C.: Application of very fast simulated annealing to the determination of the crustal structure beneath Tibet. Geophys. J. Int., vol.125 (1996) 2, 355-370.

Sen, M.K.; Stoffa, P.L.: Bayesian inference, Gibbs' sampler and uncertainty estimation in geophysical inversion. Geophys. Prosp., vol. 44 (1996) 2, 313-350.

Smilde, P.: Verwendung und Bewertung von a-priori Information bei potentiell singulären Inversionsproblemen am Beispiel der gravimetrischen Bestimmung von

Dichteverteilungen (Application and evaluation of a-priori information in potentially singular inverse problems demonstrated by the gravimetric determination of density distributions). DGK: Series C, No. 490, München: Beck, 1998, 90 pages.

Starostenko, V.I.; Kozlenko, V.G.; Kostyukevich, A.S.; Baranova, E.P.; Korenevich, K.A.; Koyfman, L.I.: Structure of the Earth's Crust in Ukraine at the II and III Geotraverses Intersection according to Seismogravimetric Modelling Data. Krystalinikum, vol. 22 (1995) 137 - 147.

Starostenko, V.I.; **Legostaeva, O.V**.: Calculation of the Gravity Field from an Inhomogeneous, Arbitrary Truncated Vertical Rectangular Prism. Izvestiya, Physics of the Solid Earth (Russ.: Fizika Zemli, 1998, No.12, 31-44).

Buryanov, V.B.; Makarenko, I.B.; **Starostenko V.I.**: Thickness and structure of the crust of the Black Sea Basin according to gravity modeling data. Geophys. J., vol. 16 (1997) 5, 603-623.

Stepanova, I.E.: The Integral Equation of the Reverse Potential Problem in Three-Dimensional Case. Dokl. Akad. Nauk, vol. 348 (1996) 2, 252-254. (Russ.)

Stepanova, I.E.: On the Numerical Algorithm of the Solution of the Three-Dimensional Reverse Problem of Potential. Dokl. Akad. Nauk, vol. 354 (1997) 2, 249-251. (Russ.)

Stepanova, I.E.: The Integral Equation of the Three-Dimensional Structural Inverse Problem. Dokl. Akad. Nauk, vol. 353 (1997) 1, 108-110. (Russ.)

Stepanova, I.E.: Reconstruction of a Gravity Source in Ore-Type Problems. Izvestiya, Physics of the Solid Earth (Russ.: Fizika Zemli, 1998, No.11, 86-89).

Strakhov, V.N.; **Schäfer, U.**; Strakhov, A.V.: Neue Lineare Approximationen Linearer Elemente des Gravitationsfeldes der Erde - Probleme und Perspektiven (New linear approximations of linear elements of the Earth gravitational field - problems and perspectives). in: Freeden, W. (ed.), Progress in Geodetic Science, Aachen: Shaker, 1998. pp. 315-322.

Strakhov, V.N.; Strakhov A.V.: On the Regularization Method of the Least Squares Method (Russ.), Geophysical Journal, vol. 20 (1998) 6, 1-24.

Strakhov, V.N.; Strakhov A.V.: On the Construction of Stable Approximating Solutions of Great and High-dimensional Systems of Linear Algebraic Equations Originating in Problems of Gravimetry and Magnetics.(Russ.) Geophysical Journal, vol. 21 (1999) 1, 1-21.

Stromeyer, D: Plate boundary forces acting on the South America Plate derived from stress field inversion. Annales Geophysicae, vol. 14, Suppl. I, C256, 1996.

Strykowski, G.: Dealing with the non-uniqueness of the solution to the inverse geophysical problems. in: Hansen, P. Ch. (ed.) Proc. Interdisciplinary Inversion Workshop 4, Danish Technical University, Lyngby, Denmark, Oct 22, 1997. pp. 67-74.

Strykowski, G.: Experiences with a Detailed Estimation of the Mass Density Contrasts and of the Regional Gravity Field using Geometrical Information from Seismograms. Phys. Chem. Earth (A) vol. 23 (1998) 9/10, 845-856.

Strykowski, G.: Elements of the Joint Gravimetric-Seismic Modelling - Coupling the Available Information. in: Bo Holm Jacobsen (ed.), Proc. Interdisciplinary Inversion Workshop 5, Dept. Earth Sciences, Univ. Aarhus, Denmark, Sept. 24, 1997. pp. 24-30.

Strykowski, G.: Some Technical Details Concerning a New Method of Gravimetric-Seismic Inversion. Phys. Chem. Earth (A)., vol.24 (1999) 3, 207-214.

Strykowski, G.: Formulation of the mathematical frame of the joint gravimetric-seismic modelling problem based on analysis of regionally distributed borehole data. In: Segawa, J.; Fujimoto, H.; Okubo, S. (eds.), Gravity, Geoid and Marine Geodesy. IAG Symposia 117, Springer-Verlag. New York, 1997. pp. 360-367.

Strykowski, G.: Borehole data and stochastic gravimetric inversion. PhD-thesis, Univ. Copenhagen, Kort & Matrikelstyrelsen, Skrifter 4. rk, bd. 3 (Public. National Survey and Cadastre, Publications 4. series, vol. 3), Copenhagen, Denmark, 1996, 110 pages.

Tziavos, I.N.; Sideris, M.G.; Suenkel, H.: The effect of surface density variations on terrain modeling; a case study in Austria. In: Tziavos, I.N.; Vermeer, M. (eds.), Techniques for local geoid determination. Reports Finn. Geod. Inst., vol.96 (1996) 2, 99-110.

Vasco, D.W.: Regularization and trade-off associated with nonlinear geophysical inverse problems: penalty homotopies. Inverse Problems, vol. 14 (1998) 1033-1055.

Vasco, D.W.: Groups, algebras and the non-linearity of geophysical inverse problems. Geophys. J. Int., vol. 131 (1997) 9 - 23.

Vasco, D.W.; Peterson, J.E.; Majer, E.L.: Nonuniqueness in traveltime tomography: Ensemble inference and cluster analysis. Geophysics, vol.61 (1996) 1209-1227.

Vasco, D.W.: A transformation approach to geophysical inverse problems. Geophys. J. Int., vol. 123 (1995) 1, 183-212.

Wang Qianshen; Yang Xinshe: Stratified Gravity Image and Its Application - The Test and Combined Application of Seismic Tomography. Paper submitted to the First Meeting of IAG-SSG 4.170 "Integrated Inverse Gravity Modelling", Walferdange, Luxembourg, October 28-30, 1996, (booklet of the meeting, 6 pages).

Wang Qianshen; Yang Xinshe: Stratified Gravity Image and Its Application Acta Geophysica Sinica, vol.40 (1997) No.5, 649-659.

Wang Qianshen; Wu Chuanzhen; Jiang Weiwei: Gravity field and crustal structure of Gyirong-Lugu Region in western Xizang (Tibet) Plateau. Chinese Sci. Bull., vol.42 (1997) 8, 669-673.

Kong Xiangru; **Wang Qianshen**; Xiong Shaobai: Comprehensive geophysics and lithospheric structure in the western Xizang (Tibet) Plateau. Science in China. Series D, Earth Sciences., vol. 39 (1996) 4, 348-358. 1996.

Yegorova, T.P.; Kozlenko, V.G.; **Starostenko, V.I.**; Shen, E.L.; Botev, E.A.: Density inhomogeneities of the upper mantle of the Central Balkans. Geophys. J. Int., vol. 132 (1998) 283-294.

Yegorova, T.P.; **Starostenko, V.I**; Kozlenko, V.G.; Pavlenkova, N.I.: Three-dimensional gravity modelling of the European Mediterranean lithosphere. Geophys. J. Int., vol. 129 (1997) 2, 355-367.

Yegorova, T.P.; **Starostenko, V.I.**: Gravity Modeling Constraints on the Structure of the Transition Zone between Western Europe and East European Platform. (Russ.: Fizika Zemli, 1998, No. 6, 19 - 36.) Izvestiya, Physics of the Solid Earth.

Zeyen, H.; **Achauer, U.**: Joint Inversion of Teleseismic Delay Times and Gravity Anomaly Data for Regional Structures. in: Fuchs, K. (ed.), Upper Mantle Heterogeneities from Active and Passive Seismology, NATO-ASI series 1, vol.17, Kluwer Academic Publishers, Dordrecht, Netherlands, 1997, pp. 155-168.

Shaorong Zhao: Detection of the active segment at the Red River fault zone by inversion of observed gravity changes. J. Geodyn., vol. 20 (1995) 1, 41-62.

Shaorong Zhao: Joint inversion of observed gravity and GPS baseline changes for the detection of the active fault segment at the Red River fault zone. Geophys. J. Int., vol.122 (1995) 1, 70-88.

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Report of IAG Special Study Group 4.176

MODELS OF TEMPORAL VARIATIONS OF THE GRAVITY FIELD
for the period 1995 - 1999

by

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Scientific program

SSG 4.176 *Models of temporal variations of the gravity field* was established in response to the growing need of developing geodynamical models for the interpretation of the time-dependent gravity field as better data are provided by superconducting and absolute gravimeters or are expected from planned satellite gravity missions. Whereas the principal activity of SSG 4.176 was defined to be the development of improved theoretical models for the individual types of forcing responsible for gravity variations, a substantial portion of its research during the period 1995-1999 also involved the application of existing theory. This included the calculation of other measures of deformation, such as displacement and stress. The broader scope of the research performed is also reflected by the large number of publications of members of SSG 4.176 not concerned with gravity variations. However, in accordance with the topic of SSG 4.176, this report concentrates on that part of the research which is concerned explicitly with gravity variations. Clearly, this restriction is somewhat arbitrary in view of the fact that the same theory governs gravity variations, displacements, stresses and other measures of deformation. Another restriction is that research predominantly concerned with tidal gravity variations was largely excluded. This reflects that research on earth tides is represented in the IAG structure separately.

Membership

The following scientists were regular members of SSG 4.176:

Veronique Dehant	(Royal Observatory of Belgium, Brussels, Belgium)
Martin Ekman	(National Land Survey of Sweden, Gävle, Sweden)
Johannes Engels	(University of Stuttgart, Germany)
José Fernández	(Ciudad University, Madrid, Spain)
Erik Grafarend	(University of Stuttgart, Germany)
Paul Johnston	(Australian National Un iversity, Canberra, Australia)
Xi-lin Li	(Chinese Academy of Sciences, Wuchang, China)
James Merriam	(University of Saskatchewan, Saskatoon, Canada)
Jerry Mitrovica	(University of Toronto, Canada)
Shubei Okubo	(University of Tokyo, Japan)
Lars Sjöberg	(Royal Institute of Technology, Stockholm, Sweden)
Giorgio Spada	(University of Urbino, Italy)
Leif Svensson	(Lund Institute of Technology, Lund, Sweden)
Bert Vermeersen	(Delft University of Technology, Delft, Netherlands)
Hans-Georg Wenzel	(University of Hannover, Germany)
Detlef Wolf	(GeoForschungsZentrum, Potsdam, Germany)

Scientific results

The research completed in SSG 4.176 may be caterogized as follows:

Theory: Fundamental theoretical studies are due Grafarend *et al.* (1997), who formulated a theory for the space-time gravitational field of a deformable earth without assumptions on the geometry and constitution of the earth model. Varga *et al.* (1999) computed in particular the variation of the degree-2 harmonic of the gravity field and pointed out an apparent discrepancy with observational results. The classical problem of gravitational-elastic perturbations of a spherically symmetric earth model was revisited by Sun & Sjöberg (1998, 1999a), who calculated the radial variations of the Love-Shida numbers for realistic parameter values. The modification of the relation between changes of gravity and inertia effected by the choice of the core-mantle interface conditions was investigated by Spada (1995). The theory of gravitational viscoelastodynamics was developed in systematic form by Wolf (1997, 1998). A number of papers are concerned with solutions of these field equations for special cases. Thus, Johnston *et al.* (1997) introduced into the theory the modifications required in the presence of phase boundaries. An analytic solution of the field equations for the case of an earth model composed of homogeneous incompressible shells was derived by Vermeersen & Sabadini (1997). Martinec & Wolf (1998) considered the same type of earth model and derived explicit expressions for the propagator matrix entering into the solution. The problem of solving the viscoelastic field equations in the case of compressibility was investigated by Vermeersen *et al.* (1996). A number of papers are concerned with the solution of the field equations on the assumptions of lateral variations of the viscosity. Thus, D'Agostino *et al.* (1997) employed a spectral method to solve the equations for a spherical earth in this more general case. Kaufmann & Wolf (1999) used the perturbation approach valid on the assumption of small variations of viscosity and derived analytical solutions for a number of simple 2-D plane earth models. Tromp & Mitroviva (1999a, b) developed a more general perturbation approach valid for a 3-D spherical earth. A special model consisting of two eccentrically nested spheres and designed for testing numerical codes valid for arbitrarily large 2-D variations of viscosity was developed by Martinec & Wolf (1999).

Topographic and glacial loading: Using the technique of mass condensation, the incremental gravity generated by topographic masses and their isostatic compensation was studied by Engels *et al.* (1996). The authors concluded that the observed geoid heights confirm that the earth's crust cannot be represented by a constant-density shell. In a related study, Sun & Sjöberg (1999b) calculated gravity changes generated by topographic loads on the assumption of a perfectly elastic earth model. In view of the observed geoid heights, they pointed out that dynamic processes must also be responsible for the anomalies. Ekman & Mäkinen (1996) analysed gravity variations in Fennoscandia and related them in terms of a simple flow model to glacial-isostatic adjustment. Johnston & Lambeck (1999) considered in particular the temporal variation of the degree-2 harmonic of the gravity field and investigated the sensitivity of the predictions on the details of the earth and load models. In similar studies, Vermeersen *et al.* (1997) and Milne *et al.* (1998) determined the influence of the viscosity stratification on the degree-2 harmonic. Wolf *et al.* (1997a, b) and Thoma & Wolf (1999) predicted deglaciation-induced gravity variations for Iceland and Fennoscandia, respectively, and suggested that the signals be observable after a period of several years.

Internal and tidal loading: The problem of calculating the gravity signatures associated with convective density inhomogeneities in a Newtonian-viscous compressible earth model with phase boundaries was studied by Defraigne *et al.* (1996). The same problem was considered for a viscoelastic earth by Mitrovica & Forte (1997), who also investigated the consistency of the earth's viscosity stratification inferred from dynamic geoid anomalies with that inferred from glacial-isostatic adjustment. The tidal loading problem was revisited for the case of a spherical elastic earth model in an initial state of hydrostatic equilibrium by Grafarend *et al.* (1996), who derived an integral relation between the Love-Shida numbers. Mathews *et al.* (1997) also calculated Love-Shida numbers, taking into account effects due to ellipticity, rotation and anelasticity. Later, Dehant *et al.* (1998, 1999) further generalized the problem and studied tidal loading for an aspherical earth model with an inelastic mantle and in a non-hydrostatic initial state. Wieczerkowski & Wolf (1998) were also concerned with tidal loading. The emphasis of their study was on assessing the modifications introduced by compressibility and by different types of viscoelasticity.

Seismotectonic forcing: In a number of papers, the gravity changes caused by various types of forcing associated with seismic, tectonic or volcanic activity are considered. Thus, Fernández et al. (1997a, b) and Yu *et al.* (1997) studied several types of faulting and volcanic intrusions and computed the associated deformation and gravity change for plane elastic or viscoelastic earth models. In similar studies, Piersanti *et al.* (1997) and Sun & Okubo (1998) employed spherical elastic or viscoelastic earth models to determine the co- or post-seismic deformation and gravity change on a global scale. Soldati & Spada (1999) considered in particular the earthquake-generated degree-2 harmonic of the gravitational field for a viscoelastic earth model and also studied the implications for the earth's rotation.

Miscellaneous: Brimich *et al.* (1995) investigated the effects produced by heat sources in layered elastic earth models. In a theoretical study, Degryse & Dehant (1995) readdressed the problem of computing the period of the Slichter modes of the inner core, which may be detectable in the records of superconducting gravimeters. Neumeyer *et al.* (1997) computed the direct attraction of the atmosphere and the secondary contributions due to the earth's deformation in response to the atmospheric loading. In a related study, Neumeyer *et al.* (1999) also estimated the effects due to rainfall and groundwater.

Other activities

The research carried out in SSG 4.176 was reported by its members in two meetings held in Walferdange, Luxembourg, during March 17-19, 1997 (9 presentations) and in Potsdam, Germany, during November 23-25, 1998 (15 presentations). Both meetings were financially supported by the IAG; for the first meeting, additional funding was provided by the European Centre for Geodynamics and Seismology. Abstracts of the presentations given were issued subsequently (Wolf, 1997, 1998). A further activity of SSG 4.176 was the compilation of a bibliography on the theory and modelling of temporal gravity variations for the period 1960-1999 (Wolf, 1999). The abstract volumes and the bibliography are available from the chairperson of SSG 4.176 upon request.

Selected publications of members: 1995-1999

Brimich, L., *Fernández, J.*, Granell, R.D.R., Hvož dara, M., 1995. Some comments on the effects of earth models on ground deformation modelling. *Stud. Geophys. Geod.*, **40**, 14-24.

Defraigne, P., D*ehant, V.*, Wahr, J.M., 1996. Internal loading of an inhomogeneous compressible earth with phase boundaries. *Geophys. J. Int.*, **125**, 173-192.

Degryse, K., *Dehant, V.*, 1995. Analytical computation of modes for an earth with viscous boundary layers, and influence of viscosity on the non-ratating Slichter period. *Man. Geod.*, **20**, 498-514.

Dehant V., Defraigne P., Wahr J.M., 1998. Tides for an earth in a non-hydrostatic equilibrium, in Ducarme, B., Pâquet, P., eds., *Proc. 13th Int. Symp. Earth Tides, Brussels*, pp. 261-263. Royal Observatory of Belgium, Brussels.

Dehant, V., Defraigne, P., Wahr, J.M., 1999. Tides for a convective earth. *J. Geophys. Res.*, **104**, 1035-1058.

D'Agostino, G., *Spada, G.*, Sabadini, R., 1997. Postglacial rebound and lateral viscosity variations: a semi-analytical approach based on a spherical model with Maxwell rheology. *Geophys. J. Int.*, **129**, F9-F13.

Ekman, M., Mäkinen, J., 1996. Recent postglacial rebound, gravity change and mantle flow in Fennoscandia. *Geophys. J. Int.*, **126**, 229-234.

Engels, J., Grafarend, E.W., Sorcik, P., 1996. The gravitational field of topographic-isostatic masses and the hypothesis of mass condensation II - the topographic-isostatic geoid. *Surv. Geophys.*, **17**, 41-66.

Fernández, J., Rundle, J.B., Yu, T.-T., Carrasco, J.M., 1997a. Displacement and gravity changes due to different sources in layered media. *Compt. Rend. J. Luxemb. Geodyn.*, **82**, 55-60.

Fernández, J., Yu, T.-T., Rundle, J.B., 1997b. Geodetic signature produced by different sources in a gravitational layered earth model. *Publ. Inst. Astron. Geod.*, **191**, 1-32.

Grafarend, E., Engels, J., Varga, P., 1996. The gravitational potential of a deformable massive body generated by tidal and load potentials. *Acta Geod. Geophys. Hung.*, **31**, 283-292.

Grafarend, E., Engels, J., Varga, P., 1997. The spacetime gravitational field of a deformable body. *J. Geod.*, **72**, 11-30.

Johnston, P., Lambeck, K., 1999. Postglacial rebound and sea level contributions to changes in the geoid and the earth's rotation axis. *Geophys. J. Int.*, **136**, 537-558.

Johnston, P., Lambeck, K., *Wolf, D.*, 1997. Material vs isobaric internal boundaries in the earth and their influence on postglacial rebound. *Geophys. J. Int.*, **129**, 252-268.

Kaufmann, G., *Wolf, D.*, 1999. Effects of lateral viscosity variations on postglacial rebound: an analytical approach. *Geophys. J. Int.*, **137**, 489-500.

Martinec, Z., *Wolf, D.*, 1998. Explicit form of the propagator matrix for a multi-layered, incompressible viscoelastic sphere. *Sci. Techn. Rep. GFZ Potsdam*, **STR98/08**, 1-13.

Martinec, Z., *Wolf, D.*, 1999. Gravitational-viscoelastic relaxation of eccentrically nested spheres. *Geophys. J. Int.*, **138**, 45-66.

Mathews, P.M., *Dehant, V.*, Gipson, J.M., 1997. Tidal station displacements. *J. Geophys. Res.*, **102**, 20469-20477.

Milne, G.A., *Mitrovica, J.X.*, Forte, A.M., 1998. The sensitivity of glacial isostatic adjustment predictions to a low-viscosity layer at the base of the upper mantle. *Earth Planet. Sci. Lett.*, **154**, 265-278.

Mitrovica, J.X., Forte, A.M., 1997. Radial profile of mantle viscosity: results from the joint inversion of convection and postglacial rebound observables. *J. Geophys. Res.*, **102**, 2751-2769.

Neumeyer, J., Barthelmes, F., *Wolf, D.*, 1997. Atmospheric pressure correction for gravity data using different methods, in Ducarme, B., Pâquet, P., eds., *Proc. 13th Int. Symp. Earth Tides, Brussels*, pp. 431-438. Royal Observatory of Belgium, Brussels.

Neumeyer, J., Barthelmes, F., *Wolf, D.*, 1999. Estimates of environmental effects in superconducting gravimeter data. *Bull. Inf. Mareés Terr.*, **131**, 10153-10159.

Piersanti, A., *Spada, G.*, Sabadini, R., Bonafede, M., 1997. Global post-seismic deformation. *Geophys. J. Int.*, **120**, 544-566.

Soldati, G., *Spada, G.*, 1999. Large earthquakes and earth rotation: the role of mantle relaxation. *Geophys. Res. Lett.*, **26**, 911-914.

Spada, G., 1995. Changes in the earth inertia tensor: the role of boundary conditions at the core-mantle interface. Geophys. *Res. Lett.*, **22**, 3557-3560.

Sun, W., *Okubo, S.*, 1998. Surface potential and gravity changes due to internal dislocations in a spherical earth-II. Application to a finite fault. *Geophys. J. Int.*, **132**, 79-88.

Sun, W., *Sjöberg, L.E.*, 1998. Gravitational potential changes of a spherically symmetric earth model caused by a surface load. *Phys. Chem. Earth*, **23**, 47-52.

Sun, W., *Sjöberg, L.E.*, 1999a. Gravitational potential changes of a spherically symmetric earth model caused by a surface load. Geophys. J. Int., **137**, 449-468.

Sun, W., *Sjöberg, L.E.*, 1999b. A new global topographic-isostatic model. *Phys. Chem. Earth*, **24**, 27-32.

Sun, W., *Okubo, S.*, Vaníèek, P., 1996. Global displacements caused by point dislocations in a realistic earth model. *J. Geophys. Res.*, **101**, 8561-8577.

Thoma, M., *Wolf, D.*, 1999. Bestimmung der Mantelviskosität aus Beobachtungen der Landhebung und Schwere in Fennoskandien. *Sci. Techn. Rep. GFZ Potsdam*, **STR 99/02**, 1-101.

Tromp, J., *Mitrovica, J.X.*, 1999a. Surface loading of a viscoelasic earth-I. General theory. *Geophys. J. Int.*, **137**, 847-855.

Tromp, J., *Mitrovica, J.X.*, 1999b. Surface loading of a viscoelastic earth-II.~Spherical models. *Geophys. J. Int.*, **137**, 856-872.

Varga, P., *Grafarend, E.W.*, *Engels, J.*, 1999. Earth tide generated variations of second degree geopotential. *Bull. Inf. Mareés Terr.*, **131**, 10217-10223.

Vermeersen, L.L.A., Sabadini, R., 1997. A new class of stratified viscoelastic models by analytical techniques. *Geophys. J. Int.*, **129**, 531-570.

Vermeersen, L.L.A., Sabadini, R., Spada, G., 1996. Compressible rotational deformation. *Geophys. J. Int.*, **126**, 735-761.

Vermeersen, L.L.A., Fournier, A., Sabadini, R., 1997. Changes in rotation induced by Pleistocene ice masses with stratified analytical earth models. *J. Geophys. Res.*, **102**, 27689-27702.

Wieczerkowski, K., *Wolf, D.*, 1998. Viscoelastic tidal dissipation in planetary models, in Ducarme, B., Pâquet, P., eds., *Proc. 13th Int. Symp. Earth Tides, Brussels*, pp. 277-285. Royal Observatory of Belgium, Brussels.

Wolf, D., 1997. Gravitational viscoelastodynamics for a hydrostatic planet. Veröff. Deut. Geodät. Komm., Reihe C, **452**, 1-96

Wolf, D., 1998. Gravitational-viscoelastic field theory, in Wu. P., ed., *Dynamics of the Ice Age Earth: A Modern Perspective*, pp. 55-86. Trans Tech Publications, Uetikon.

Wolf, D., Barthelmes, F., Sigmundsson, F., 1997a. Predictions of deformation and gravity variation caused by recent change of Vatnajökull ice cap, Iceland. *Compt. Rend. J. Luxemb. Geodyn*., **82**, 36-42.

Wolf, D., Barthelmes, F., Sigmundsson, F., 1997b. Predictions of deformation and gravity change caused by recent melting of the Vatnajökull ice cap, Iceland, in Segawa, J., Fujimoto, H., Okubo, S., eds., *Gravity, geoid and marine geodesy*, pp. 311-319. Springer, Berlin.

Yu, T.-T., *Fernández, J.*, Rundle. J.B., 1997. Subsurface deformation and geoid changes due to earthquakes. *Publ. Inst. Astron. Geod*., **191**, 33-50.

Abstracts, bibliography

Wolf, D., ed., 1997. Special Study Group 4.176: Models of Temporal Variations of the Gravity Field, First Meeting, Walferdange, Luxembourg, 17-19 March 1997, *Abstracts*, GeoForschungsZentrum, Potsdam.

Wolf, D., ed., 1998. Special Study Group 4.176: Models of Temporal Variations of the Gravity Field, Second Meeting, Potsdam, Germany, 23-25 November 1998, *Program and Abstracts*, GeoForschungsZentrum, Potsdam.

Wolf, D., ed., 1999. Special Study Group 4.176: Models of Temporal Variations of the Gravity Field, *Bibliography: 1960-1999*, GeoForschungsZentrum, Potsdam.

Report of International Association of Geodesy Section V

GEODYNAMICS

for the period 1995-1999

President: M. Feissel, France
Secretaries: C. Wilson, USA
H.-G. Wenzel (Commission V), Germany
T. Tanaka (CommissionVII), Japan

Introduction

IAG Section V "Geodynamics" deals with topics at the frontier of geodesy and geophysics. It is concerned by a number of interdisciplinary research and service activities. The interactions between geodesy and geophysics are both ways: global geodetic results homogeneous in time and space provide essential information for understanding the dynamics of deformations and interactions of the various layers of our planet, while the precise knowledge of the influence of these phenomena on the stations is indispensible for using the full precision capability of the observing techniques. Typical of Section V are also the interactions between the research and service activities: studies performed in Commissions, Special Commissions or Special Study Groups may help in the development of the services, while topical research developped in the latter in order to maintain state of the art performance results in an increased capability for the whole community. The general research themes under Section V can be summarized as follows.

Global references, solid earth deformations :

- International Terrestrial Reference System and Frame
- Crustal deformations
- Earth tides

Kinematics and dynamics of fluid layers (atmosphere, oceans, ground water):

- Geodetic effects (ocean loading, pressure effects,…)
- Geophysical interpretation of time variations of the gravity field
- Influence on the Earth's orientation
  (length of day, precession-nutation, polar motion)
- Influence on the motion of the geocenter

References and models

These topics are basic to ensure the accuracy and consistency of geodetic results that will be used in geophysical studies. A number of Section V-related activities are devoted to them.

The *geodetic constants and models* imply the maintenance of the international atomic time scale TAI (Temps Atomique International) by the Time Section of the Bureau International des Poids et Mesures (BIPM). The Fundamental Constants in use in geodesy are dealt with by Special Commission 3, while the IERS maintains a set of state of the art models necessary in the estimation and interpretation of the Earth's rotation and deformations, the IERS Conventions (most recent issue in 1996, next one due in 2000).

The provision of accurate and dense *terrestrial references* at a precision level that matches the most demanding scientific research is one of the basic responsibilties of the International Earth Rotation Service (IERS), in charge of the maintenance of the International Terrestrial Reference Frame (ITRF), in close cooperation with technique-oriented services currently linked to Section II : the International GPS Service (IGS), and the newly created International Laser Ranging Service (ILRS) and International VLBI Service for Geodesy and Astrometry (IVS, also linked to the International Astronomical Union). The IERS set up a Working Group on the ITRF Datum that clarified the various problems raised by the definition of a conventional terrestrial reference system.

The *geodetic monitoring of tide gauges* is indeed a key constituent of the study of global sea level changes and their climatic implications. Its is currently performed jointly by the Permanent Service for Mean Sea Level (PSMSL) and the IGS, with the support of Special Commissions 8 on Sea Level and Ice Sheet Variations.

The *Earth orientation monitoring* is another basic responsibility, performed at the level of accuracy of a fraction of one milliarcsecond (mas) by the IERS.

Earth deformations

Data collection, validation, analysis and distribution of results on *Earth tides* is the responsibility of the International Center for Earth Tides (ICET), supported by the Earth Tides Commission (Commission V). Studies beyond the Earth tides *per se* make use of a worldwide network of cryogenic gravimeters to investigate regional phenomena such as tidal loading, atmospheric pressure effects, underground water effects, as well as global modes of the Earth's core and mantle, in the framework of the Global Geodynamic Project (GGP), whose Data Center is at ICET.

Crustal deformations and the geodetic aspects of *natural hazards* are intensively studied in the general scientific community. In the last quadrienniums, the implication Section V in these studies was under the Commission on Recent Crustal Movements (CRCM, Commission VII), while a Section II sub-commission, WEGENER, delt with Europe and the Eastern Mediterranean region. Following an examination of means and objectives in this research field by Section V, the IAG Executive Committee decided to merge these two bodies into a new Commission on Crustal Deformations under Section V. Two SSGs have studied geodetic effects associated with earthquakes: gravity changes (SSG 5.172) and plumb line changes (SSG 5.173).

Geodetic implications of atmospheric and oceanic effects

This field is by definition a place for *interdisciplinary cooperations* between Geodesy, Geophysics, Oceanography, and Atmospheric Sciences. The intent in creating in 1995 a Special Commission 8 on Sea Level and Ice Sheet Variations was to offer a support to these interactions by fostering interdisciplinary studies and projects, with the expectation to provide a connection with the International Geosphere Biosphere Project (IGBP). Due to various circumstances within Section V, the intense activity that took place in this field during the 1995-1999 period was only loosely linked to this Special Commission. Nevertheless, the the IAG Executive Committee decided to persist in this action, where its role of international coordination could be of special importance.

The control of *site motions* for the validation and interpretation of observed sea level changes is a matter of interest and responsibility for the ICET, the Earth Tides Commission, the IGS and the IERS, while the *sea level monitoring* is the responsibility of the PSMSL, in cooperation with international projects outside IAG, such as the Global Sea Level Observing System (GLOSS), a project of the Intergovernmental Oceanographic Commission (IOC).

Section V bodies have played a prominent role in the study of a number of *global geophysical processes.*

The IAU-IUGG Working Group on *Nutation of the non rigid Earth* completed a comprehensive analysis of all aspects concerned by the phenomenon : seismic input models for computing the Earth's transfer function for nutations, construction of this transfer function, validation of the rigid Earth nutation theories (at the level of a few tens of microarcseconds), convolution between the transfer function and the rigid Earth nutation theory, and finally the comparison with the VLBI observations.

The geophysical interpretation of *temporal variations of the geopotential* were studied by SSG 5.174, while the IERS/ITRF Datum WG conducted a very successful *Geocenter motion* analysis campaign.

SSG 5.173 on 'Interaction of the Atmosphere and Oceans with the Earth's Rotational Dynamics' continued the action of a series of SSGs started in 1983 for the study of the *atmospheric and oceanic influence on the Earth's rotation*, in close interaction with the IERS. This long term project could provide an inspiring example of specific IAG action and influence in the Earth Sciences through two types of organisational devices, SSGs and Services working in mutual support. The first two SSGs of the series fostered the evolution of knowledge and performance in atmospheric excitation of the Earth's rotation irregularities that led to the creation of an Atmospheric Angular Momentum sub-bureau (SBAAM) in the newly formed IERS (1988). Then the SSGs in the series served as research support to this service activity, while continuing the extension of the research to other global geophysical fluids (ocean, groundwater, core,…). When IERS organized in 1996 a general review of its activity and performance, time was ripe for recommending an extension of its mission to the monitoring of these phenomena. The establishment of the Geophysical Fluid Centers activity under the IERS, in 1997, now offers a structure to provide data and to further stimulate research in this area. There is common ground with other important geodetic problems, notably the study of time variable gravity from space, variations in the geocenter, and the study of nutation and precession. The 1999-2003 item in the series of SSGs will be an joint IAG/IAPSO Working group which will engage geodetic and oceanographic communities, while strengthening the efforts of the IERS Geophysical Fluid Center for the Oceans.

Summary of the structure, 1995-1999

A total of 13 bodies were connected to Section V during the 1995-1999 term, including 8 permanent ones . The reports and recommendations of these bodies can be found in this volume.

Two commissions :

- Commission V: Earth tides, President: H.-G. Wenzel (Germany)
- Commission VII: Recent Crustal Movements, President: T. Tanaka (Japan)

Two special commissions :

- Special Commissions 3: Fundamental Constants, President: E. Groten (Germany)
- Special Commissions 8: Sea Level and Ice Sheet Variations, President: W.E. Carter (USA), then G. Blewitt (UK)

Three FAGS services:

- International Center of Earth Tides (ICET). Director: P. Melchior (Belgium) until the end of 1995; B. Ducarme (Belgium) starting in 1996.
- International Earth Rotation Service (IERS). Chairman of the Directing Board: C. Reigber (Germany). Director of the Central Bureau: M. Feissel (France) until the end of 1997; D. Gambis (France) starting in 1998.
- Permanent Service for Mean Sea Level (PSMSL). Director: P. L. Woodworth (UK)

One other permanent service:

- The Time Section of the BIPM (Bureau International des Poids et Mesures). Director: C. Thomas (France) until the end of 1998 ; acting Director: G. Petit (France) starting in 1999.

And five limited-term study/working groups :

- SSG5.172 Understanding Natural Hazards-The Geodetic Contribution, Chair: S. Okubo (Japan)
- SSG5.173 Seafloor Interaction of the Atmosphere and Oceans with Earth's Rotational Dynamics, Chair: C. Wilson (USA)
- SSG5.174 Geophysical Interpretation of Temporal Variations of the Geopotential, Chair: A. Cazenave (France)
- SSG5.175 Interannual Variations of the Vertical and Their Interpretation, Chair: Z.X. Li (China)
- Joint IAU-IUGG Working Group on Nutation of the nonrigid Earth, Chair: V. Dehant (Belgium)

REPORT OF THE ACTIVITY OF THE COMMISSION ON RECENT CRUSTAL MOVEMENTS FOR THE PERIOD 1995- 1999

Commission VII

President: Torao Tanaka
Kanazawa University
Faculty of Science
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Kanazawa 920-11
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The objectives of the Commission on Recent Crustal Movements(RCM) are:
- to promote the study of recent crustal movements,
- to promote and coordinate international cooperation in research of recent crustal movements, and
- to support to exchange information and to publish the results of international studies.

We decided the programs of activities for these objectives as:

- investigation of recent crustal movements by space techniques and conventional methods from the global viewpoint of geodynamics,
- improvement of methods for monitoring recent crustal movements of various scales as well as for data processing and analysis to develop modelling the dynamical process and to understand the mechanism of the movements,
- cooperation with CSTG and geophysical study groups in order to promote the above activitites, and
- cooperation with oceanic science research groups in order to understand the crustal movements under the ocean bottom.

National Representatives:

F.J.J. Brouwer (The Netherlands)
G.Carrera (Canada)
K.Feigl (France)
B. Ducarme (Belgium)
K.Heki (Japan)
I.Joo (Hungary)
J. Krynski (South Africa)
J.Mierlo (Germany)
J. B.Minster (USA)
E.R.Pujol (Spain)
A. Tealeb (Egypt)

Bureau:

President: T. Tanaka (Japan)
Vice-president: P.Vanicek (Canada)
H.G. Kahle (Switzerland)
Secretary: Wolfgang Augath (Germany)
Member of Bureau: P.Vyskocil (Czech)

Chair of Subcommissions:

African Subcommission: A. Tealeb (Egypt)
Central and South America Subcommission: Heinz G. Henneberg (Venezuela)
Geodetic and Geodynamic Programmes of the Central European Initiative Subcommission: H.J. Sledzinski (Poland)

Activity in 1995 – 1999

IAG Regional Symposium on Deformations and Crustal Movements Investigations Using Geodetic Techniques

The Symposium was held from August 31 to September 5, 1996 in Szekesfehervar Hungary. The main topics were 1. Crustal deformations, 2. Recent crustal movements, 3. Data processing and data analysis, 4. Applications of up-to-date geodetic and seismological techniques, and 5. Deformations of special engineering structures. The symposium was organized by Geodesy Department of College for Surveying and Land Management of the University of Forestry and Wood Sciences, lead by Prof. I.Joo. 47 people participated from 14 countries and presented papers. The proceedings were also published by the College, which include 34 papers. The following resolutions were agreed to issue by the participants.

Resolution 1: The Symposium on Deformations and Crustal Movements

Investigations:
Noting the Resolutions No.3 and No.4 of the IAG Subcommission for Europe(EUREF) accepted in its last symposium held in Ankara, Turkey, May 22-25, 1996. Recognizing the importance of establishment of the recommended fundamental height reference system to be used in recent crustal movement studies for the whole area of the European continent; and Recommends that all the CRCM specialists and collaborating institutions work in their respective countries for realizing this goal. Similar unified height system should be suitable for other continents.

Resolution 2: The Symposium on Deformations and Crustal Movements

Investigations:
Recognizing the importance of space technique, and especially GPS technology for RCM studies. Recommends to all specialists and cooperating institutions to exchange experiences in planning, organizing GPS measurements and analyzing data at the establishment of local or regional networks. Furthermore emphasizes the necessity to investigate the conditions under which GPS technology can be applied to crustal movement studies including heights. It is also useful to calculate combined leveling and GPS networks together.

Resolution 3: The Symposium on Deformations and Crustal Movements

Investigations:
Recognizing the importance of the present results of the latest investigations for deformations and recent crustal movement (RCM) studies; Points out that the uplifting- subsiding tendencies of several regions are not supported geodetically; thus Recommends to establish new investigation lines at typical areas and to repeat their measurements at regular intervals.

Resolution 4: The Symposium on Deformations and Crustal Movements

Investigations:
Recognizing the importance of geological, geophysical, tectonic information in connection with deformations and crustal movement investigations; Recommends the usage of these information.

Resolution 5: The Symposium on Deformations and Crustal Movements

Investigations:
Recognizing that in many cases the effects of technogen interventions and crustal movements appear jointly; Recommends to consider the above mentioned at analysing measurement data and to separate them from one another as it is possible.

Resolution 6: The Symposium on Deformations and Crustal Movements

Investigations:
Recognizing that deformations of smaller intensity (movements of smaller velocity) can be investigated by repeated measurements executed within longer periods; Recommends the analysis of the data of previous measurements and their usage if they are suitable in the present investigations.

Resolution 7: The Symposium on Deformations and Crustal Movements

Investigations:
Recognizing the importance of the activities of the CERCOP group establishing CEGRN as a frame network for local geodynamic studies in Central and Eastern Europe recommends to give this initiative support from the IAG Commission "Recent Crustal Movements".

Resolution 8: The Symposium on Deformations and Crustal Movements

Investigations:
Considers the symposium and other events related to it as successful and fruitful and a remarkable advance in RCM studies, and expresses their heartfelt thanks to the Local Organizing Committee chaired by Prof. Istvan Joo for this wonderful organization and hospitality offered to all of participants during their stay in Szekesfehervar.

Report of the Ninth International Symposium on Recent Crustal Movements (CRCM'98)

The Symposium was originally scheduled to be held in Luxor. But due to the outrageous terrorist attack in Luxor in November 1997, there was a long e-mail discussion between the Local Organizing Committee and the IAG to decide under which security conditions the IAG would confirm its sponsorship to the Sympopsium to be held in Egypt. By big efforts of A.Tealeb, the Chair of the local Organizing Committee, and Egyptian colleagues, and K.-P.Schwarz, the President of IAG, and the supports by IAG officers, members of Scientific Organizing Committee and Convenors the place of the Symposium was eventually moved to Cairo and the IAG confirmed its sponsorship. The Symposium was successfully held in Cairo as scheduled from November 14 to 19, 1998 under quiet and comfortable conditions.

Session topics were (1) Advances in geodetic techniques applied to crustal movements, (2) Modelling of crustal movements for geophysical parameter estimation, (3) Global-scale crustal movements and the stability of plate interiors, (4) Crustal movements around plate boundaries, (5) Quaternary crustal movements and comparison with geodetic motion, (6) Application of geodesy to natural hazards research, and (7) Local deformation monitoring and regional control.

The number of participants were 46 from Egypt and 48 from 15 other countries, and about 70 papers were actually presented. The folloowing Symposium Recommendations were approved by the participants;

1. The 9th International Symposium on Recent Crustal Movements (RCM'98) in Cairo, 14-19 Nov.1998 looks forward to a continued support of IAG to international cooperation for the study of crustal deformations.
2. Recognizing the significant contribution to crustal deformation studies of consistent global references provided by the ITRF and the IGS GPS orbits, the 9th International Symposium on Recent Crustal Movements thanks the International Earth Rotation Service (IERS) and the International GPS Service for geodynamics (IGS) for their excellent work, and requests all stations of regional and even local RCM (recent crustal movements) projects to be connected to the ITRF.
3. Recognizing the importance of measuring crustal deformations at the regional scale for understanding the geophysical phenomena involved in the collision of the Africa, Arabia and Eurasia plates, the 9th International Symposium on Recent Crustal Movements strongly encourages the establishment of multi-national projects between interested countries for this purpose.
4. The 9th International Symposium on Recent Crustal Movements welcomes the proposal of the Finnish Geodetic Institute and Finnish National Committee of IUGG to host in Finland an International symposium on crustal deformations. It is suggested that this symposium concentrates on a limited number of themes.

Report of CRCM Meetings

1. Date: September 5, 1997 , 13:15-14:15

Place: Rio Centro Room G1, Rio de Janeiro , Brasil

Attendants: Ruizhi Chen, Jean Dickey, Martine Feissel, Marco Fermi, Erich Gubler, Heinz G. Henneberg, Salah Mahmoud, Juhani Kakkuri, Fabio Radicioni, Kamal Sakr, Buskhasel Schaffin, B. Kolimershe Sledzinski, Habil Janusz Sledzinski, Torao Tanaka, Petr Vanicek

Items :T.Tanaka reported the IAG Regional Symposium held at Szekesfehervar in Hungary from Aug.31 to Sept.5, 1996.

J. Sledzinski, Chairman of Subcommission "Geodetic and Geodynamic Programs of the DEI(Central European Initiative)", reported the establishment of Subcommission and its activity following the printed report, "Geodetic and Geodynamic Programmes of the CEI(Central European Initiative)" & poster S3.2-07-P). Attendants mourned the death of Prof.Yu.Boulanger (Bureau member of CRCM), and agreed to send our condolatory compliments to Mrs Boulanger.

Reports of subcommission activities: S.Mahmoud and K.Sakr reported that Egyptian colleagues were preparating satisfactorily the CRCM'98 Symposium in Luxor, Egypt. Attendants agreed the change of the chairman of the Central and South America Subcommission from Prof. Milton de Azevedo Campos to Prof.Heinz Henneberg. J.Dickey and T.Tanaka introduced the idea and proposal about "Crustal Deformation Bureau", which is a kind of expansion of the previous ICRCM(International Center for Recent Crustal Movements)

Information of future Symposium/Congress;

1. Current Crustal Movementand Hazard Reduction in East Asia and South-east Asia, in Wuhan, PR. China, Nov.4-7, 1997.
2. CRCM'98 International Symposium in Luxor, Egypt, Nov.14-19, 1998.
3. IUGG/IAG General Assembly, in Birmingham UK, July 18-30, 1999.

The National Representative for the Netherlands is Dr. Ir. Frits J.J. Brouwer, Phone: +31-15-2691111, Fax: +31-15-2618962, e-mail: f.j.j.brouer@mdi.rws.minvenw.nl

2. Date: November 16, 1998

Place: Movenpik Hotel(Cairo)

Attendants: Makoto Murakami, Yoshimitsu Okada, Gero W. Michel, Istvan Joo, Johani Kakkuri, Salah M. Mahmoud, St.Stiros, A.Tealeb, A.Grachev, T.Grachev, T.Guseva, S.Baranova, S.Takemoto, P.Bridle, W.Augath, K.Sakr, M.Dubrov, M.T.Prilepin

Items: M.Feissel explained the recent policy of IAG that CRCM as well as holding the next CRCM International Symposium should be reviewed and the reforming and the future of CRCM be discussed at the IAG Executive Committee Meeting since crustal deformation (movements) has now become an important subject not only in IAG but also Geophysics and other field.

Participants discussed the future activity of CRCM and agreed that the continuation and extension of the present activity in CRCM and holding International Symposium are important and necessary for the future development in the RCM research, and these opinions were included in the Resolutions. As to the next CRCM Symposium, J.Kakkuri commented that the Finnish Geodetic Institute/Finnish National Committee of IUGG would be able to organize the next meeting of the CRCM if accepted.

3. Date: July 22, 1999, 18:00-19:00

Place: Room 111, Law Building, University of Birmingham, UK

Attendants: Suzanna Zerbini, M.Negusin, Alessandro Capra, J.Kakkuri, Kosuke Heki, Ashraf Mousa, Salah Mahmoud, Janusz Sledzinski, H.Tealeb, M.Kumar, Heinz Henneberg, Jaroslav Simek, Petr Holota, Clark R.Wilson, Jack A.Weightman, Martine Feissel, Torao Tanaka

Items: T.Tanaka reported briefly the activity of CRCM in the term from 1995 to 99 based on the draft of the IAG Travaux. H.Tealeb reported the Ninth International Symposium on Recent Crustal Movements (CRCM'98) held in Cairo, from November 14 to 19, 1998. Attendants thanked H.Tealeb and Egyptian colleagues for their efforts. H.Henneberg, Chairman of Central and South America Subcommission, H.Tealeb, Chairman of African Subcommission and J.Slezinski, Chairman of Subcommission "Geodetic and Geodynamic Programs of the DEI(Central European Initiative)" gave brief reports of their activities as summarized in the Appendixes [1],[2] and [3] in the following. T.Tanaka reported that the IAG has decided the change of Commission VII Recent Crustal

Movement to"Crustal Deformation Commission" and S.Zerbini has been elected as the president of the Commission. According to the Symposium Recommendation approved at the CRCM'98 in Cairo, the CRCM Meeting asked J.Kakkuri about the possibility of holding the next Symposium in Finland. Since the next IAG Scientific Meeting is planned to be held in 2001, the next Symposium should be held in 2002. J.Kakkuri commented that it will be possible to prepare to hold the Symposium in 2002. S.Zerbini mentioned the future of the Crustal Deformation Commission in IAG should be discussed in the next two years, and that the topics and themes of the next symposium in Finland are also considered and fixed in this new Commission.

Regarding the activity of new Commission, H.Henneberg commented importance of role of North American members especially, not only for the Central and South American Subcommission but also for the RCM community, and asked to the new president to include the members from the United States and Canada in the New Commission and expect active cooperation. M.Feissel and T.Tanaka gave their sincere thanks to the participants for their kind contributions to CRCM.

Appendix [1] :

REPORT OF SUB COMMISSION CENTRO-SOUTH AMERICA OF IAG COMMISSION ON RECENT CRUSTAL MOVEMENT (CRCM)

Introduction

The chairman of the subcommission designated in Boulder-Colorado 1995 during the last General Assembly of IUGG did not report any activities in this area, and was not present in the Scientific Assembly of IAG in Rio de Janeiro 1997. During this Assembly of IAG in Rio, the president of CRCM, Prof. Torao Tanaka, on occasion of the CRCM-Meeting proposed to reappoint the undersigned to organize again the subcommission as acting chairman, which was accepted by the present members.

Summary of the CRCM Sub-Commission Report presented at the 3. Venezuelan Congress on Geodesy, February 1998-cosponsered by IAG.

A. Transcription (partial) of the CRCM Meeting, Sept.5, 1998, Rio de Janeiro, Rio Centro Room G.1.
B. Introduction. Historical overview of the origen of the subcommission.
C. Geodynamics of the Caribbean:
   a) Near field and middle range neotectonic Geodesy.
   b) Continental and global neotectonic Geodesy.
   c) General Aspects of recent crustal movements and earth surface changes - national and international cooperation.
D. Different Progress Reports of the Sub Commission.
E. Report of the Geotraverse of the Venezuelan Andes (Saler-Linkwitz).
F. Large Scale Absolute Gravity Control in South America (The Jilag Campaigns).
G. Tectonic Movement Control of "El Tigre Fault in Argentina".
H. The Panama Report.
I. Report Costa Rica.
J. The CASA 93 program.
K. The Geodynamic Interaction of the mayor tectonic plates. Cocos, Nazca, South America, Caribbean.
L. Crustal Deformation along the Caribbean-South American plate Boundary derived from the CASA GPS project.

Remark:

a) The full report contains 17 pages with references in detail and is publishes in the proceedings of the congress 1998.

b) Independently, copies of the report were sent to: President of CRCM of IAG, President of IAG, Secretary of IAG.

1998 – 1999: Recent Developments, Contacts and Meeting Results.

1. 20 years of high precision gravimetric control along Bocomo Fault - Venezuelan Andes - Maracaibo 1998. (Hermann Drewes, Herbert Tremel, Klaus Stuber, Melvin Hoyer, Eugen Wildermann, Napoleon Hernandez, Angel Daal).
2. Crustal Deformations along the limit of the tectonic plates (Caribbean and South American) in Venezuela determined by the CASA Project - Maracaibo 1998. (Hermann Drewes, Klaus Kaniuth, Klaus Stuber, Herbert Tremel, Napoleon Hernandez, Melvin Hoyer, Eugen Wildermann, Hans Gert Kahle, Christian Straub).
3. High precision Near Field Geodetic Measurements, 1999, in the Mucubaji - Mitisus and Bocono Networks in Venezuela (field campaigns in execution at present) (Antonio Gonzalez).
4. Space Geodetic Observations of Nazca - South America Convergence across the Central Andes. (Edmundo Novabuena, Lisa Leff ler-Griffin, Ailin Mao, Timothy Dixon, Seth Stein, I.Selwyn Sacks, Leonidas Ocola, Michael Ellis - Science 1998, Vol.279).
5. Report "Brazil".
1) nominated and accepted Prof.Paulo Cesar L.Segantine (Univ. of Sao Paulo) as National Delegate of the CRCM Sub Commission.
2) Prof.H.Erwes reports. Strong earth surface movements in the mountain areas near Novo Friburgo (North of Rio de Janeiro). These movements affected very strongly roads and their environments. He proposes the application of terrestrial photogrammetry to evaluate the damages and to look for solutions (reconstruction).
6. Splitting of the "Humboldt-Glaciar" (Andes Venezolanos). First observations were realized 10 years ago by CEAPRIS(Comision Especial de prevencion de Riesgos Sismicos), the movement goes on - no measurements were realized (Seismic swarms were observed in no traditional areas).
7. Report Drewes 1999.
The 1999 CASA campaign along the Caribbean - South American plate Boundary was realized this year from March 3 to March 15. In Colombia a tide gage station was included in the measurements. (in Venezuela, tide gage stations were already included in the campaigns 1993 and 1996) (The complete paper will be presented in IUGG General Assembly 1999).
8. The Linkwitz Report - April 1999 (Extract of the personal contribution).
"Remarks for the continuation of the research work of the Andes Traverse (A.T.)". The research in the AT started 1988. Between 1983 - 1995 were realized several field campaigns and published. From the scientific point of view it is desirable to continue the geodetic research work toward the future. The following items are the contents of this "Free Air Laboratory". Measurement techniques, Cinematics in networks, Geoid changes, 3D Crustal Deformation (Bocono Fault), effectivity of inclination measurements in the fault area (a clinometric system is already installed) application of photogrammetry to study cinematic point fields, height reference sistems in the context of levelling, GPS, trigonometric height transfer and special items for interdisciplinary research (Geodesy, Geology, Geophysics). This Report 1999 was finished the 5th of May 1999 in Pechina ? Spain, Heinz G. Henneberg, Acting Chairman, Sub-Commission Central and South America of CRCM-IAG. Email: emalco@larural.es

Appendix [2]

REPORT OF THE "SUB-COMMISSION RCM IN AFRICA"

The activities of the "Sub-Commission in Africa" during the period 1995 - 1999 were slow according to various problems related with the situation in Africa as the finance needed for the cooperations between the African countries and running the proposed programs. For that reason most of the African countries are working individually and only for local problems. There is no any motions for the bulk of the African countries to cooperate in regional problems such as the establishment of a unified geodetic reference for Africa.
Except of the above mentioned conditions, different activities exist such as;
-- Operating laser ranging stations in Egypt (Helwan) and South Africa,
-- Operating permanent GPS station in Egypt (Helwan), Kenya and South Africa,
-- Cooperation between different countries to study the geodynamics of the east Mediterranian region (USA, Turkey, Bulgaria, Greece, Egypt, ...)
-- Cooperation between different countries to study the geodynamics of the west Mediterranian region (Italy, France, Aspain, Algeria, Morocco, ...)
-- The establishment and GPS measurement of different regional geodetic networks to study the geodynamics of different i,portant areas in Egypt (Sinai, greater Cairo, Aswan),

-- Setting programs for the geodynamic studies of Red Sea using GPS technique,
-- Operating earth tide gravimeter in Egypt (Helwan),
-- The establishment and measurement of geodetic networks to study local problems (El- Asnam in Algeria, Aswan in Egypt, ...)
-- Holding the 9th International Symposium on RCM in Cairo, Egypt from 14-19 November 1998.

Other Programs were prepared in order to study the geodynamics of;
-- The east African rift system,
-- The Red Sea, which of course need intensive cooperations between the interested African countries and international support.

Appendix [3]

PROGRESSIVE REPORT OF THE SUBCOMMISSION "GEODETIC AND GEODYNAMIC PROGRAMMES OF THE CENTRAL EUROPEAN INITIATIVE (CEI)"

1. Introduction

In February 1996 the present subcommission was founded to initiate the cooperation links between CEI WGST Section C and IAG. Prof.Dr.J.Slezinski(Poland) was elected as the Chairman.

The general charter duties are:
(1) coordination and/or integration of the international geodetic and geodynamic programmes supported by IAG and CEI,
(2) creation of close links between running projects of IAG and those of CEI (e.g. CEL CERGOP -Central Europe Regional Geodynamics Project and IGS and EUREF, use of CEI permanent GPS stations within IGS and other programmes for maintenance of the ETRF and ITRF, etc.),
(3) initialisation of common geodetic and geodynamic projects for the region of Central Europe and Europe,
(4) fostering the cooperation among universities and research centres from Central Europe and Western countries in the filed of geodesy and geodynamics, promoting actions contributing to the development of innovative technologies and participation of CEI scientists in international IAG research programmes.

The members and respective areas of activities are :
Janusz Sledzinski(Poland) - Chairman of the Subcommission,
Jozsef Adam(Hungary) - links between national geodetic/geodynamic networks and EUREF,
Kazimierz Czarnecki(Poland) - cooperation between European universities (links between CEI and FIG or IAG similar bodies, the Subcommission scientific secretary,
Istvan Fejes(Hungary) - links between CERGOP and other geodynamic IAG projects,
Jan Hefty(Slovakia) - problems of coordinate systems, EUREF,ITRF and ETRF,
Iginio Marson(Italy) - interregional gravimetric connections, gravimetric projects of IAG/CEI,
Peter Pesec(Austria) - geodynamic use of CEI permanent GPS stations within IGS programmes,
Ewald Reinhart(Germany) - links/coordination and fostering a collaboration among projects of EU (e.g.ESA) and those of IAG and CEI,
Jerzy Rogowski(Poland) - geodynamic use of CEL permanent GPS stations within
IGS and other IAG programmes,
Jaroslav Simek(Czech Republic) - problems of homogeneity and time changes of precise levelling networks and vertical datum in Central Europe.

2. Geodynamic Programmme CERGOP and Its Relation to Other European Projects

The main objectives of the project are: to integrate the geodynamic research in the Central European region based on high accuracy space geodetic measurements, to investigate the most profound geotectonic features in the Central European region, the Teisseyre-Tornquist zone, the Carpathians, the Bohemian Massif, the Pannonian Basin and the Alpine-Adria region as well as to provide a stable Central European GPS Reference Network(CEGRN) for sub-regional, local or across the borders investigations and deformation studies. 11 countries joined the Project in 1994.

Since 1994 five epoch monitoring campaigns of satellite GPS (Global Positioning System) have been carried out on this network in 1994, 1995, 1996, 1997 and 1999. The CERGOP Data Centre was established in 1994 and is hosted by the Observatory Lustbuhel, Graz, Austria. In a later stage of the project the number of processing centers increased to 8. A major development of the project was the establishment of CERGOR Study Groups(CSGs). The groups were formed by the collaboration of scientists from two or more member countries to carry out research in a particular field. The project participants have met regularly at the semi-annual CERGOP Working Conferences. The proceedings of these conferences were published in REPORTS ON GEODESY, by the Warsaw University of Technology. The scientific results were mainly presented at the bi-annual International Seminar on " GPS in Central Europe", organized by the FOMI Satellite Geodetic Observatory, Penc, in Hungary. The proceedings were also published in the REPORTS ON GEODESY series. Based on the results of CERGOP the velocity fields in the regions have been evaluated and the EUREF reference frame maintained.

First phase of the Project was concluded on 30 June 1998. The second phase of the project CERGOP-2 will include three new member countries; extension of the CEGRN will result in accepting in total more than 65 CERGOP(CEGRN) sites. There is a number of complementary investigations to CERGOP-2 which overlap our region and contribute to the understanding of the geophysical and structural complexity of Central Europe. The most significant overlapping projects are WEGENER, EUROPROBE, DOSE and UNIGRACE.

3. CEGRN and Levelling Networks: Status of Works on Levelling Networks and Vertical Datum in CEI Countries

The work has been mainly based on the activities of the study group CSG6,"CEGRN and Precise Height Determination". The main objective is to assign a couple of quantities, one geometrical and one physical - ellipsoidal height and geopotential number, respectively- to each CEGRN station and to investigate their possible time changes. The activities of the CSG6 are closely related to a number of projects developed under the umbrella of different scientific and governmental institutions.

At the initial stage the work of the CSG6 was mainly concentrated to the determination of geopotential numbers of CEGRN stations, namely a joint adjustment of primary levelling networks of CEI countries within the Unified European Levelling Network (UELN), and regional and local connection of CEGRN stations to UELN nodal points. The next stage is repeated CEGRN height determinations and interpretation of gravity field changes and geopotential model testing. The workshop of the CSG6 was held in Prague in April 25-26, 1996. Altogether 16 participants of 7 CEI countries took part in the workshop.

Up to now the necessary requirement for the unification of national vertical networks has been fulfilled in most CEI countries thanks to the activities of the BKG Frankfurt am Main (Aussenstelle Leipzig). At present the UELN is extended, in addition to "historical UELN countries" like Germany, Austria and Italy to the territories of Poland, Czech Republic, Slovak Republic, Hungary and Slovenia. Necessary levelling connections have been made between Croatia and Hungary, as well as between Slovakia, Hungary and Ukraine.

An important step towards unification of European vertical datums is the establishment of the European Vertical Network(EUVN). The realization stage of the project EUVN started in May 1997 by the EUVN GPS campaign with the participation of all CEI countries. The progress in unification and improvement of national vertical networks is summarized in national reports of individual countries presented every year at the EUREF symposia.

Most CEI/CERGOP countries make efforts towards the establishment of national geodynamical networks or at least local geodynamical networks in tectonically active areas.

A new project UNIHIP, directed to the merging and common analyses of national geodynamical networks of Hungary, Poland, Slovakia and the Czech Republic, was initiated in April 1999.

The joint effort of CEI countries resulted in formulation of a new project UNIGRACE which is directed to the homogenization and improvement of gravity reference frames of Central and East European countries. Successful is also the work on the unification of gravity networks of several CEI countries on the basis of long-term gravity measurements performed in mutual cooperation (e.g. Unified Gravity Network of Hungary, Slovakia and the Czech Republic).

4. Interregional Gravimetric Connections

The main core of the activities of the Subcommission in the field of interregional gravimetric connections and gravimetric projects has been the establishment and coordination of absolute gravity projects in Central Europe. Since an advanced technology in absolute gravimetry is now available in several academic and scientific institutions in Europe, a joint effort of members of IAG and of Subcommission has made it possible to coordinate and in some cases also to establish absolute gravity projects. The first project has seen the cooperation of absolute gravity teams of Finland, Germany, Austria, Italy and USA under a project coordinated by the Gravity Commission of IAG that was aimed at the establishment of absolute gravity sites in Croatia, Slovenia, Poland, Hungary, Lithuania, Latvia and Estonia. A second project, with the endorsement of the European Union, has been promoted and is presently carried out. The project, UNIGRACE (Unification of Gravity Systems in Central and Eastern Europe), is aimed at the establishment of absolute gravity in 17 sites in Germany (Wettzell and Rostock), Austria (Graz), Bulgaria(Sofia, Burgos), Czech Republic (Pecny), Finland (Metsahovi), Hungary (Penc), Italy (Trieste), Poland (Jozefoslaw, Wladyslawowo), Romania (Gilau, Constanta), Slovakia(Moda Pesky), Slovenia (Ljubliana, Zagreb) and Croatia(Dubrovnik). The gravity observations have been and will be made by five absolute meters from Austria, Finland, Germany, Italy/France and Poland in two observation campaigns in 1998 and 1999/2000.

Four review UNIGRACE conferences are planned in Germany, Poland, Bulgaria and Italy. The First UNIGRACE Working Conference was held in Frankfurt am Main (Germany) on 2-3 February 1998. The second was organised in Warsaw on 15-16 February 1999. 5. Geodynamic Use of CEI Permanent GPS Stations in IGS and Other IAG Programmes.

The great importance of permanent stations for practical geodetic works in every country and for research has been fully recognized in the research programmes of the Central European Initiative (CEI). The programme of the Section C recommends that each member country should establish and maintain at least one permanent station. The current situation indicates that at present (as on June 1999) there are about 40 permanent GPS stations operating in CEI countries: 15 permanent stations involved in the IGS international service and 25 stations in the maintenance of the EUREF. However it should be noted that all permanent stations are located on the territory of 8 CEI countries (Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Slovakia, Ukraine). Eight CEI countries have not yet established any GPS permanent station (Albania, Belarus, Bosnia&Herzegovina, Croatia, FYROM-Macedonia, Romania, Slovenia). 6. Cooperation with Other Organisations

In the reporting period, links and coordination of the two projects within CEI * Central European Regional Geodynamics Project (CERGOP), and * Unification of Gravity Systems in Central Europe (UNIGRACE) were established and maintained to other international organisations and agencies. In order to coordinate the contacts to the EUREF Subcommission of IAG, a close cooperation was established with the Technical Working Group (TWG) and the Analysis Centres of EUREF.

Contacts are established and maintained to the International Gravity Commission (IGS) of IAG and especially to Working Group 2,"World Gravity Standards". It is intended to provide the results of the project for the establishment of a unified Gravity System for all of Europe.

The cooperation between the CEI WGST Section C "Geodesy" and the European Geophysical Society (EGS) is also worth mentioning.

7. International Conferences and Symposia

Several international symposia sponsored by the IAG and/or by other organisations in the field of geodesy and geodynamics were organised in CEI countries in the last years. The EUREF Subcommission continued to have its yearly symposia in CEI countries in Sofia, Bulgaria, 7th Symposium, 4-7 June 1997, and Prague, Czech Republic, 9th Symposium, 2-5 June 1999. International seminar series on "GPS in Central Europe" was also continued at Penc, Hungary. The Second Continental Workshop on the Geoid in Europe was held in Budapest, Hungary on 10-14 March 1998. An IAG Regional Symposium on recent crustal movements was held in Szekesfehervar, Hungary in August-September in 1996.

8. Publication of Proceedings

The proceedings of the conferences and symposia organised by CEIWGST Section C "Geodesy" are published in the series PERORTS ON GEODESY edited by the Institute of Geodesy and Geodetic Astronomy of the Warsaw Univerity of Technology. 25 volumes were published so far.

Appendix [4]

THE DISSOLUITION OF ICRCM, PROPOSAL OF CRUSTAL DEFORMATION BUREAU, AND THE FUTURE OF CRCM

The International Center on Recent Crustal Movements (ICRCM) was dissolved as an IAG organization on July 1, 1996. This was decided at the IAG Meeting in Boulder in July 1995. ICRCM has done great contributions to the extension and promotion of international cooperations of recent crustal movement studies under the leadership of Dr. P. Vyskocil, the Director of ICRCM. The Executive Committee of IAG established an ad-hoc planning committee to investigate the neccessity of a new structure such as "Crustal Deformation Bureau". Prof. W. Prescott was nominated as the Chair of the committee.
The next is the notice by Prof. Prescott:

Ad Hoc Planning Group
Establishment of a Crustal Deformation Bureau Chairman: W. Prescott (United States)

I. Function
It has been suggested that the time is ripe for the formation of a Crustal Deformation Bureau, which would play a role in the coordination of international crustal deformation activities similar to the role of the International Earth Rotation Service for earth rotation activities. It is the aim of this study group to evaluate this idea and make a recommendation as to whether the Association should move forward with plans for such a Bureau. In order to make this decision it is necessary to clearly define the activities and structure envisioned for such a Bureau. If a decision is made that such a Bureau is worthwhile, the discussion of activities and structure will serve as a useful starting point for the design of the Bureau.

II. Objectives
1. To consider the necessity and usefulness of the formation of a Crustal Deformation Bureau,
2. To make recommendations about the scope of activities of such a Bureau.
3. To make recommendations for how such a Bureau would be structured.

III. Membership
[To be determined]

Until then Review Board "Current Activities and Future Needs of the International Center on Recent Crustal Movement (ICRCM)" had considered the findings of the ICRCM Review Committee and current and future needs of the international geodetic and larger geophysical communities as follows: The desirable activities of such a center had evolved and increased since the formation of ICRCM. The ICRCM provided useful services, particularly in the area of education and linkages to developing countries; however, it was not meeting all the current scientific needs. With maturing space technologies (GPS and others) and the wealth of data available, the Review Board proposed the formation of a Crustal Deformation Bureau (CDB) in which the demands would be met by a network of centers. The structure proposed parallels that of the International Earth Rotation Service(IERS). Three coordinating centers are suggested based on three measurement types: classical terrestrial, space geodetic, and remote sensing techniques. Further, the data archiving would be based at regional centers. A Central Bureau would act as the main contact point; activities would be overseen by a Directing Board. Remote sensing techniques (such as Interferometric Synthetic Aperture Radar) are now under development. One would envisage this service being formed in a two step process with the first two coordinating centers being formed at the outset of the CDB and the third center based on Remote Sensing initiated later as the techniques evolve and mature. The scope of the Bureau was envisaged to encompass both marine and continental crustal deformation. As such, it would serve the following associations: IAG, IASPEI, IAVCEI, IAPSO, IAHS, and IAGA, IAG being the leading association. Linkages would be made with the ICL, IERS, and the International GPS Service. Appropriate representation would be sought for the Directing Board.

```
      Central Bureau-------Directing Board
           |
           |
    Coordinating Centers.
           |
           |
  ---------------------------------------------------------------
  |                              |                  |
Ground-Based           Space Geodesy      Remote Sensing
Measurements                     |                     |
  |                              |                     |
Regional centers       Regional cenetrs      Regional centers
```

By the unfortunate resignation of Prof. Prescott from the Chair of the Ad Hoc Planning Committee due to his personal condition, the Committee has stopped its activity. Considering this situation and the need for better regional/international cooperation in crustal movement studies, IAG Executive Meeting held in Paris in March 1999 decided that the CRCM should consider not only the establishment of CDB but also the future of CRCM itself in the term from 1999 to 2000 considering the change and rapid progress of crustal movement studies in geodesy and geophysics.

REPORT OF SPECIAL COMMISSION 3 ON „FUNDAMENTAL CONSTANTS“ (SCFC) AT THE GENERAL ASSEMBLY OF IUGG AT BIRMINGHAM IN 1999

Erwin Groten
Technische Hochschule Darmstadt
Institut für Physikalische Geodäsie
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At present, systems of fundamental constants are in a state of transition. Even though the uncertainties of many constants have substantially decreased, the numerical values themselves did not substantially change. On the other hand, relativistic reductions and corrections underwent a variety of substantial revisions that, however, did not yet find final agreement within the scientific working groups of international committees in charge of evaluating relevant quantities and theories. Consequently, substantial changes and revisions still have to be expected in IAU, IERS, IUGG etc. within the next few years.

Therefore SC 3, after lengthy discussions and considerations, decided not to propose, at this time, any change of existing geodetic reference systems such as WGS 84 (in its recent form updated by NIMA, 1997) and GRS 80. This would only make sense in view of relatively small numerical changes which would not justify, at this moment, complete changes of systems and would rather produce more confusion within user communities – as soon as working groups within IAU, IERS etc. have made up their minds concerning the background of new systems and will be prepared to discuss new numerical values. This should be around the year 2001.

The present situation is also reflected by the fact that in view of substantial progress in evaluating temporal changes of fundamental „constants“ and related accuracies, we should better speak about „fundamental parameters“ instead of „fundamental constants“; however, the majority of members of SC 3 preferred to preserve the traditional name of SC 3.

In view of this situation and of the fact that IERS in its „conventions“ which are edited at regular intervals SC 3 cannot and should not act independently in proposing changes of fundamental parameters, - there will consequently be relatively small changes in the following part on „current best estimates“ and only minimal changes in the part on „official numerical values“ within this report. It is, moreover, proposed to strengthen the interrelations between IERS and SC 3.

Interrelations between IERS, IAU, IAG etc. make it, however, more difficult to implement necessary changes in fundamental systems. This was particularly realized in discussing adoption of new fundamental constants. This fact may be explained by the discussion of small changes inherent in the adoption of particular tidal corrections which became relevant in view of higher accuracies of $\pm 10^{-8}$ or $\pm 10^{-9}$. It turns out to be almost impossible to explain to other scientific bodies the modern relevance of the dependence of the numerical value of the semi-major axis „a“ of the Earth on specific tidal corrections. Other temporal variations imply similar difficulties.

From the view point of SC3, i.e. in deriving fundamental parameters, it is, to some extent, confusing that a variety of global or/and regional systems exist; it would be best to use only one global terrestrial and one celestial system such as ITRF, referred to a specific epoch, and an associated celestial system, unless precise transition and transformation formulas are available such as those between ETRF, ITRF, EUREF, and perhaps WGS 84 (in updated form), IGS, GRS 80 etc. where IERS-systems, in general, could serve to maintain transformation accuracy and precision.

However, the consequent replacement of „a“ by a quantity such as the geopotential at the geoid W_0 (which is independent of tides) in a geodetic reference system (or a similar system) was not well understood and not supported by other working groups so that we finally gave up the idea of a reformation of systems of fundamental constants in this way even though quantities such as W_0 are now very precisely determined by satellite altimetry etc. Whether seasonal variations (Bursa et al., 1998a) of W_0 are significant or not is still an open question, when expressed in $R_0 = GM/W_0$ they amount to a few centimeters in global radius.

In view of this over-all situation it may not be surprising that the following report deviates little from what SC 3 presented at the last General Assembly at Boulder/Colorado in 1995.

There will be a separate report of the Ad-Hoc Working Group (president: Prof. J. Rueger) on Refractive Indices of Light, Infrared and Radio waves in the Atmosphere, to be published together with this report.

1. Current (1999) best estimates of the parameters of common relevance to astronomy, geodesy, and geodynamics

SI units are used throughout (exept for the TDB-value (value below (4))
(SI-value can be associated with TCB or TCG)

- velocity of light in vacuum

  $c = 299\,792\,458 \text{ m s}^{-1}$. (1)

- Newtonian gravitational constant

  $G = (6\,672.59 \pm 0.30) \times 10^{-14} \text{ m}^3 \text{ s}^{-2} \text{ kg}^{-1}$. (2)

- Geocentric gravitational constant (including the mass of the Earth's atmosphere); reconfirmed by J. Ries (1998, priv. comm.)

  $GM = (398\,600\,441.8 \pm 0.8) \times 10^6 \text{ m}^3 \text{ s}^{-2}$; (3)

For the new EGM 96 global gravity model, $GM = 398\,600\,441.5 \times 10^6 \text{ m}^3 \text{ s}^{-2}$ was adopted.

In TT units (the Terrestrial Time) the value is

$GM = (398\,600\,441.5 \pm 0.8)$ ´ $10^6 \; m^3 \; s^{-2}$. *(4)*

Note that if expressed in old TDB units (the solar system Barycentric Dynamical Time), the value is

$GM = 398\,600\,435.6 \times 10^6 \text{ m}^3 \text{ s}^{-2}$.

Based on well known transformation formulas we may relate GM in SI-units to TT/TCG/TCB; see IERS-Convention 1996 p. 85. The well known secular term was not originally included in the GM(E)-analysis, therefore it was related to TT, nor SI nor (TCG, TCB); as still satellite analysis occurs without the secular term, GM(E) in TT is still of geodetic interest.

- Mean angular velocity of the Earth's rotation

  $\omega = 7\,292\,115 \times 10^{-11} \text{ rad s}^{-1}$. (5)

Table 1. Mean angular velocity of the Earth's rotation 1978-1994

Year **w** $[10^{-11} \text{ rad s}^{-1}]$	Year	ω $[10^{-11} \text{ rad s}^{-1}]$	**dLOD [ms]**
min: 1978 7 292 114.903	1994	7 292 114.964	2.17
max: 1986 292 115.043	1995	9.52	2.31
	1996	9.92	1.83
	1997	9.91	1.84
	1998	-	-

- Long-term variation in ω

$$\frac{d\omega}{dt} = (-4.5 \pm 0.1) \times 10^{-22} \, rad \;\; s^{-2}. \qquad (6)$$

This observed average value is based on two actual components:

a) due to tidal dissipation

$$\left(\frac{d\omega}{dt}\right)_{tidal} = (-6.1 \pm 0.4)\times 10^{-22}\, rad\ \ s^{-2}. \qquad (7)$$

This value is commensurate with a tidal deceleration in the mean motion of the Moon n.

$$\frac{dn}{dt} = (-25.88 \pm 0.5)\ \ arc\sec\ \ cy^{-2}. \qquad (8)$$

b) non-tidal in origin

$$\left(\frac{d\omega}{dt}\right)_{non-tidal} = (+1.6 \pm 0.4)\ \times\ 10^{-22} rad\ s^{-2}. \qquad (9)$$

- Second-degree zonal geopotential (Stokes) parameter (tide-free, conventional, not normalized, Love number k_2 = 0.3 adopted)

$$J_2 = (1082\ 626.7 \pm 0.1) \times 10^{-9}. \qquad (10)$$

To be consistent with the I.A.G. General Assembly Resolution 16, 1983 (Hamburg), the indirect tidal effect on J_2 should be included: then in the zero-frequency tide system

$$J_2 = (1082\ 635.9 \pm 0.1) \times 10^{-9}. \qquad (11)$$

Table 2. The Stokes second-degree zonal parameter; marked with a bar: fully normalized; k_2 = 0.3 adopted for the tide-free system

Geopotential model	Zero-frequency tide system		Tide-free	
	$\bar{J}_2$ [10^{-6}]	J_2 [10^{-6}]	$\bar{J}_2$ [10^{-6}]	J_2 [10^{-6}]
JGM-3 EGM 96	484.16951	1082.6359	484.16537 484.16537	1082.6267

- Long-term variation in J_2

$$\frac{dJ_2}{dt} = -(2.6 \pm 0.3)\times 10^{-9}\, cy^{-1} \qquad (12)$$

- second-degree sectorial geopotential (Stokes) parameters (conventional, not normalized, geopotential model JGM-3)

$$J_2^2 = (1574.5 \pm 0.7)\times 10^{-9}, \qquad (13)$$

$$S_2^2 = -(903.9 \pm 0.7)\times 10^{-9}, \qquad (14)$$

$$J_{2,2} = \left[\ (J_2^2)^2 + (S_2^2)^2\ \right]^{1/2} = (1815.5 \pm 0.9)\times 10^{-9}. \qquad (15)$$

Table 3. The Stokes second-degree sectorial parameters; marked with a bar: fully normalized

Geopotential model	$\bar{C}_2^2$ [10^{-6}]	$\bar{S}_2^2$ [10^{-6}]
JGM-3	2.43926	-1.40027
EGM 96	2.43914	-1.40017

Only the last decimal is affected by the st. dev.

For EGM 96 Marchenko and Abrikosov (1999) found more detailed values:

Table 3a. Parameters of the linear model of the potential of 2nd degree

Harmonic coefficient	Value of coefficient $\times 10^6$	Temporal variation $\times 10^{11}$[yr^{-1}]
$\bar{C}_{20} = \bar{J}_2$	-484.165371736	1.16275534
$\bar{C}_{21}$	-0.00018698764	-0.32
$\bar{S}_{21}$	0.00119528012	1.62
$\bar{C}_{22} = \bar{J}_2^2$	2.43914352398	-0.494731439
$\bar{S}_{22}$	-1.40016683654	-0.203385232

-Coefficient H associated with the precession constant

$$H = \frac{C - \frac{1}{2}(A+B)}{C} = (3\ 273\ 763 \pm 20) \times 10^{-9}. \tag{16}$$

- The geoidal potential W_0 and the geopotential scale factor $R_0 = GM/W_0$ recently derived by Bursa et al. (1998) read

$$W_0 = (62\ 636\ 855.611 \pm 0.5)\ m^2s^{-2},$$
$$R_0 = (6\ 363\ 672.58 \pm 0.05)\ m. \tag{17}$$

$W_0 = (62636856.4 \pm 0.5)\ m^2s^{-2}$ J. Ries (priv. comm, 1998) found globally.

If W_0 is preserved as a primary constant the discussion of the ellipsoidal parameters could become obsolete; as the Earth ellipsoid is basically an artifact. Modelling of the altimeter bias and various other error influences affect the validity of W_0-determination. The variability of W_0 and R_0 was studied by Bursa (Bursa et al., 1998) and associates recently; they detected interannual variations of W_0 and R_0 amounting to 2 cm.

The relativistic corrections to W_0 were discussed by Kopejkin (1991); see his formulas (67) and (77) where tidal corrections were included. Whereas he proposes average time values, Grafarend insists in corrections related to specific epochs in order to illustrate the time-dependence of such parameters as W_0, GM, J_n, which are usually, in view of present accuracies, still treated as constants in contemporary literature.

Based on recent GPS data, E. Grafarend and A. Ardalan (1997) found locally (in the Finnish Datum for Fennoscandia):

$W_0 = (6\ 263\ 685.58 \pm 0.36)$ kgal m.

The temporal variations were discussed by Wang and Kakkuri (1998), in general terms.

- Mean equatorial gravity in the zero-frequency tide system

$$g_e = (978\ 032.78 \pm 0.2) \times 10^{-5} m\ s^{-2}. \tag{18}$$

- Equatorial radius of the Reference Ellipsoid (mean equatorial radius of the Earth) in the zero-frequency tide system (Bursa et al. 1998)

$$a = (6\ 378\ 136.62 \pm 0.10)\ m. \tag{19}$$

- The corresponding value in the mean tide system (the zero-frequency direct and indirect tidal distortion included) comes out as

$$a = (6\,378\,136.72 \pm 0.10)\text{ m} \quad (20)$$

and the tide-free value

$$a = (6\,378\,136.59 \pm 0.10)\text{ m}. \quad (21)$$

The tide free-value adopted for the new EGM-96 gravity model reads a = 6 378 136.3 m.

- Polar flattening in the zero-frequency tide system, computed (adopted GM, ω, and J_2 in the zero-frequency tide system)

$$1/f = 298.25642 \pm 0.00001 \quad (22)$$

The corresponding value in the mean tide system comes out as

$$1/f = 298.25231 \pm 0.00001 \quad (23)$$

and the tide-free

$$1/f = 298.25765 \pm 0.00001 \quad (24)$$

- Equatorial flattening (geopotential model JGM-3).

$$1/\alpha_1 = 91\,026 \pm 10. \quad (25)$$

- Longitude of major axis of equatorial ellipse, geopotential model JGM-3

$$\Lambda_a = (14.9291° \pm 0.0010°)\text{ W}. \quad (26)$$

In view of the small changes (see Table 3) of the second degree tesserals it is close to the value of EGM 96. We may raise the question whether we should keep the reference ellipsoid in terms of GRS 80 (or an alternative) fixed and focus on W_0 as a parameter to be essentially better determined by satellite altimetry, where however the underlying concept (inverted barometer, altimeter bias etc.) has to be clarified.

Table 4. Equatorial flattening α_1 and Λ_a of major axis of equatorial ellipse

Geopotential model	$\frac{1}{\alpha_1}$	Λ_a [DEG]
JGM-3	91026	14.9291 W

- Coefficient in potential of centrifugal force

$$q = \frac{\omega^2 a^3}{GM} = (3\,461\,391 \pm 2) \times 10^{-9}. \quad (27)$$

Computed by using values (3), (5) and a = 6 378 136.6

- Principal moments of inertia (zero-frequency tide system), computed using values (11), (15), (3), (2) and (16)

$$\frac{C-A}{Ma_0^2} = J_2 + 2J_{2,2} = (1086.267 \pm 0.001) \times 10^{-6}, \quad (28)$$

$$\frac{C-B}{Ma_0^2} = J_2 - 2J_{2,2} = (1079.005 \pm 0.001)\times 10^{-6},$$
$$\frac{B-A}{Ma_0^2} = 4J_{2,2} = (7.262 \pm 0.004)\times 10^{-6};$$
$$Ma_0^2 = \frac{GM}{G} a_0^2 = (2.43014 \pm 0.00005)\times 10^{38} kg\ m^2, \quad (29)$$

(a_0 = 6 378 137 m);

$$C–A = (2.6398 \pm 0.0001) \times 10^{35} \text{ kg m}^2, \quad (30)$$

$$C–B = (2.6221 \pm 0.0001) \times 10^{35} \text{ kg m}^2,$$

$$B–A = (1.765 \pm 0.001) \times 10^{33} \text{ kg m}^2;$$

$$\frac{C}{Ma_0^2} = \frac{J_2}{H} = (330\ 701 \pm 2)\times 10^{-6}, \text{ B–A} = (1.765 \pm 0.001) \times 10^{33} \text{ kg m}^2;$$

(31)

$$\frac{A}{Ma_0^2} = (329\ 615 \pm 2)\times 10^{-6},$$
$$\frac{B}{Ma_0^2} = (329\ 622 \pm 2)\times 10^{-6};$$

$$A = (8.0101 \pm 0.0002) \times 10^{37} \text{ kg m}^2,$$
$$B = (8.0103 \pm 0.0002) \times 10^{37} \text{ kg m}^2, \quad (32)$$
$$C = (8.0365 \pm 0.0002) \times 10^{37} \text{ kg m}^2,$$

(33)

$$\alpha = \frac{C-B}{A} = (327\ 353 \pm 6)\times 10^{-8}, \quad \gamma = \frac{B-A}{C} = (2\ 196 \pm 6)\times 10^{-8}.$$
$$\beta = \frac{C-A}{B} = (329\ 549 \pm 6)\times 10^{-8},$$

II Primary geodetic Parameters, discussion

It should be noted that parameters a, f, J_2, g_e, depend on the tidal system adopted. They have different values in tide-free, mean or zero-frequency tidal systems. However, W_0 and/or R_0 are independent of tidal system (Bursa 1995). The following relations can be used:

$$\text{a (mean)} = \text{a (tide-free)} + \frac{1}{2}(1+k_s)R_0\frac{\delta J_2}{k_s}, \quad (34)$$

$$\alpha \text{ (mean)} = \alpha \text{ (tide-free)} + \frac{3}{2}(1+k_s)\frac{\delta J_2}{k_s};$$

$$\text{a (zero-frequency)} = \text{a (tide-free)} + \frac{1}{2}R_0\delta J_2; \quad (35)$$

$$\alpha \text{ (zero-frequency)} = \alpha \text{ (tide-free)} + \frac{3}{2}\delta J_2;$$

k_s = 0.9383 is the secular Love number, δJ_2 is the zero-frequency tidal distortion in J_2. First, the internal consistency of parameters a, W_0, (R_0) and g_e should be examined:

(i) If

$a = 6\ 378\ 136.7$ m

is adopted as primary, the derived values are

$W_0 = 62\ 636\ 856.88\ m^2\ s^{-2}$, (36)

($R_0 = 6\ 363\ 672.46$ m), (37)

$g_e = 978\ 032.714 \times 10^{-5}\ m\ s^{-2}$. (38)

(ii) If

$W_0 = (62\ 636\ 855.8 \pm 0.5)\ m^2\ s^{-2}$,

$R_0 = (6\ 363\ 672.6 \pm 0.05)$ m,

is adopted as primary, the derived values are (mean system)

$a = 6\ 378\ 136.62$ m, (39)

$g_e = 978\ 032.705 \times 10^{-5}\ m\ s^{-2}$. (40)

(iii) If (18)

$g_e = (978\ 032.78 \pm 0.2) \times 10^{-5}\ m\ s^{-2}$,

is adopted as primary, the derived values are

$a = 6\ 378\ 136.38$ m, (41)

$W_0 = 62\ 636\ 858.8\ m^2\ s^{-2}$ (42)

($R_0 = 6\ 363\ 672.26$ m). (43)

There are no significant discrepancies, the differences are about the standard errors.

However, the inaccuracy in (iii) is much higher than in (i) and/or (ii). That is why solution (iii) is irrelevant at present.

If the rounded value

$W_0 = (62\ 636\ 856.0 \pm 0.5)\ m^2\ s^{-2}$ (44)

$R_0 = (6\ 363\ 672.6 \pm 0.1)$ [m] (45)

is adopted as primary, then the derived length of the semimajor axis in the mean tide system comes out as

$a = (6\ 378\ 136.7 \pm 0.1)$ m mean: 6 378 136.7
zero: 136.6 (46)

which is just the rounded value (20), and (in the zero frequency tide system)

$g_e = (978\ 032.7 \pm 0.1) \times 10^{-5}\ m\ s^{-2}$. (47)

However, SCFC recommends that, at present, GRS 1980 should be retained as the standard.

III Consistent set of fundamental constants (1997)

- Geocentric gravitational constant (including the mass of the Earth's atmosphere)

$GM = (398\ 600\ 441.8 \pm 0.8) \times 10^{6}\ m^{3}\ s^{-2}$,
[value (3)]

- Mean angular velocity of the Earth's rotation

$\omega = 7\ 292\ 115 \times 10^{-11}\ rad\ s^{-1}$
[value (5)]

- Second-degree zonal geopotential (Stokes) parameter (in the zero-frequency tide system, Epoch 1994)

$J_2 = (1\ 082\ 635.9 \pm 0.1) \times 10^{-9}$
[value (11)]

- Geoidal potential

$W_0 = (62\ 636\ 856.0 \pm 0.5)\ m^2\ s^{-2}$,
[value (44)]

- Geopotential scale factor

$R_0 = GM/W_0 = (6\ 363\ 672.6 \pm 0.05)$ m
[value (45)]

- Mean equatorial radius (mean tide system)

$a = (6\ 378\ 136.7 \pm 0.1)$ m
[value (46)]

- Mean polar flattening (mean tide system)

$1/f = 298.25231 \pm 0.00001$
[value (23)]

- Mean equatorial gravity

$g_e = (978\ 032.78 \pm 0.1) \times 10^{-5}\ m\ s^{-2}$,
[value (18)]

Grafarend and Ardalan (1999) have evaluated a (consistent) normal gravity field based on a unique set of current best values of four parameters (W°, ω, J_2 and GM) as a "follow-up" to the Geodetic Reference System GRS 80 leading to a level-ellipsoidal normal gravity field with a spheroidal external field in the Somigliana-Pizetti sense. By comparing the consequent values for the semimajor and semi-minor axes of the related equipotential ellipsoid with the corresponding GRS-80 axes (based on the same theory) the authors end up with axes which deviate by –40 and –45 cm, respectively from GRS 80 axes and within standard deviations from the current values such as in (21); but no g-values are given.

IV Appendix

A1. Zero-frequency tidal distortion in J_2

($J_2 = -C_{20}$)

$$\delta J_2 = k_s \frac{GM_L}{GM}\left(\frac{\overline{R}}{\Delta_{\oplus L}}\right)^3\left(\frac{\overline{R}}{a_0}\right)^2 (E_2 + \delta_{2L}) + $$
$$+ k_s \frac{GM_S}{GM}\left(\frac{\overline{R}}{\Delta_{\oplus S}}\right)^3\left(\frac{\overline{R}}{a_0}\right)^2 (E_2 + \delta_{2S}),$$

$$E_2 = -\frac{1}{2} + \frac{3}{4}\sin^2 \varepsilon_0 ,$$

$$\delta_{2L} = \frac{3}{4}\left(\sin^2 i_L - e_L^2\right) + \frac{9}{8} e_L^2 \left(\sin^2 \varepsilon_0 - \sin^2 i_L\right),$$

$$\delta_{2S} = -\frac{3}{4} \; e_S^2 \; \left(1 - \frac{3}{2}\sin^2 \varepsilon_0\right),$$

$$\overline{R} = R_0 \left(1 + \frac{25}{21} \; v^3 q - \frac{10}{7} \; v^2 J_2\right)^{1/5}$$

GM_L = 4 902.799 × 10^9 m^3s^{-2} (selenocentric grav. Const.),
GMS = 13 271 244.0 × 10^{13} m^3s^{-2},
$\Delta_{\oplus L}$ = 384 400 km (mean geocentric distance to the Moon),
$\Delta_{\oplus S}$ = 1 AU = 1.4959787 × 10^{11} m,
a_0 = 6 378 137 m (scaling parameter associated with J_2),
ε_0 = 23°26'21.4" (obliquity of the ecliptic),
e_L = 0.05490 (eccentricity of the orbit of the Moon),
i_L = 5°0.9' (inclination of Moon's orbit to the ecliptic),
e_S = 0.01671 (eccentricity of the heliocentric orbit of the Earth-Moon barycenter),
ν = a_0/R_0 = 1.0022729;
k_s = 0.9383 (secular-fluid Love number associated with the zero-frequency second zonal tidal term);
$\delta J_2 = -\delta C_{20}$ = (3.07531 × 10^{-8}) k_s (conventional);
$d\overline{J}_2 = -d\overline{C}_{20}(1.37532 \times 10^{-8)} k_s$ (fully normalized).
L = Lunar
S = Solar

A2. Definition

Because of tidal effects on various quantities, the tide-free, zero-frequency and mean values should be distinguished as follows:

- A tide-free value is the quantity from which all tidal effects have been removed.
- A zero-frequency value includes the indirect tidal distortion, but not the direct distortion.
- A mean tide value included both direct and indirect permanent tidal distortions.

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References

Bursa M (1992) The four primary geodetic parameters. Studia geoph. et geod. 36, 199-206

Bursa M (1995) Special Commission 3, Fundamental Constants (SCFC), Report submitted to IAG, IUGG Gen. Ass., Boulder, Travaux IAG, Tome 30, 370-384, Paris 1995

Bursa M, J Kouba, K Radej, SA True, V Vatrt, M Vojtiskova (1997) Monitoring geoidal potential on the basis of Topex/Poseidon altimeter data and EGM 96. Geodesy on the Move, IAG Sci. Ass. Rio de Janeiro, Sept. 3-9, 1997, Springer Verlag 1998, 352-358

Bursa M, K Radej, Z Sima, SA True, V Vatrt (1997) Tests for accuracy of recent Geopotential models. Intern. Geoid Service, Bulletin 6, 167-188, Milano

Bursa, M, J Kouba, K Radej, SA True, V Vatrt, M Vojtisková (1998a) Monitoring Geoidal Potential on the Basis of Topex/Poseidon Altimeter Data. Aviso Altimetry Newsletters 6, 130-131

Bursa M, J Kouba, A Muller, K Radej, SA True, V Vatrt, M Vojtiskova (1998b) Determination of Geopotential Differences between local vertical Datums and realization of a world height system. Pres. Symp. IAG, München

Bursa M, GV Demianov, MI Yurkina (1998c) On the determination of the earth's model – the mean equipotential surface. Studia geoph. et geod. 42, 467-471

Bursa M, J Kouba, K Radej, SA True, V Vatrt, M Vojtiskova (1998d) Mean earth's equipotential surface from Topex/Poseidon altimetry. Studia geoph. et geod. 42, 459-466

Bursa M, J Kouba, K Radej, SA True, V Vatrt, M Vojtiskova (1998e) Final Report on testing accuracy of geopotential models EGMX05. EGM 96. Intern. Geoid Service, Bulletin N. 7

Cheng MK, RJ Eanes, BD Tapley (1992) Tidal deceleration of the Moon's mean motion. Geophys. J. Int. 108, 401-409

Defraigne P, V Dehant (1996) Toward new non-rigid Earth nutations. Proc. Journ. De Reference 1995, ed. Capitaine N, Warsaw, 45-52

Dehant V, M Capitaine (1997) On the luni-solar precession, the tilt-over-mode, and the oppolzer terms. Celest. Mech. (Manuscript in press)

Dehant V, P Defraigne (1997) New nutation for a non-rigid Earth. Proc. Journ. Syst. de Reference, Sept. 1996 Paris, ed. N Capitaine (Manuscript in press)

Dehant V, N Capitaine, P Defraigne (1997) Comparison between values of the dynamical flattening of the Earth derived from various kinds of observations. Precession J_2 Seismology, Proc. Journ. Syst. de Reference, Sept. 1996 Paris, ed. N Capitaine (Manuscript in press)

Dickey JO, PL Bender, JE Faller, XX Newhall, RL Ricklefs, JG Ries, PJ Shelus, C Veillet, AL Whipple, JR Wiant, JG Williams, CF Joder (1994) Lunar laser ranging: a continual legacy of the appollo program. Science 265, 482-490

Fukushima T (1993) IAU Standards – What's it? Pres. IAG. Gen. Ass. Beijing

Fukushima T (1994) Time ephemeris. Proc. of 26th Symp. on "Cel. Mechanics", Tokyo, Japan, Jan 12-13, eds. H Kinoshita and H Nakai, 149-159

Grafarend E, F Sanso (1984) The multibody space-time geodetic boundary value problem and the Honkasalo term. Geophys. J. R. astr. Soc. 78, 255-275

Grafarend E, AA Ardalan (1997) W_0: an estimate in the Finnish Height Datum N60, epoch 1993.4, from twenty-five GPS points of the Baltic Sea Level Project. Journal of Geodesy, 71: 673-679

Grafarend E, AA Ardalan (1999) The form parameters of the Somigliana-Pizetti level ellipsoid from current best estimates of fundamental geodetic parameters based on a functional analytical review of the Somigliana-Pizetti gravitational field. Submitted to J. Geodesy

Groten E (1994) A comment on fundamental geodetic constants. SCFC 1991-1995, pres. aAt IAU General Ass. The Hague

Groten E (1994) Global tidal parameters. Studia geoph. et geod. 38, 221-234

Kinoshita H (1994) Is the equatorial radius of the Earth a primary constant, or a defining constant? Studia geoph. et geod. 38, 2, 109-116

Kopejkin SM (1991) Relativistic manifestations of gravitational fields in gravimetry and Geodesy. Manuscripta Geodaetica, 16, 5, 301-312

Lemoine et al. (1996) The development of the NASA GSFC and NIMA joint geopotential model. Paper presented at IAG Symposium, Tokyo, Sept. 1996 McCarthy DD ed. (1992) IERS Standards. Technical Note 13, Observatoire de Paris

Marchenko, AN and OA Abrikosov (1999) Evolution of the Earth principal axes and moments of inertia. J. Geodesy, in press

McCarthy DD (1996) IERS Conventions

Nerem RS, BF Chao, AY Au, JC Chan, SM Klosko, NK Pavlis, RG Williamson (1993) Temporal variations of the Earth's gravitational field from satellite laser ranging to LAGEOS. Geophys. Res. Let. 20, 7, 595-598

Nerem RS, FJ Lerch, RG Williamson, SM Klosko, JW Robbins, GB Patel (1994) Gravity model improvement using the DORIS tracking system on the SPOT 2 satellite. JGR 99, B2

Nerem RS, FJ Lerch, JA Marshall, EC Pavlis, BH Putney, BD Tapley, RJ Eanes, JC Ries, BE Schutz, CK Shum, MW Watkins, SM Klosko, JC Chan, SB Luthcke, GB Patel, NK Pavlis, RG Williamson, RH Rapp, R Biancale, F Nouel (1994) Gravity model development for TOPEX/POSEIDON: Joint gravity models 1 and 2. JGR 99, C12, 24, 421-24, 447

Nesvorný D, Z Sima (1994) Refinement of the geopotential scale factor R_0 on the satellite altimetry basis. Earth, Moon, and Planets 65, 79-88

NIMA National Imagery and Mapping Agency, Technical Report TR 8350.2, Third Edition, Department of Defense World Geodetic System, 1984, Its Definition and Relationships with Local Geodetic Systems

Rapp RH (1987) An estimate of equatorial gravity from terrestrial and satellite data. Geophys. Res. Lett. 14, 7, 730-732

Rapp RH (1993) Geoid undulation accuracy. IEEE Transaction on geoscience and remote sensing 31, 2, 365-370

Rapp RH, Y Yi, YM Wang (1994) Mean sea surface and geoid gradient comparison with Topex altimeter data. JGR 99, C12, 24, 657-24, 667

Ries JC, RJ Eanes, CK Shum, MM Watkins (1992) Progress in the determination of the gravitational coefficient of the Earth, GRL 19, 6, 529-31

Ries JC (1998) Personal communications

Stephenson, FR, LV Morrison (1994) Long-term fluctuations in the Earth's rotation: 700 BC to AD 1990. Phil. Trans. Royal Soc. (London) Ser. A

Wang Z, J Kakkuri (1998) The time dependency of gravity potential on the geoid. (Submitted to J. Geodesy)

Williams JG, XX Newhall, JO Dickey (1993) In contributions of space geodesy to geodynamics: Earth Dynamics, eds. DE Smith, DL Turcotte. Geodynamics series 24, AGU, Washington, 83

Williams JG (1994) Contributions to the Earth's obliquity rate, precession and nutation. Astron. J. 108, 2, 711-724

Yan HJ, E Groten (1994) The celestial and terrestrial departure points and their various aspects in geodesy and astrometry. Studia geoph. et geod. 38, 2, 117-130

Yurkina MI (1993) Determination of Stokes' constants respecting zero-frequency tidal term due to the Moon and the Sun. Studia geoph. et geod. 37, 4, 317-325

International Association of Geodesy

Report of the Ad-Hoc Working Party on

REFRACTIVE INDICES OF LIGHT, INFRARED AND RADIO WAVES IN THE ATMOSPHERE

of the IAG Special Commission SC3 – Fundamental Constants (SCFC)

1993 – 1999

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Abstract

This ad-hoc working group of the IAG Special Commission (SC3) has carefully reviewed the progress in the measurement and modelling of the refractive index of air. For light and near infrared waves, a closed simple formula is proposed for electronic distance measurement (EDM) to not better than one part per million (1 ppm) precision. For EDM of higher precision, a computer routine is proposed that uses the full Lorentz-Lorenz relationship, the new temperature scale of 1990, the BIPM density equations and the recently revised water vapour refractivity. The group notes that the perceived accuracy of any continuum formula is invalidated by anomalous refractivity near absorption lines. Further work on the effect of absorption lines on the phase and group refractive indices of air is strongly recommended, as are new absolute measurements of the refractivity of the constituent gases of the atmosphere (including water vapour) at non-laboratory conditions.

1. Introduction

In 1991, at the 20th General Assembly of the International Association of Geodesy (IAG) in Vienna, it was suggested that new IUGG resolutions on refractive indices be prepared for adoption at a future General Assembly of IUGG. An *Ad-hoc Working Party on Refractive Indices of Light, Infrared and Radio waves in the Atmosphere* was formed in 1993 under the umbrella of the International Association of Geodesy (IAG) Special Commission SC3 – Fundamental Constants (SCFC).

The last resolutions of the International Union of Geodesy and Geophysics (IUGG) on refractive indices date back to 1963. For light waves, the 1963 IUGG resolution recommended two interchangeable formulae for standard air by Barrell & Sears (1939) and Edlén (1953) as well as a simplified interpolation formula to ambient condition based on Barrell & Sears (1939). (To recommend two competing formulae was not such a good idea, considering that uniformity was to be achieved.) The formulae provided group refractive indices accurate to 0.1 ppm at standard conditions for carrier wavelengths between 185 and 644 nm. They were thought to give an accuracy of 2 ppm at ambient conditions. This was appropriate in 1963 when electro-optical distance meters were specified at ±(10 mm + 2-5 ppm). Today, the best commercial electro-optical distance meters have a precision of ±(0.1 mm + 0.1 ppm). Also, the state-of-the-art measurement of atmospheric parameters gives computed refractive indices with standard deviations of 1 to 5×10^{-8} (see Matsumoto et al. 1988, Birch & Downs 1993, for example). The formulae adopted in 1963 are not accurate enough for today's precision measurements, do not include post 1953 refractivity measurements and have not been designed for the near infrared spectrum where most distance meters operate today. This situation has led to the use of a variety of "non-approved" formulae in geodesy and surveying.

This report summarises the activities of the Ad-Hoc Working Party of the IAG Special Commission SC3 – Fundamental Constants (SCFC) for the period 1993 to 1999. In short, the working party was considering recent determinations of the refractive index of air, the carbon dioxide content of air, the extension of the formulae into the infrared and the implementation of the Lorentz-Lorenz relationship. So far, the working party concentrated on the refractive index in the visible and near infrared spectrum, because of an apparent lack of interest from geodesists working with GPS and VLBI. Work on proposals for refractive index formulae for the radio and millimetre waves has started, however, and some suggestions have been arrived at.

Three resolutions have been prepared by the working party for adoption at the 22nd General Assembly of IUGG (1999). They are reprinted in the Appendix. The first resolution recommends two solutions for the refractive index of light and near infrared waves, namely a simple closed formula (for the reduction of measurements of not better than one part per million) and a computer routine (for the reduction of measurements to better than one part per million). The second resolution makes recommendations on further work on the refractive index of light and infrared waves, with special emphasis on anomalous refractivity due to absorption lines. The third resolution recommends further work on the refractive index of infrared and radio waves.

The views expressed in this report are those of the author, but are based on consultations with the members of the group. The working party plans to publish a joint paper on its work soon. The extensive literature section includes references mentioned to in the text as well as other literature relevant to the work of the group.

2. Membership

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3. Refractive Index of Light and Near Infrared Waves in the Atmosphere

3.1 Phase, Group, Signal and Pulse Velocity and Corresponding Refractivity

The phase refractive index (and the phase velocity) is required for the reduction of measurements with the classic Michelson interferometer and the HP (Doppler) interferometer. Traditionally, it has been assumed that electronic distance meters (EDM instruments) using amplitude, frequency or phase modulation of the carrier of flight time measurements require the group refractive index (and the group velocity). The same group refractive index is also required for the pulse distance meters used in surveying and geodesy and instruments using polarisation modulation, such a the Kern Mekometer ME 5000. (The latter is equivalent to a phase modulation as the phase of the vertical polarisation is changing against the phase of the horizontal polarisation.) White light interferometers, beat interferometers and interferometers modulated by a second wavelength also require the group index. As the next paragraph shows, the *group velocity concept* is an approximation that applies only if there are no absorption lines near or within the signal spectrum.

The term *signal velocity* was first defined by Brillouin (1960). Only recently, Oughstun et al. (1989) gave a corrected definition of signal velocity for absorptive and dispersive media. Based on Oughstun's work, Hill (in Ciddor & Hill 1999) derived the limiting conditions of the applicability of group velocity and, thus, group refractivity. Within these limits, where dispersive and absorptive distortions are negligible, the signal and the group velocities are the same. Beyond these limits, the terms *group velocity* and *group refractive index* lose their meaning because of the distortion of the wave packets. In these cases, Hill suggests to evaluate the signal velocity for specific EDM instruments using the algorithms developed by Xiao & Oughstun (1998). An alternative way accounting for the influence of resonances on (the phase and) group refractive index of air was proposed by Galkin & Tatevian (1997). A numerical comparison of the two methods has not (yet) been carried out.

The term *velocity of pulse propagation* is being used by Mandel & Wolf (1995, p. 822, Eq. 16.3-25). The members of the working party believe that this phenomenon likely applies to very short pulses in condensed media (with very non-linear dispersion) and to highly dispersive and/or absorbing media. The pulse velocity after Mandel & Wolf (1995) is, thus, assumed to be irrelevant to the work of the working party.

3.2 Continuum Refractivity (Dispersion)

After some lengthy discussions on the relative merits of the Edlén (1966) and the Peck & Reeder (1972) dispersion equations, preference was eventually given to Peck & Reeder. In consequence, Ciddor based his computer procedures on it (Ciddor 1996, Ciddor & Hill 1999). The advantages of the Peck & Reeder (1972) formulation are outlined in the Section on the "Two-Term Dispersion Formula" of their 1972 paper. Their arguments are convincing, particularly as the working party wants a formula that extends into the NIR. The Peck & Reeder 1972 equation differs from the Edlén 1966 equation in the following ways: (a) seven new (relative) measurements between 723 nm and 1530 nm, not used by Edlén, accuracy 1 part in 10^9, (b) renormalised 8 earlier data (Edlén uses initial values), (c) two earlier values (used by Edlén) omitted, (d) root mean squares of fit of 51 out of 59 data is $\pm 1.7 \times 10^{-9}$ whereas Edlén is $\pm 3.1 \times 10^{-9}$ (between 0.23 μm and 1.69 μm), (e) P&R has an average offset of 0.2×10^{-9} in the infrared whereas the Edlén 1966 equation has a 4.3×10^{-9} offset. This is clearly not acceptable for a state-of-the-art equation for geodesy.

Galkin & Tatevian indicated that they are not entirely happy with the accuracy and documentation of the original data used by Edlén and Peck & Reeder Formula. They have repeated the curve fit to the Peck & Reeder data and did not find a better solution. Galkin & Tatevian (1997a) pointed out that each absorption line in the visible and near infrared causes a small upward shift of the continuum dispersion curve towards larger wavelengths. These small increases of the refractivity with increasing wavelength cannot be modelled by the Sellmeier equations used by Peck & Reeder (and Edlén). One could add a linear term to the standard 2-3 term Sellmeier equations or add additional Sellmeier terms to the standard 2-3 term formula for resonances at about 0.7 µm, 2.5 µm and 8 µm, for example. All existing dispersion formulae could also be improved by introducing the recent absolute and relative refractivity data (e.g. data by Matsumoto, Birch & Downs, Bönsch & Potulski) and by using a better mathematical model of the curve fit that allows data sets, that were converted from relative to absolute, to float up and down as a group. Before any new curve fit one would also have to investigate the possible effect of absorption lines on old refractivity measurements.

3.3 Refractivity of Moist Air

Birch & Downs (1988a, 1988b, 1989) found an error in the original water vapour refractivity measurements of Barrell & Sears (1939). As all subsequent refractivity data were scaled to Barrell & Sears, this error is present in most existing refractivity formula. The findings by Birch & Downs were confirmed by Beers & Doiron (1992) and Bönsch & Potulski (1998). The latter confirm Birch and Downs data to within 1 part in 10^8. The Ciddor formulae (Ciddor 1997, Ciddor & Hill 1999) are based on Birch & Downs' new moist air refractivity data.

All new data were established at laboratory conditions. In support of outdoor measurements, new absolute measurements of water vapour refractivity over a wide range of temperatures and pressures are strongly recommended.

3.4 Lorentz-Lorenz Relationship

The limitations of the Lorentz-Lorenz relationship were referred to by Owens (1967) and by Ciddor & Hill (1999). The latter note that there is no difference in terms of "practical precision" between the Lorenz-Lorentz equation (Böttcher & Bordewijk 1978, Eq. 12.2, p. 286) and the corrected Lorenz-Lorentz equation (Böttcher & Bordewijk 1978, Eq.12.16, p.292) at atmospheric densities. The magnitude of the difference was not quantified. Ciddor believes the difference to be at the 1 part in 10^{12} level. According to Hill, the corrected L-L equation is only required for dense media.

Ciddor (1996) did not fully implement the Lorentz-Lorenz (L-L) relation in the new computer procedure for the refractive index of light and near infrared waves. Ciddor (1996) stated that the difference between his solution and the full LL relationship does not exceed 2 parts in 10^9 at an altitude of 2000 m above sea level. Later, Hill computed a difference of 5 parts in 10^9 for an altitude of 4500 m. Ciddor's newest computer procedure (Ciddor & Hill 1999) now includes the full (uncorrected) L-L relationship.

3.5 Anomalous Refractivity

Anomalous refractivity may be defined as the deviation from the smooth continuum dispersion curve near absorption lines. It is the contribution from anomalous dispersion by resonances to the total refractivity of air. As discussed in Section 3.1, the signal velocity after Oughstun et al. (1989) and Xiao & Oughstun (1998) will give directly the total refractivity (continuum and anomalous component) near absorption lines. The approach followed by Galkin and Tatevian (1997a, 1997b) provides only the contribution (to the total refractivity) from anomalous dispersion by resonances. Their concept is similar to the one used by Hill for infrared and radio waves (Hill et al 1980a 1980b).

According to Galkin & Tatevian (1997), the original phase refractivity data may be affected by up to 1 part in 10^9 due to local resonance effects. Anomalous group refractivity may reach 0.7 ppm. However, there are errors that are very much larger (several ppm!) than the published value of 0.7 ppm. Unfortunately, the magnitude of anomalous phase and group refractivity is still unknown for most wavelengths covered by the Ciddor formula. A correcting term for anomalous refractivity in Ciddor's formula is required; it could be obtained from a software package for PCs based on Galkin & Tatevian's work and suitable spectroscopic data.

Galkin & Tatevian see a certain need for a general purpose software for the computation of anomalous refractivity for wide spectrum instruments. They presently consider the following absorption lines for inclusion: N_2, O_2, CO_2 plus water vapour. Other contenders are SO, CO, NO. They believe that CO_2 and O_2 can be ignored between 0.75 µm and 0.95 µ and that the water absorption lines listed in HITRAN are sufficient. It would be very useful to know the magnitude of the correction and, possibly, the average correction.

3.5.1 Single Line (Laser) Instruments

As far as the visible and NIR spectrum is concerned, the modelling of anomalous phase and, in particular, group refractivity is still an open question. According to Galkin & Tatevian, very strong absorption lines can affect the phase refractive index by about one part in 10^{-12} to 10^{-13} in the visible spectrum. Near 0.77 µm, there is an effect of 1 part in 10^{-11} due to an oxygen line. The group refractive index is affected more by five to six orders of magnitude.

Ideally, one would like to see something like Liebe's PC-based MPM software package (e.g. Liebe 1989). As most IR instruments are not single wavelength instruments but have an (approximately) Gaussian distribution of wavelengths, the software would also have to cater for this. Investigations of anomalous group refractivity are of great interest for the following gas laser wavelengths (narrow band): 441.6 (HeCd), 632.8 nm (HeNe), 1064 nm and 532 nm (Nd:YAG). The first two are used for terrestrial dual-colour distance measurements and the latter for satellite ranging. Even though anomalous refractivity can be computed by hand, software is required if many lines are to be computed. Galkin & Tatevian do not predict a good accuracy of such computations because the (assumed) Lorenzian line shape is a model and its far-wings a problem. There is also some doubt if the AFCL HITRAN atlas lists resonances with less than 5% absorption. In the whole, Galkin and Tatevian believe that a correction for stabilised laser instruments is feasible.

3.5.2 Broadband (Diode) Instruments

Considering that, presently, about 99% of all commercial distance meters operate in the near infrared (NIR), it would be of great importance to know the effect of water vapour resonances on the group refractive index of these instruments. It is likely that the magnitude of anomalous refractivity on infrared (IR) distances meters will be reduced by the fact that they feature a Gaussian spread of the emission wavelength, usually about ±20-30 nm about the centre wavelength (at 50% power points). But this would have to be demonstrated.

Considering the 220 instrument types listed in Rüeger (1996), three popular wavelengths emerge: 820 nm, 860 nm and 910 nm. Not shown in the list are the emerging AlGaInP visible laser diodes (VLD) operating between 650 to 690 nm. It would be of great interest to know the magnitude of anomalous group refractivity at these wavelengths (670 nm, 820 nm, 860 nm, 910 nm), assuming spectral widths (at 50% power) of 3.5 nm and 40 nm for laser diodes and high radiance emitting diodes, respectively. It is known (Rüeger 1996) that the wavelengths are temperature dependent (about 0.25 to 0.35 nm/°C) and that the actual wavelength of a diode may differ by as much as 15 nm from the nominal value. So, any computations of anomalous refractivity will only be able to indicate the magnitude of the problem for diode instruments.

Galkin & Tatevian correctly point out that all depends on the number and width of the absorption lines relative to the spectral width of the EDM instrument. The effect of a narrow resonance line would be significantly reduced by a broad spectral width instrument whereas even a broad spectral width instrument would suffer greatly from anomalous refractivity if multiple absorption lines were to be distributed evenly and tightly over the spectral range of the instrument. Galkin & Tatevian note that there are more than 4000 water resonance lines between 0.75 µm and 0.95 µm.

3.6 Carbon Dioxide Content and Dispersion

A number of standard laboratories have started to use a default CO_2 content of laboratory air of 400 ppm or 450 ppm. Most standard laboratories now measure the actual content and correct for it. A CO_2 content of 450 ppm is clearly too high for measurements in the open (see Taylor 1994, for example). Rüeger (1998) has considered the matter and suggests 375 ppm (likely to be current in 2004) for all fixed CO_2 content formulae. The proposed resolutions for simple, closed formulae are based on this assumption. The accurate formulae have an input for the actual carbon dioxide content.

The computer procedures for the accurate computation of the refractive index of air for light and near infrared waves by Ciddor (1996) and Ciddor & Hill (1999) use the Birch and Downs (1994) implementation of Edlén's (1966) CO_2 correction. The deviation of the CO_2 term used from that of Old et al. (1971) and Simmons (1978) is less than 1 part in 10^8. Even so, the Old et al.'s (1971) dispersion formula is more appropriate, as it includes the resonance effects from 4.25 µm and, thus, extrapolates much better into the infrared.

The inclusion of Old's CO_2 refractivity equation in the proposed computer procedures for the accurate refractivity is of value, in particular when two-colour measurements and group refractivity are concerned. This work has begun and will be documented in the "Guidelines for the Implementation" of the Ciddor (1996) and Ciddor & Hill (1999) procedures, as foreshadowed in the proposed resolution.

3.7 Water Vapour near Saturation

The proposed simple refractivity equation and the computer procedure for a more accurate refractivity include water vapour terms. When the relative humidity increases above 70% to 90%, small water droplets may begin to form and the air may become a mixture of gases and liquid water in form of an aerosol. When operating in high humidity, it must be noted that the proposed formulae do not take account of aerosols (liquid water droplets). The resolutions cover this aspect by specifying that the formulae apply to "non-condensing "conditions only.

It might be prudent to assume the claimed accuracy of the formulae to be valid only for relative humidities below 90%. The refractive index of water (rain) in the context of electronic distance measurement (EDM) was recently investigated by Rüeger (1996b, 1999). Drizzle (1 mm/h) changes the total refractivity by about 0.03 ppm whereas heavy rain (20 mm/h) changes it by 0.3 ppm. This indicates that small quantities of liquid water will not significantly affect the continuum refractivity.

4. Resolutions on the Refractive Index of Air for Visible and NIR Waves

4.1 First Resolution

The working party has prepared two resolutions on the refractive index of air for visible and NIR waves. The first paragraph of the first resolution recommends a computer procedure for measurements to better than one part per million. The computer procedures are fully documented in Ciddor (1996) and Ciddor & Hill (1999). The Ciddor formulas produce refractivities to a few parts in 10^8. They match recently reported measurements within the experimental error and are expected to be reliable over very wide ranges of atmospheric conditions and wavelength. These formulas use the BIPM density equations that are valid over ranges of at least -40 to +100 °C, 800 to 1200 hPa and 0 to 100% relative humidity, and so include all practical atmospheric conditions. The formulas apply over the wavelength range from below 350 nm to above 1300 nm and, thus, cover the wavelengths at which modern surveying instruments operate. The equations take into account all known factors (except for suspended aerosols, atmospheric contaminants such as oil vapours and the effects of absorption lines) and embody the latest values of physical parameters and units.

The basic form of the phase refractive index formula used by Ciddor is as follows:

$$N_{amb} = \frac{\rho_a}{\rho_{asx}} N_{avs} + \frac{\rho_{wv}}{\rho_{wvs}} N_{wvs} \quad (1)$$

where
- N_{amb} = refractivity of ambient moist air
- N_{asx} = refractivity of dry standard air at standard conditions (15°C, 1013.25 hPa, x ppm CO_2)
- N_{wvs} = refractivity of water vapour at standard conditions (20°C, 13.33 hPa)
- ρ_{asx} = density of standard air (with x ppm CO_2)
- ρ_{wvs} = density of standard water vapour
- ρ_a = density of dry component of ambient air
- ρ_{wv} = density of water vapour component of ambient air

T [°C]	PWVP p_w [hPa]	CIDDOR 1996 N_L $\times 10^{-8}$	OWENS 1967 N_L $\times 10^{-8}$	EDLÉN 1966 N_L $\times 10^{-8}$	IUGG 1963 N_L $\times 10^{-8}$	Differences (4-3) $\times 10^{-8}$	(5-3) $\times 10^{-8}$	(6-3) $\times 10^{-8}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
λ = 650 nm, CO_2 content = 300 ppm (0.03%), total pressure = 1000 hPa								
60	199.26	23626.92	23537.14	23413.97	23564.92	-89.78	-212.95	-62.00
45	95.85	25066.14	25018.14	24978.36	25042.27	-48.00	-87.78	-23.87
30	42.43	26484.65	26462.35	26453.76	26479.96	-22.30	-30.89	-4.69
15	17.04	27955.58	27946.75	27946.76	27957.72	-8.83	-8.82	+2.14
0	6.10	29536.31	29533.76	29533.96	29538.14	-2.55	-2.35	+1.83
-15	0.00	31283.16	31284.67	31280.87	31281.10	+1.51	-2.29	-2.06
-30	0.00	33221.68	33223.60	33215.56	33210.86	+1.92	-6.12	-10.82
λ = 850 nm, CO_2 content = 300 ppm (0.03%), total pressure = 1000 hPa								
60	199.26	23199.45	23112.02	22986.56	23156.05	-87.43	-212.89	-43.40
45	95.85	24629.37	24582.71	24542.14	24614.12	-46.66	-87.23	-15.25
30	42.43	26032.10	26010.60	26001.80	26030.60	-21.50	-30.30	-1.50
15	17.04	27482.34	27473.94	27473.96	27485.00	-8.40	-8.38	+2.66
0	6.10	29038.32	29036.07	29036.32	29039.46	-2.25	-2.00	+1.14
-15	0.00	30756.90	30758.62	30754.88	30753.44	+1.72	-2.02	-3.46
-30	0.00	32662.81	32664.95	32657.05	32650.64	+2.14	-5.76	-12.17

Table 1: Comparison of visible and NIR group refractivity N_L (in parts per 10^8) from the Ciddor (1996) and a number of earlier formulae. The Owens'97 data are based on Owens (1967, Eqs. (30), (31), (42); the Edlén'66 data are based on Edlén (1966, Eqs. (1) and (22), as converted from phase to group, and Eq. (12)). The IUGG'63 data follow from a subset of the equations recommended by the IUGG Resolution of 1963 (see Rüeger 1996, Eqs. (5.15) and (5.13)).

The proposed resolution refers to "Guidelines for Implementation". These will summarise the computer procedures of Ciddor (1996) and Ciddor & Hill (1999), as amended to include the Old et al. (1971) carbon dioxide dispersion formula, because of its appeal and theoretical basis in the infrared. This requires a switch from a differential correction to the computation of the total CO_2 contribution, thus leading to the summation of three terms (rather than the sum of two shown in Eq. (1)), namely one each for dry air (free of carbon dioxide and water vapour), carbon dioxide and water vapour.

The second paragraph of the first resolution recommends a closed formula for measurements to not better than 1 ppm. For the latter, a subset of the equations recommended by the 1963 IUGG Resolution is being used, as amended for a value of 375 ppm for the CO_2 content of the atmosphere. Table 1 shows that the chosen simple formula performs much better (at high humidity) than two formulae (OWENS'67 and EDLÉN'66) previously thought to be superior. The excellent agreement in Table 1 is due, in part, because of the use of the same values (exactly) of carbon dioxide content and partial water vapour in all formulae. Practising surveyors and geodesists will use differing equations for the saturation water vapour pressure, might omit the enhancement factor and will, typically, ignore any deviation of the actual CO_2 content from the default value. For these reasons and because anomalous refractivity can amount to more than 0.7 ppm and the measurement of the atmospheric parameters can easily introduce errors of similar magnitude, the closed formula is only suggested for measurements of not better than one part per million. Please note that Table 1 is based on 300 ppm CO_2 content, because all old formulae assume this content. The new formula is based on a carbon dioxide content of 375 ppm.

4.2 Second Resolution

The second resolution on the refractive index of air for visible and NIR waves suggests further work on some open questions. Firstly, the effect of absorption lines on the phase and group refractive indices of air needs to be evaluated to be able to quantify the magnitude of anomalous refractivity for specific instruments, or, in other words, the difference between the group refractivity and the signal refractivity. The numerical agreement between the approaches of Galkin & Tatevian (1997) and Oughstun (1991) should be investigated. Ideally, software should be written to evaluate the magnitude of these effects and, where possible, to correct for such effects. Such software may require better and more spectroscopic data of weak absorption lines.

As suggested earlier, it would be very useful if additional absolute and, possibly, relative measurements of the refractivity of the constituent gases of the atmosphere (including water vapour) be carried out at *non-laboratory conditions*, with special emphasis on near infrared wavelengths. In addition, measurements could be made in some doubtful points (for example 644 nm) of the visible spectrum.

Furthermore it should be considered to include the post-P&R data (including, in a suitable manner, relative measurements) in a revised P&R formula and to use the latter in an amended Ciddor formula. Initial steps for an amended P&R formula have been carried out by Galkin & Tatevian.

5. Refractive Index of Radio and Infrared Waves in the Atmosphere

This section is a summary of the review carried out by Rüeger (1998b) and subsequent discussions with the working group members. Refer to Rüeger (1998b) for more details.

5.1 Accuracy

Boudouris (1963) and Hartmann (1991) quoted an accuracy of the radio refractivity of 0.5% (for moist air, p_w = 27 hPa) whereas Thayer (1974) claims 0.02% for dry air and 0.05% for "extremely moist air". Walter (1990 p.101, quoting Liebe 1983) states an accuracy of 0.05 ppm. As the accuracy of the radio wave refractivity is heavily dependent on the water vapour content, it is best to quote the accuracy of the dry and the wet terms separately, as done by Thayer (1974). The widely differing views on the accuracy of the water vapour refractivity may be because some authors ignore the mathematical correlation between the two water vapour terms (K_2 and K_3) when applying the propagation law of variances whereas others do not. (Refer to the differences between Columns 8 and 9 in Table 2 below, for example. Boudouris' (1963) accuracy estimate seems to be on the conservative side and Thayer's (1974) estimate (for the accuracy of the water vapour terms) on the optimistic side.

5.2 Continuum Formulae and Compressibility Factors

Thayer (1974, Eq. (1)) suggested a closed formula (with compressibility factors Z) of the following form:

$$N_r = (n_r - 1) \times 10^{-6} = K_1 \frac{p_d}{T} Z_d^{-1} + K_2 \frac{p_w}{T} Z_w^{-1} + K_3 \frac{p_w}{T^2} Z_w^{-1} \quad (2)$$

The same author noted that the omission of compressibility factors leads to errors in the radio wave refractivity of 0.04 ppm in the dry term and 0.1 ppm in the wet term at high humidities. The former is of the same magnitude as the accuracy of the dry terms whereas the latter is half of the wet term accuracy claimed by Thayer and a twentieth of the accuracy quoted by others. In consequence, it is suggested to propose a closed formula for geodesy and surveying without compressibility factors.

The International Radio Consultative Committee (CCIR) of the International Telecommunication Union (ITU), at the 16th Plenary Assembly, Dubrovnik 1986, in Recommendation 453-1, considering the necessity of using a single formula, unanimously recommended the following formula for the refractive index of radio waves:

$$N = (77.6/T) \ (P + 4810 \ (e/T)) \qquad (3)$$

with e, P in hPa, T in K. Report 563-3 gives an equivalent formula (after Bean and Dutton), with an error of less than 0.5% for frequencies of less than 100 GHz. The formula adopted by CCIR does not comprise compressibility factors and only one 'dry' term and one 'wet' term. The second (K_2) term of Eq. (2) is missing.

Some authors did use compressibility factors when reducing their measured refractivities to standard conditions whereas others did not. So, one could argue that coefficients K_i that were reduced with compressibility factors can be used directly in formulae with compressibility factors. On the other hand, coefficients K_i that were determined without compressibility factors can be used directly in formulae without compressibility factors. Considering Eq. (2), it becomes clear that the coefficients K_i in formulae without compressibility factors really cannot be numerically the same as those in formulae with compressibility factors. This aspect must yet be verified in all known formulae of interest in this context.

It might be desirable that precision formulae use compressibility factors Z_i and the matching K_i constants for dry (carbon dioxide free) air, water vapour and carbon dioxide terms even though the compressibilities change refractivity by less than the claimed accuracy of the formulae. To be consistent with the recommended formulae for the visible and NIR waves, the compressibility factors should be computed with the BIPM formulae. See Ciddor (1996) for reference.

5.3 Carbon Dioxide

Following the recommendations in the proposed resolutions on the refractivity of light and near infrared waves, it is again suggested to use a 375 ppm fixed CO_2 content in all new closed formulae, like those for hand calculations. This has been implemented in Eq. (6) (Rüeger 1998b). The change from 300 to 375 ppm changes the radio wave refractivity by only 0.01 ppm at standard conditions. To be consistent, it is suggested that precise formulae and models should include the CO_2 content as input variable. A default of 375 ppm CO_2 could be implemented in MPM as well as an optional CO_2 content input.

5.4 Upper Frequency Limit for Closed Refractivity Formula

Different authors quote different upper limits for the non-dispersive region of radio wave refractivity. For example, Hartmann (1991) quoted 5 GHz, Thayer (1974) 20 GHz and Boudouris (1963) 30 GHz. These limits vary because of the magnitude of spurious effects tolerated and the accuracy of formulae assumed by these authors. Rüeger (1998b) suggested 1 GHz as cut-off as Liebe (1996) suggests additional terms for dispersive refractivity above 1 GHz. This limit is sufficiently removed from the nearest resonance frequencies of water vapour and oxygen. Liebe (1983) and Hartmann (1991) list, for example, H_2O resonances at 22.23 GHz, 67.81 GHz, 119.99 GHz, 321.22 GHz, and O_2 resonances between 53.59 GHz and 66.30 GHz and at 118.75 GHz. Further evaluation of the magnitude of the effect of absorption lines might permit to extend the validity range of simple closed formulae to 5 GHz or 10 GHz.

5.5 Dispersive Refractivity (to 1 THz)

As Hill et al. (1980) and Liebe (1989) did, dispersive refractivity can be added to experimental refractivity. Liebe's **M**illimetre-Wave **P**ropagation **M**odel (MPM) is the only operational model to account for 44 oxygen and 30 local water resonance lines plus an empirical water vapour continuum to offset experimental discrepancies. The CO_2 resonance at 15 µm should be sufficiently distant to cause anomalous refractivity between 1 Hz and 1THz.

5.6 Phase, Group and Signal Velocity

In geodesy and surveying, it has been generally assumed that the refractive index of radio waves is not dependent on the carrier frequency and, thus, only the phase refractive index must be considered. Microwave electronic distance measurements (EDM) used frequency modulation techniques to derive the distance measurements. GPS signals are code modulated but reconstructed carrier waves are usually used for the actual measurement in geodesy. It could be argued that, since some of the radio wave spectrum is dispersive, the concept of group or signal refractivity might have to be introduced where the propagation of modulated waves is used for measurements. If the visible spectrum can be taken as a guide then the anomalous group refractivity can be 100'000 times larger than the anomalous phase refractivity.

The question now arises if the concept of group velocity or signal velocity has to be introduced in the dispersive regions of the radio wave spectrum. According to Hufford, "signal velocity" is already used for the wave propagation in wave guides. Hufford (1987) did compute the millimetre-wave pulse distortion by a single absorption line simulating the terrestrial atmosphere and, therein, gives a reference to Trizna & Weber (1982), which also discuss the signal velocity for pulse propagation in a medium with resonant anomalous dispersion.

Further investigation and quantification of the difference between phase and signal velocity in the frequency ranges 1 Hz to 1 GHz (non-dispersive) and 1 GHz to 1THz (dispersive) are clearly required.

5.7 Anomalous Refractivity Effect in Historic Data

Most radio wave refractivity data were measured above 1 GHz, were dispersive refractivity starts to have an effect. For example: Birnbaum & Chatterjee (1952; 9.28 GHz, 24.8 GHz), Boudouris (1963; 7 GHz to 12 GHz), Newell & Baird (1965; 47.7 GHz), Liebe (1969; 22.235 GHz), Liebe et al (1977; 53.5 to 63.5 GHz). The last two determinations accounted for anomalous refractivity whereas the first three did not.

To get consistent data for the derivation of a dispersion-free radio wave refractivity, it would be of great benefit if anomalous refractivity were removed from experimental data. In particular, it would be worthwhile to remove anomalous refractivity from the values in Newell & Baird's Table III (1965) for dry air and oxygen. The poor agreement of Froome's oxygen value could be entirely due to dispersive oxygen refractivity.

6. Refractivity for IR and Radio Waves: Work to Date and Pending Work

6.1 Formula for Hand Calculations (1 Hz to about 1 GHz, ¥ m to 0.3 m)

It is valuable to have a relative simple and closed solution for the refractive index of radio waves for easy calculation with pocket calculators and personal computers. The equations given here are empirical, based on experiment and ignore the non-ideal gas behaviour (compressibility) of air.

When ignoring compressibility factors, the refractivity N_r of radio waves (in ppm) can be expressed as:

$$N_r = (n_r - 1) \times 10^6 = K_1' \frac{p_{d-c}}{T} + K_2 \frac{p_w}{T} + K_4 \frac{p_w}{T^2} + K_4 \frac{p_c}{T} \qquad (4)$$

where $p_{d\text{-}c}$ (= $p_d - p_c = p_{tot} - p_w - p_c$) is the (partial) pressure of the dry and carbon-dioxide-free air, p_d is the (partial) pressure of the dry air (= p_{tot} - p_w), p_w is the partial water vapour pressure, p_c is the partial carbon dioxide pressure, the K_i are constants and T the temperature (in K). The coefficient K'_1 is the constant K_1 without the CO_2 component. Because of its polar nature, water vapour has a density and a density-temperature term.

Based on the coefficients by Boudouris (1963: K_2 and K_3) and Newell & Baird (1965: K_1 and K_4) Rüeger (1998b) constructed a three-term equation for air with 0.03% (300 ppm) CO_2 content:

$$N_r = (n_r - 1) \times 10^6 = 77.691 \frac{p_d}{T} + 71.97 \frac{p_w}{T} + 375406 \frac{p_w}{T^2}$$

where the dry air (including carbon dioxide) pressure p_d (= p_{tot} - p_w) and the partial water vapour pressure p_w are taken in hPa and the temperature T in K. The accuracy of an equivalent equation is estimated by Boudouris (1963, p. 661) to be within 0.5% for temperatures between -50°C and +40°C, (total) pressures between 187 and 1013.25 hPa, partial water vapour pressures between 0 and 27 hPa and frequencies between 1 Hz and 30 GHz.

Recomputing the K_1 term for the carbon dioxide content of 375 ppm (0.0375%), expected to be current around the year 2004, gives the final form of a possible new formula for the non-dispersive radio wave refractivity N_r (after Boudouris-Newell-Baird, in units of K and hPa)

$$N_r = (n_r - 1) \times 10^6 = 77.695 \frac{p_d}{T} + 71.97 \frac{p_w}{T} + 375406 \frac{p_w}{T^2} \qquad (6)$$

A comparison of this equation with other formulae can be found in Table 2.

6.2 Computer Routine (1 Hz to about 1 THz, ¥ m to 0.3 mm)

A practical model that simulates the complex refractive index for the propagation calculation of electromagnetic waves through the atmosphere has been developed by Liebe et al. over many years. The **M**illimetre-Wave **P**ropagation **M**odel (MPM) is as a program for frequencies below 1000 GHz in the atmosphere running on personal (IBM compatible) computers. The MPM "consists of 44 oxygen and 30 local water resonance lines, of non-resonant spectra for dry air and of an empirical water vapour continuum that reconciles experimental discrepancies" (Liebe et al. 1992). The model is applicable for barometric pressures between 0 and 1200 hPa, ambient temperatures between -100 and +50°C, relative humidity between 0 and 100% and suspended water droplets and ice particle densities between 0 and >5 g/m^3. (Other versions of MPM also model rainfall conditions.) The complete (complex) refractivity model is as follows (Liebe et al. 1992, Liebe et al. 1993, Liebe 1996):

$$\mathbf{N} = \mathbf{N}_D + \mathbf{N}_V + \mathbf{N}_{W,I} \qquad (7)$$

where the complex dry-air refractivity is denoted by $\mathbf{N}_D$, the refractivity of atmospheric water vapour by $\mathbf{N}_V$ and the complex refractivity of suspended water droplets and ice particles by $\mathbf{N}_{W,I}$. Complex parameters are shown in bold type. Only the real-part is required for the computation of the refractivity. The refractivity of suspended water droplets and ice particles (for example in fog and in clouds) is of no direct interest in this context. The complex dry-air refractivity $\mathbf{N}_D$ is computed (in ppm) from (Liebe et al. 1992, Liebe 1996)

$$\mathbf{N}_D = N_d + \Sigma_k S_k \mathbf{F}_k + S_o \mathbf{F}_o + i\, S_n F_{n,}'' \qquad (8)$$

where N_d is the non-dispersive (dry-air) term, k is the index of the 44 oxygen resonances, S_k is the line strength and F_k the complex spectral shape function. S_o and F_o model the non-resonant refractivity below 10 GHz from the oxygen relaxation spectrum. The $S_n F_{n,}''$ term models the pressure-induced nitrogen absorption above 100 GHz. The MPM computes the refractivity of atmospheric water vapour $\mathbf{N}_V$ (in ppm) as follows (Liebe et al. 1992, Liebe et al. 1993, Liebe 1996):

$$\mathbf{N}_V = N_v + \sum_l S_l F_l + S_o \mathbf{F}_o + \mathbf{N}_C \qquad (9)$$

where N_v is the non-dispersive water vapour refractivity, l is the index of the 30 local water resonances, S_l is the line strength and F_l the shape function. The continuum refractivity N_C models contributions over and above the 30 local lines and is partly based on the work by Hill (1988).

The MPM makes use of spectral data and is supported by many laboratory measurements to validate and enhance the overall performance of the model. The authors note that MPM dry-air absorption values agree with measured ones at the 1% level. "Model predictions involving water vapour and water droplets are estimated to lie in the 10 per cent range" (Liebe et al. 1992). MPM does not consider the weak spectra of trace gases such as O_3, CO and N_2O nor does it provide an input for the CO_2 content. Presumably, a carbon dioxide content of 0.03% is assumed and included in the dry-air non-dispersive term.

6.3 Comparison of Formulae

Table 2 shows a comparison of the Millimetre-Wave Propagation Model (MPM, non-dispersive refractivity (N_d) only) with the simple formulae by Essen & Froome (1951), Boudouris (1963), a formula based on Liebe's (1977) coefficients and the B-N-B formula developed above (Eqs. (5) and (6), after Boudouris (1963) and Newell & Baird (1965)). At a later stage, it might be of interest to compare Eq. (3) adopted by the International Telecommunications Union.

A total pressure (p_{tot}) of 1000 hPa exactly was used for the comparison. To be consistent with the historical equations, the B-N-B formula for a CO_2 content of 0.03% (300 ppm) was used (Eq. (5) rather than Eq. (6)). The relative humidity was set at 100% for temperatures between 0°C and 60°C. The saturation water vapour pressures used for the computations of Columns 4, 5, 6 and 7 are shown in Column 2 and were taken from Rüeger (1990, 1996, Appendix B, after Goff & Gratch 1946). MPM uses relative humidity as input and converts it to partial water vapour pressure using Goff & Gratch (1946). The precision of the new B-N-B formula (Eq. (6)) was predicted using the propagation law of variances and the given precisions of the constants K_1, K_2 and K_3. Column 8 gives the precision without consideration of the correlation between the constants K_2 and K_3. Column (9) uses a correlation coefficient of 0.995 between the two constants to compute the covariance between them. (The correlation coefficient was obtained from a repeat of Boudouris' curve fit.)

T [°C]	PWVP p_w [hPa]	MPM93 N_r $\times 10^{-6}$	E&F51 N_r $\times 10^{-6}$	Liebe77 N_r $\times 10^{-6}$	Boud63 N_r $\times 10^{-6}$	B-N-B N_r $\times 10^{-6}$	Prec B-N-B $\times 10^{-6}$	Prec B-N-B $\times 10^{-6}$	(4-3) $\times 10^{-6}$	(5-3) $\times 10^{-6}$	(6-3) $\times 10^{-6}$	(7-3) $\times 10^{-6}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
							±	±				
60	199.26	902.2	892.9	902.2	903.5	903.7	8.3	1.2	-9.2	0.0	1.4	1.6
45	95.85	597.1	592.3	597.1	597.7	598.0	4.2	0.5	-4.8	0.0	0.6	0.9
30	42.43	428.3	426.0	428.4	428.5	428.8	2.0	0.2	-2.3	0.1	0.2	0.5
15	17.04	346.0	345.0	346.1	346.0	346.3	0.9	0.1	-1.0	0.1	0.0	0.3
0	6.10	314.8	314.3	314.9	314.6	315.0	0.3	0.0	-0.5	0.1	-0.1	0.2
-15	0.00	300.8	300.7	300.9	300.6	301.0	0.0	0.0	-0.1	0.1	-0.2	0.2
30	0.00	319.3	319.2	319.5	319.1	319.5	0.0	0.0	-0.1	0.0	-0.2	0.2

Table 2: Comparison of the non-dispersive part of the radio wave refractivity N_r (in parts in per million) from the Millimetre-Wave Propagation Model (MPM'93) and a number of simple formulae.

Table 2 shows clearly that the Essen & Froome equation (1951), adopted by IUGG in 1963, differs significantly from the other three models at high temperature and humidity. The Essen & Froome formula agrees better than any other with Liebe's MPM below freezing point and at zero humidity. The water vapour refractivity used by Essen & Froome is not optimal. Not unexpectedly, the formula ("Liebe77") based on the K_1, K_2 and K_3 terms by Liebe et al. (1977b) agrees very well with the MPM. The differences in Column 11 of Table 2 do not exceed 0.15 ppm between -30°C and +60°C. Boudouris' formula agrees slightly better with the MPM than the Boudouris-Newell-Baird formula derived above. The B-N-B formula gives values that are, on average, 0.3 ppm higher than those of Boudouris. This is expected as Newell & Baird's K_1 constant is slightly larger than that of Boudouris and as the B-N-B formula (Column 7) uses the same K_2 and K_3 constants as Boudouris (Column 6). It is also evident that the Boudouris and the B-N-B formulae have offsets from the MPM of the same magnitude but of different sign at negative temperatures and zero humidity. The differences (6)-(3) and (7)-(3) compare better with the precision values in Column (9), which take account of the (mathematical) correlation between K_2 and K_3, than with those in Column (8), which don't. It follows that the correlation between K_2 and K_3 should not be ignored when predicting the precision of computed refractivity.

It follows from Table 2 that it might be appropriate the Liebe 1977 formula if MPM'93 were to be adopted for precision measurements in geodesy. On the other hand, if the new B-N-B formula of Eq. (6) were adopted as a simple equation, then it might be necessary to change MPM and REFRAC-IAG (see below) accordingly.

6.4 Proposal for REFRAC-IAG

The Millimetre-Wave Propagation Model (MPM) of the (US) National Telecommunications and Information Administration (NTIA) in Boulder presently best meets the IAG requirements for a computer procedure for the computation of the phase refractive index of radio and millimetre waves. Mr. M. Cotton of NTIA/ITS has started work for an IAG version of the MPM derivative program REFRAC, provisionally named REFRAC-IAG. Some changes to MPM suggested by Hill (1988, Eq.9, Table II) have already been implemented. Work for the input of a variable CO_2 content has begun. It will be based on K_4 = 133.5 ±0.15 (K/hPa)and used a default content of 375 ppm. The user interface of REFRAC-IAG has been changed from that of REFRAC to simplify the use of the program.

Further questions to be addressed are that of using the BIPM saturation water vapour pressure formula (and enhancement factor) as used in Ciddor (1996) and Ciddor & Hill (1999), the sources and history of Liebe's K_1, K_2 and K_3 terms and the question of the suitability or necessity of compressibility factors. It is possible, that an introduction of compressibility factors into MPM and REFRAC-IAG could compromise the integrity of the package.

7. Resolutions on the Refractive Index of Air for Radio and NIR Waves

The third resolution proposed for adoption at the 22nd General Assembly of IUGG notes that the radio refractive index formula (after Essen & Froome) recommended in Resolution No. 1 of the 13th General Assembly of IUGG (Berkley 1963) is now clearly out of date, as the Column 10 in Table 2 shows. With new absolute and relative measurements of the mid-infrared to radio wave refractive index of air and considerable advances having been made with the computation of anomalous refractivity in the mid-infrared to radio wave spectrum, there is a clear need to amend the 1963 IUGG resolutions.

Although some progress has been made towards new recommendations for a simple closed formula and a more accurate computer procedure, more work is clearly required. Sections 5 and 6 indicate the progress made and the open questions that remain. In particular, the need for compressibility factors needs to be investigated and the significance of the difference between the signal velocity and the phase velocity in geodetic measurements through the atmosphere established. The ad hoc working party is looking for interested scientists that are able to contribute to this work on a new recommendation for the mid-infrared to radio (phase and signal) refractive index in air. Depending on the choice of a best possible simple formula, the coefficients K_1, K_2 and K_3 used by MPM and REFRAC-IAG might have to be adjusted.

8. Outlook

The ad-hoc working party considers its work on the continuum refractive index of visible and near infrared waves completed. Some possible improvements to the dispersion equation have been indicated all the same. From now onwards, the ad-hoc working party proposes to concentrate on the effects of absorption lines in the visible and near infrared regions of the spectrum on one hand and on the radio refractive index on the other. It is hoped that resolutions on the remaining aspects can be formulated well before the next General Assembly. Experts, particularly in the field of radio wave refractivity, that are able to contribute to the work are invited to join the group.

9. Bibliography and Literature

Balsamo, A., Zangirolami, M. 1995. An Absolute Refractometer for Precise Length Measurement. *Proc., Int Precision Engineering Seminar (IPES'95)*, Compiègne, France, 93-96.

Barrell, H., Sears, J. E. 1939. The Refraction and Dispersion of Air for the Visible Spectrum. *Philos. Trans. R. Soc. London*, Ser. A **238**: 1-64.

Bechler, A. 1999. Quantum Electrodynamics of the Dispersive Dielectric Medium – A Path Integral Approach. *J. Modern Optics*, **46**(5), 901-921.

Beers, J., Doiron, T. 1992. Verification of Revised Water Vapour Correction to the Index of Refraction of Air. *Metrologia*, **28**: 315-316.

Birch, K. P. 1991. Precise Determination of Refractometric Parameters for Atmospheric Gases, *J. Opt. Soc. Am. A*, **8**(4):647-651.

Birch, K. P., Downs, M. J. 1994. Corrections to the Updated Edlén Equation for the Refractive Index of Air. *Metrologia*, **31**:315-316.

Birch, K. P., Downs, M. J. 1993. An Updated Edlén's Equation for the Refractive Index of Air. *Metrologia*, **30**:155-162.

Birch, K. P., Downs, M. J. 1989. Error Sources in the Determination of the Refractive Index of Air. *Applied Optics*, **28**(5): 825-826.

Birch, K. P., Downs, M. J. 1988a. *The Precise Determination of the Refractive Index of Air*, National Physical Laboratory, NPL Report MOM90, July 1988, 35 pages.

Birch, K. P., Downs, M. J. 1988b. The Results of a Comparison Between Calculated and Measured Values of the Refractive Index of Air. *J. Phys. E: Sci. Instrum.*, **21**: 694-695.

Birch, K. P., Reinboth, F., Ward, R. E., Wilkening, G. 1993. The Effect of Variations in the Refractive Index of Industrial Air upon the Uncertainty of Precision Length Measurement. *Metrologia*, **30:** 7-14.

Birnbaum, G., Chatterjee, S. K. 1952. The Dielectric Constant of Water Vapour in the Microwave Region. *J. App. Phys.*, **23**: 220-223.

Bönsch, G. Potulski, E. 1998a. Measurement of the Refractive Index of Air and Comparison with Modified Edlén's Formulae. *Metrologia*, 35: 133-139.

Bönsch, G., Potulski, E. 1998b. Fit of Edlén's Formulae to Measured Values of the Refractive Index of Air. *Proc. Recent Developments in Optical Gauge Block Metrology.* 20-12 July 1999, San Diego, USA, Vol. 3477, SPIE Proceedings Series, 0277-786X/98, 62-67.

Böttcher, C. J. F. 1952. *Theory of Electric Polarisation*. Elsevier, Amsterdam.

Böttcher, C. J. F. 1973. *Theory of Electric Polarisation*. 2nd ed., Vol. I, Elsevier, Amsterdam.

Böttcher, C. J. F., Bordewijk, P. 1978. *Theory of Electric Polarisation*. 2nd ed., Vol. II, Elsevier, Amsterdam.

Born, M., Wolf, E. 1980. *Principles of Optics*. 6th ed., Pergamon, Oxford, UK.

Boudouris, G. 1963. On the Index of Refraction of Air, the Absorption and Dispersion of Centimetre Waves by Gases. *J. of Res. of the Nat. Bureau of Standards – D. Radio Propagation*, **67D**(6): 631–684.

Brillouin, L. 1960. *Wave Propagation and Group Velocity*. Academic Press, New York.

Ciddor, P. E., Hill, R. J. 1999. Refractive Index of Air. 2. Group Index. *Applied Optics (Lasers, Photonics and Environmental Optics)*, **38**(9): 1663-1667.

Ciddor, P. E. 1996. Refractive Index of Air: New Equations for the Visible and Near Infrared. *Applied Optics (Lasers, Photonics and Environmental Optics)*, **35**(9): 1566-1573.

Cuthbertson, C., Cuthbertson, M. 1920. On the Refraction and Dispersion of Carbon Dioxide, Carbon Monoxide and Methane. *Proc. R. Soc. London,* Ser.A **97**: 152-159.

Davies, R. S. 1992. Equation for the Determination of the Density of Moist Air (1981/91). *Metrologia*, **29**:67-90

Deichl, K. 1984. Der Brechungsindex für Licht- und Mikrowellen. *Allgemeine Vermessungsnachrichten (AVN),* **91**:85-100.

Edge, R. C. A. 1960. Report of IAG Special Study Group No.19 on Electronic Distance Measurement using Ground Instruments. Presented at 12th General Assembly of IUGG, Helsinki, 1960.

Edlén, B. 1966. The Refractive Index of Air. *Metrologia*, **2**(2): 12-80.

Edlén, B. 1953. The Dispersion of Standard Air. *J. Opt. Soc. Am,* **43**: 339-344.

Erickson, K. E. 1962. Investigation of the Invariance of Atmospheric Dispersion with a Long-Path Refractometer. *J. Opt. Soc. of America*, **52**(7):777-780.

Earnshaw, K. B., Owens, J. C. 1967. A Dual-Wavelength Optical Distance Measuring Instrument which Corrects for Air Density. *IEEE J. Quantum Electron*., **QE-3**: 544-550.

Essen, L., Froome, K. D. 1951. The refractive indices and dielectric constants of air and its principal Constituents at 24 GHz. Proc Phys Soc (London) B-64:862-875.

Galkin, Y. S., Tatevian, R. A. 1997a. The Problem of Obtaining Formulae for the Refractive Index of Air for High-Precision EDM. *Journal of Geodesy*, **71**:483-485.

Galkin, Y. S., Tatevian, R. A. 1997b. Influence of Resonances on the Phase and Group Refractive Indices of Air. *Journal of Geodesy*, **71**:680-684.

Genike, A. A., Galkin, Y. S. 1975. The Effect of Molecular Resonances on the Group Velocity of Light in Electromagnetic Distance Measurement. Presented at the 16th General Assembly of IUGG, Grenoble, France, August 1997, 14 pages.

Giacomo, P. 1982. Equation for the Determination of the Density of Moist Air. *Metrologia,* **18**:33-40.

Gobulev, A. N. 1985. On the Problem of the Velocity of Light Determination in Optical Distance Measurement. *Proc., Institute of Higher Education Series Geodesy and Aerial Surveying*, USSR, No. 5, 20-29 (in Russian)

Goff, J. A., Gratch, S. 1946. Low Pressure Properties of Water from -160 to 212°F. *Transactions, American Society of Heating and Ventilating Engineers*, **52**:95-122.

Guzzi, R., Rizzi, R. Water Vapour Absorption in the Visible and Near-Infrared: Results of Field Measurements. *Applied Optics*, **23**(11): 1853-1861.

Hartmann, G. K. 1991. The Determination of Tropospheric Conditions (Especially H_2O) Affecting the Accuracy of Position Measurements. Paper presented at 20th General Assembly, IUGG, Vienna, 23 August 1991, (*Symposium on Environmental Effects on Spacecraft Trajectories and Positioning*), 28 pages.

Hartmann, G. K., Leitinger, R. 1984. Range Errors due to Ionospheric and Tropospheric Effects for Signal Frequencies above 100 MHz. *Bulletin Géodésique*, **58**: 109-136.

Heimann, M. 1996. Closing the Atmospheric CO_2 Budget: Inferences from new Measurements of $^{13}C/^{12}C$ and O_2/N_2 Ratios. *Global Change (IGBP) Newsletter*, **28**: 9-11.

Hill, R. J. 1996. Refractive Index of Atmospheric Gases. Chapter II.3.1.1 in: Dieminger-Hartmann-Leitinger (eds), *The Upper Atmosphere*, Springer-Verlag, Berlin-Heidelberg-New York, 261-270.

Hill, R. J. 1988. Dispersion by Atmospheric Water Vapour at Frequencies less than 1 THz. *IEEE Trans. on Antennas and Propagation*, **36**(3): 423-430.

Hill, R. J., Lawrence, R. S. 1986. Refractive Index of Water Vapour in Infrared Windows. *Infrared Physics*, **26**(6): 371-376.

Hill, R. J., Lawrence, R. S., Priestley, J. T. 1982. Theoretical and Calculational Aspects of the Radio Refractive Index of Water Vapour. *Radio Science*, **17**(5): 1251-1257.

Hill, R. J., Clifford, S. F. 1981. Contributions of Water Vapour Monomer Resonances to Fluctuations of Refraction and Absorption for Submillimetre Through Centimetre Wavelengths. *Radio Science*, **16**(1):77-82.

Hill, R. J., Clifford, S. F., Lawrence, R. S. 1980a. Refractive Index and Adsorption Fluctuations in the Infrared caused by Temperature, Humidity and Pressure Fluctuations, *J. Opt. Soc. Am.*, **70**(10): 1192-1205.

Hill, R. J., Clifford, S. F., Lawrence, R. S. 1980b. *Computed Refraction and Absorption Fluctuations caused by Temperature, Humidity and Pressure Fluctuations – Radio Waves to 5 mm.* NOAA Technical Memorandum, Environmental Research Laboratories, Wave Propagation Laboratory, ERL WPL-59, 64 pages.

Hinderling, J., Sigrist, M. W., Kneubühl, F. K. 1987. Laser-Photoacoustic Spectroscopy of Water-Vapour Continuum and Line Absorption in the 8 to 18 mm Atmospheric Window. *Infrared Physics*, **27**(2): 63-120.

Hou, W., Thalmann, R. 1994. Accurate Measurement of the Refractive Index of Air. *Measurement*, **14**: 307-314.

Hufford, G. 1987. *Millimetre-Wave Pulse Distortion by a Single Absorption Line Simulating the Terrestrial Atmosphere*. NTIA Report 87-229, National Telecommunications and Information Administration (NTIA), 325 Broadway, Boulder CO 80303, 39 pages.

Hyland, R. W., Wexler, A. Formulations for the Thermodynamic Properties of the Saturated Phases of H_2O from 173.15 K to 473.15 K. *ASHRAE Trans.*, **89**: 500-511.

IUGG (International Union of Geodesy and Geophysics). 1963. Resolutions, 13th General Assembly, 19-31 August 1963, Berkeley, California, USA. *Bulletin Géodésique*, **70**:390.

Jansco, G., Pupezin, J., Van Hook, W. A. 1970. The Vapour Pressure of Ice between $+10^{+2}$ and -10^{+2}. *J. Phys. Chem.*, **74**: 2984-2989.

Jones, F. E. 1981. The Refractivity of Air. *J. Res. Natl. Bur. Stand.*, **86**: 27-32.

Jones, F. E. 1980. Simplified Equation for Calculating the Refractivity of Air. *Appl. Opt.*, **19**: 4129-4130.

Langley, R. B. 1992. The Effect of the Ionosphere and Troposphere on Satellite Positioning Systems. Abstract in: DeMunck, J. C. & Spoelstra, T. A. T. (eds.) Proc., *Symposium on Refraction of Transatmospheric Signals in Geodesy*, 19-22 May 1992, The Hague, Netherlands Geodetic Commission, Publications on Geodesy, New Series, No.36, p. 97 (full paper 10 pages).

Leitinger, R. 1996. Transatmospheric Propagation of Radio Waves: The Role of the Atmosphere in Communication, Navigation, Geodesy etc. Chapter I.7 in: Dieminger - Hartmann, Leitinger (Eds.), *The Upper Atmosphere – Data Analysis and Interpretation,* Springer-Verlag, Berlin-Heidelberg-New York, 169-187.

Liebe, H. J. 1996. Models for the Refractive Index of the Neutral Atmosphere at Frequencies Below 1000 GHz. Chapter II.3.1.2 in: Dieminger-Hartmann-Leitinger (eds.), *The Upper Atmosphere – Data Analysis and Interpretation*. Springer-Verlag, Berlin-Heidelberg-New York, 1996, 270-287.

Liebe, H. J. 1989. MPM – An Atmospheric Millimetre Wave Propagation Model. *Int. Journ. Infrared and Millimetre Waves*, **10**(6): 631-650.

Liebe, H. J. 1983. *An Atmospheric Millimetre Wave Propagation Model*. NTIA Report 83-137, National Telecommunications and Information Administration (NTIA), 325 Broadway, Boulder CO 80303, 110 pages.

Liebe, H. J. 1969. Calculated Tropospheric Dispersion and Absorption due to the 22 GHz Water Vapour Line. *IEEE Transactions on Antennas and Propagation*, **AL-17**(5): 621-627.

Liebe, H. J. 1966. Über Untersuchungen des Brechungsindex von Wasserdampf-Stickstoff im Bereich 3 bis 14 GHz. *Nachr. Techn. Z.*, **19**:79-83.

Liebe, H. J., Hufford, G. A., Cotton, M. G. 1993. Propagation Modeling of Moist Air and Suspended Water/Ice Particles at Frequencies below 1000 GHz. *AGARD, 52nd Specialists' Meeting of the Electromagnetic Wave Propagation Panel*, Palma da Mallorca, Spain, 17-21 May 1993, 3-1 to 3-10.

Liebe, H. J., Hufford, G. A., Cotton, M. G. 1992. Progress in Atmospheric Propagation Modelling at Frequencies below 1000 GHz. *Proc., 1992 Battlefield Atmospherics Conference*, 1-3 December 1992, Fort Bliss, El Paso, Texas, 247-256.

Liebe, H. J., Hufford, G., Manabe, T. 1991. A Model for the Complex Permittivity of Water at Frequencies below 1 THz. *Int. Journ. Infrared and Millimetre Waves*, **12**(7): 659-675.

Liebe, H. J., G. A. Hufford, R. O. DeBolt. 1991. *The Atmospheric 60-GHz Oxygen Spectrum: Modelling and Laboratory Measurements*. NTIA Report 91-272, National Telecommunications and Information Administration (NTIA), 325 Broadway, Boulder CO 80303, 36 + 124 pages.

Liebe, H. J., D. H. Layton. 1987. *Millimetre-Wave Properties of the Atmosphere: Laboratory Studies and Propagation Modelling*. NTIA Report 87-224, National Telecommunications and Information Administration (NTIA), 325 Broadway, Boulder CO 80303, 74 pages.

Liebe, H. J., Hopponen, J. D. 1977a. Variability of EHF air Refractivity with Respect to Temperature, Pressure and Frequency. *IEEE Trans. on Antennas and Propagation,* **AP-25**(3): 336-345.

Liebe, H. J., Gimmestad, G. G., Hopponen, J. D. 1977b. Atmospheric Oxygen Microwave Spectrum – Experiment versus Theory. *IEEE Trans. on Antennas and Propagation,* **AP-26**(3): 327-335.

McCoy, J. H., Rensch, D. B., Long, R. K. 1969. Water Vapour Continuum Absorption of Carbon Dioxide Laser Radiation near 10 mm. *Applied Optics,* **8**(7):1471-1478.

Mandel, L., Wolf, E. 1995. *Optical Coherence and Quantum Physics*. Cambridge University Press, UK.

Marti, J., Mauersberger, K. 1993. A Survey and New Measurements of Ice Vapour Pressure at Temperatures between 170 K and 250 K. *Geophys. Res. Lett*., **20**: 363-366.

Matsumoto, H. 1987. The Refractivity of CO_2 Gas in the Region of 10 μm. *Applied Physics B*, **44**:147-149.

Matsumoto, H. 1984. The Refractivities of Water Vapour for CO_2 Laser Lines. *Optics Communications*, **50**(6): 356-358.

Matsumoto, H. 1982a. Measurement of the Group Refractive Index of Air by Two-Wavelength Interferometry. *Optics Communications*, **44**(1): 5-7.

Matsumoto, H. 1982b. The Refractive Index of Moist Air in the 3 µm Region. *Metrologia*, **18**:49-52.

Matsumoto, H., Zeng, L. 1994. High-Accuracy Measurement of Air Refractive Index using two Frequency-Doubling Crystals. *Optics Communications* **104**:241-244

Matsumoto, H., Kurosawa, T., Iwasaki, S. 1988. Verification of the Accuracy of a CO_2 Laser Interferometer for Distance Measurement. *Metrologia*, **25**:95-97.

Mendes, V. B. 1999. *Modelling the Neutral-Atmosphere Propagation Delay in Radiometric Space Techniques*. PhD dissertation, Department of Geodesy and Geomatics Engineering Technical Report No. 199, University of New Brunswick, Fredericton, New Brunswick, Canada, 353 pages.

Mujlwijk, R. 1988. Update of the Edlén Formulae for the refractive Index of Air. *Metrologia,* **25**: 189. C. Rischel and P. S. Ramanujam, Refractive Index of Air – Errata, *Metrologia*, **26**: 263 (1989).

NASA. 1987. *From Pattern to Process: The Strategy of the Earth Observing System* – EOS Science Steering Committee Report, Vol. II, 140 pages.

Newell, A. C., Baird, R. C. 1965. Absolute Determination of Refractive Indices of Gases at 47.7 GHz. *Journal of Applied Physics*, **36**(12): 3751-3759.

Old, J. G., Gentili, K. L., Peck, E. R. 1971. Dispersion of Carbon Dioxide. *J. Opt. Soc. Of America*, **61**(1): 89-90.

Oughstun, K. E. 1991. Pulse Propagation in a linear, causally dispersive Medium. *Proc. IEEE*, **79**(10), 1370-1390.

Oughstun, K. E., Wyns, P., Foty, D. 1989. Numerical Determination of the Signal Velocity in Dispersive Pulse Propagation. *J. Opt. Soc. Am*., **A 6**, 1430-1440.

Owens, J. C. 1967. Optical Refractive Index of Air: Dependence on Pressure, Temperature and Composition. *Applied Optics,* **6**(1): 51-59.

Peck, E. R. 1986. Precise Measurements of Optical Dispersion using a new Interferometric Technique: Comment. *Appl. Opt*., **25**: 3597-3598.

Peck, E. R., Reeder, K. 1972. Dispersion of Air. *Journal of the Optical Society of America*, **62**(8): 958-962.

Peck, E. R., Khanna, B. N. 1962. Dispersion of Air in the Near-Infrared. *Journal of the Optical Society of America*, **52**(4): 416-419

Preston-Thomas, H. 1990. The International Temperature Scale of 1990 (ITS-90). *Metrologia,* **27**:3-10

Rothman, L. S., Schroeder, J., McCann, A., Gamache, R. R., Wattson, R. B., Flaud, J.-M., Perrin, A., Dana, V., Mandin, J.-Y., Goldman, A., Massie, S., Varassi, P., Yoshino, K. The 1996 HITRAN Molecular Spectroscopic Database and HAWKS (HITRAN Atmospheric Workstation), submitted to *Journal of Quantitative Spectroscopy and Radiative Transfer.*

Rothman, L. S., Gamache, R. R., Tipping, R. H., Rinsland, C. P., Smith, M. A. H., Chris Benner, D., Malathy Devi, V., Flaud, J.-M., Camy-Peyret, C., Perrin, A., Goldman, A., Massie, S. T., Brown, L. R., Toth, R. A. 1992. The HITRAN Molecular Database: Editions of 1991 and 1992. *J. Quant. Spectrosc. Radiat. Transfer*, **48**(5/6): 469-507.

Rüeger, J. M. 1999. Refractive Index of Water and Electro-Optical Distance Measurement through Rain. *Survey Review*, **35**(271): 11-22.

Rüeger, J. M. 1998a. Refractive Index Formulae for Electro-Optical Distance Measurement. *Proc., Commission 5, 21st International Congress (FIG'98), International Federation of Surveyors*, 19-25 July 1998, Brighton, UK, 191-208.

Rüeger, J. M. 1998b. Refractive Index Formulae for Electronic Distance Measurement with Radio and Millimetre Waves, 13 pages (in Preparation).

Rüeger, J. M. 1996a. *Electronic Distance Measurement – An Introduction*. 4th ed. Springer-Verlag, Berlin-Heidelberg-New York, 276 + xix pages.

Rüeger, J. M. 1996b. Einfluss von Regen auf die elektronische Entfernungsmessung, XII. Int. Kurs für Ingenieurvermessung, Graz, 9-14 September 1996, in: Brandstätter/Brunner/Schelling (Eds.), *Ingenieurvermessung 96*, Vol. 1, Dümmler, Bonn, 1996, A10/1 - A10/10.

Rüeger, J. M. 1990. *Electronic Distance Measurement – An Introduction*. 3rd ed. Springer-Verlag, Berlin-Heidelberg-New York, 266 + xvii pages.

Schellekens, P., Wilkening, G., Rinboth, F., Downs, M. J., Birch, K. P., Spronck, J. 1986. Measurements of the Refractive Index of Air using Interference Refractometers. *Metrologia*, **22**: 279-287.

Schiebener, P., Straub, J., Levelt Sengers, J. M. H., Gallagher, J. S. 1990. Refractive Index of Water and Steam as Function of Wavelength, Temperature and Density. *J. Phys. Chem. Ref. Data*, **19**: 677-715.

Simmons, A. C. 1978. The Refractive Index and Lorentz-Lorenz Functions of Propane, Nitrogen and Carbon-Dioxide in the Spectral Range 15803-22002 cm^{-1} and 944 cm^{-1}, *Opt. Commun*., **25**: 211-214.

Taylor, J. A. 1994. Fossil Fuel Emission Required to Achieve Atmospheric CO_2 Stabilisation. Proc., International Symposium of *Global Cycles of Atmospheric Greenhouse Gases*, Tohoku University, Sendai, Japan, 7-10 March 1994, 308-314.

Thayer, G. D. 1974. An Improved Equation for the Radio Refractive Index of Air. *Radio Science*, **9**(10): 803-807.

Taylor, J. A. 1994. Fossil Fuel Emission Required to Achieve Atmospheric CO_2 Stabilisation. Proc., International Symposium of *Global Cycles of Atmospheric Greenhouse Gases*, Tohoku University, Sendai, Japan, 7-10 March 1994, 308-314.

Terrien, J. 1965. An Air Refractometer for Interference Length Metrology. *Metrologia*, **1**: 80-83.

Trizna, D. B., Weber, T. A. 1982. Brillouin Revisited: Signal Velocity Definition for Pulse Propagation in a Medium with Resonant Anomalous Dispersion. *Radio Sci*., **17:** 1169-1180.

Velsko, S. P., Eimerl, D. 1986. Precise Measurements of Optical Dispersion using a new Interferometric Technique. *Appl. Opt*., **25**: 1244-1349.

Walter, S. J. 1990. *Measurement of the Microwave Propagation Delay Induced by Atmospheric Water Vapour*, PhD Thesis, Department of Physics, University of Colorado, Boulder, 236 pages.

Xiao, H., Oughstun, K. E. 1998. Hybrid Numerical-Asymptotic Code for Dispersive-Pulse Propagation Calculations. *J. Opt. Soc. Am.* **A 15**, 1256-1267.

Zhevakin, S. A., Naumov, A. P. 1967a. Refraction of Millimetre and Submillimetre Radio Waves in the Lower Atmosphere. *Radio Engineering and Electronic Physics* (translated and published by IEEE), **12**(1): 885-894.

Zhevakin, S. A., Naumov, A. P. 1967b. The Index of Refraction of Lower Atmosphere for Millimetre and Submillimetre Radio Waves – The Rotational Part of the Dielectric Permittivity of Atmospheric Water Vapour at Wavelengths greater than 10 Micrometres. *Radio Engineering and Electronic Physics* (translated and published by IEEE), **12**(7):1067-1076.

Proposed

RESOLUTIONS

OF THE

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

(related to Geodesy) on the occasion of its

22nd General Assembly (IUGG 99), 18 to 30 July 1999, Birmingham, UK

RESOLUTION No. A

The International Union of Geodesy and Geophysics,

recognising that:

a) the accuracy of the instrumentation used for terrestrial electronic distance measurement and for measurements to satellites has improved greatly since IUGG adopted a resolution on the refractive index of air in 1963;

b) new absolute and relative measurements of the refractive index of air have been made since 1963;

c) more accurate refractive index formulae have been developed and older formulae have been found to be in error since 1963;

d) the international temperature scale was revised in 1990; and

e) a carbon dioxide content of air of 300 ppm is no longer appropriate;

cancels:

sub paragraphs (a) and (b) of Resolution No. 1 of the 13th General Assembly of IUGG (Berkley 1963);

noting that:

the continuum dispersion formulas used by the recommendation below do not account for the effects of anomalous refractivity due to molecular resonances in the visible and near-infrared;

recommends that:

a) the group refractive index in air for electronic distance measurement to better than one part per million (ppm) with visible and near infrared waves in the atmosphere be computed using the computer procedure published by Ciddor & Hill in Applied Optics (1999, Vol.38, No.9,1663-1667) and Ciddor in Applied Optics (1996, Vol. 35, No.9, 1566-1573). Guidelines for the implementation will be published separately. The listed papers also include a computer procedure for the calculation of the phase refractive index.

b) the following closed formulas be adopted for the computation of the group refractive index in air for electronic distance measurement (EDM) to not better than 1 ppm with visible and near infrared waves in the atmosphere:

$$N_L = (n_L - 1) \times 10^6 = \left(\frac{273.15}{1013.25} \times \frac{Ng \times p}{T}\right) - \frac{11.27e}{T}$$

where N_L is the group refractivity of visible and near infrared waves in ambient moist air, T is the temperature in kelvin (ITS-90), T = 273.15 + t, t is the temperature in degrees Celsius (°C), p the total pressure in hectopascal (hPa) and e the partial water vapour pressure in hectopascal (hPa).

The group refractivity N_g of standard air with 0.0375% CO_2 content at T = 273.15 K (0°C), p = 1013.25 hPa, e = 0.0 hPa is as follows

$$N_g = (n_g - 1) \times 10^6 = 287.6155 + \frac{4.88660}{\lambda^2} + \frac{0.06800}{\lambda^4}$$

where λ is the carrier wavelength of the EDM signal (in micrometre, μm) and n_g the corresponding group refractive index.

These closed formulas deviate less than 0.25 ppm from the accurate formulas (see (a) above) between -30°C and +45°C, at 1000 hPa pressure, 100% relative humidity (without condensation) and for wavelengths of 650 nm and 850 nm, for example. The 1 ppm stated before makes some allowance for anomalous refractivity and the uncertainty in the determination of the atmospheric parameters.

Where required, the phase refractivity N_{ph} of standard air with 0.0375% CO_2 content at T = 273.15 K (0°C), p = 1013.25 hPa, e = 0.0 hPa may be calculated as follows

$$N_{ph} = (n_{ph} - 1) \times 10^6 = 287.6155 + \frac{1.62887}{\lambda^2} + \frac{0.01360}{\lambda^4}$$

where λ is the carrier wavelength of the signal (in micrometre, μm) and n_{ph} the corresponding phase refractive index.

Sponsored by the Ad-Hoc Working Group on *Refractive Indices of Light, Infrared and Radio Waves in the Atmosphere* (convener: J. M. Rüeger) of the IAG Special Commission SC3 on Fundamental Constants (SCFC).

15 June1999

RESOLUTION No. B

The International Union of Geodesy and Geophysics,

recognising that:

a) the accuracy of any continuum refractive index formula for the visible and near infrared spectrum is ultimately limited by anomalous refractivity due to absorption lines, particularly for the group refractive index;

b) present dispersion formulae are based on very few absolute refractivity measurements of dry air and moist air, particularly in the near infrared; and

c) very few direct measurements of the group refractive index are available;

noting that:

preliminary work on the computation of the magnitude of anomalous phase and group refractivity in the visible and near-infrared has been done;

recommends that:

a) further work on the effect of absorption lines on the phase and group refractive indices of air be carried out in order to be able to quantify the magnitude of anomalous refractivity for specific instruments and, ideally, to provide software to correct for such effects; and

b) new absolute measurements of the refractivity of the constituent gases of the atmosphere (incl. water vapour) be carried out at non-laboratory conditions, with special emphasis on near infrared wavelengths.

Sponsored by the Ad-Hoc Working Group on *Refractive Indices of Light, Infrared and Radio Waves in the Atmosphere* (convener: J. M. Rüeger) of the IAG Special Commission SC3 on Fundamental Constants (SCFC).

15 June 1999

RESOLUTION No. C

The International Union of Geodesy and Geophysics,

recognising that:

a) the radio refractive index formula recommended in sub paragraph (c) of Resolution No. 1 of the 13th General Assembly of IUGG (Berkley 1963) has not been generally adopted and is now obsolete;

b) new absolute and relative measurements of the mid-infrared to radio wave refractive index of air have been made since 1963;

c) considerable advances have been made with the computation of anomalous refractivity in the mid-infrared to radio wave spectrum;

d) the international temperature scale was revised in 1990; and

e) a carbon dioxide content of air of 300 ppm is no longer appropriate;

noting that:

preliminary work on a new recommendation on the radio refractive index has been done;

recommends that:

interested scientists contribute to the work on a new recommendation for the mid-infrared to radio refractive index in air.

Sponsored by the Ad-Hoc Working Group on *Refractive Indices of Light, Infrared and Radio Waves in the Atmosphere* (convener: J. M. Rüeger) of the IAG Special Commission SC3 on Fundamental Constants (SCFC).

15 June1999

Special Study Group 5.172

UNDERSTANDING NATURAL HAZARDS - GEODETIC CONTRIBUTION

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Missions

- Applying theoretical, observational, and instrumental techniques to better understand natural hazards such as earthquake, volcanic eruption, and land slide.
- Developing techniques to detect hidden seismic faults, premonitory signals of volcanic eruption/land slide from geodetic data. Emphasis will be placed on air-borne precise gravimetry, SAR interferometry, Satellite altimetry, dense GPS monitoring network.
- Improving theory, which predicts changes of the geodetic bservables: baseline change, elevation change, gravity change, strain and tilts changes and so on.

Organisation

Results

Differential InSAR

Differential use of interferometric SAR (Synthetic Aperture Radar) is one of highlights in recent geodetic works. Murakami's group successfully applied the technique to detect co-seismic and volcanic deformations of the ground surface. The 1995 Kobe earthquake (M7.2) was one of such successful examples (Murakami et al. 1995) as well as other events in Izu (Fujiwara et al. 1998a), Kyushu (Fujiwara et al. 1998b), Iwate, California (Murakami et al. 1996) and Sakhalin (Tobita et al. 1998). The SAR interferogram together with a dense GPS data enabled Murakami to estimate the fault mechanism of the Kobe earthquake (Ozawa et al. 1997).

Okubo's group evaluated the potential of the JERS-1 L-band SAR interferometry to detect subtle crustal movements even in mountainous region in Japan and its geodetic accuracy by comparing and combining other geodetic and seismological observations. They succeeded to detect crustal deformations for several cases as listed below (Kobayashi 1998 ab).

- fault motion by the Kagoshima earthquake (M6.3),
- volcano inflation and the following earthquake (M6.1) around Mt. Iwate in 1998,
- tensile deformation associated with earthquake swarms around the monogenic volcano area in the Izu Peninsula in 1997 and 1998, (4) volcanic deformations of Mt. Unzen during 1992 to 1993.

Secular Gravity Monitoring in a Seismic Risk Region

Gravity changes before a coming great earthquake in a seismic risk region of Tokai District have been monitored with both absolute and relative gravimeters by Okubo and Murakami with technical assistance of Niebauer. They expect detecting secular change of gravity there. This can be associated with the subsidence at Omaezaki observed by spirit leveling, due to the subduction of the Philippine Sea Plate. They compared their results in 1995 and in 1996 with previous ones by the Geographical Survey Institute, Japan in 1987 and by the National Astronomical Observatory in 1992 (Okubo, Yoshida and Araya, 1997). They found regional gravity decrease during an interseismic period at the subduction plate boundary where the land is steadily subsiding. This paradoxical finding poses a challenging problem on the subduction dynamics at converging plate boundaries.

Gravity Change in an Earthquake Swarm Region

Okubo's group carried out both absolute and relative gravity measurements in the Izu Peninsula just before and after the March 1997 earthquake swarm occurred (Yoshida et al., 1999). The measurements revealed significant absolute gravity changes associated with the volcanic activity that caused the earthquake swarm. The gravity changes can be used to detect underground mass movement. For this purpose, they first use crustal movement observations to construct an elastic dislocation model with two tensile faults and a left lateral fault. Then they use the gravity changes to constrain the density of the material, which filled the tensile faults. They find that the density is likely to be small, and that the gravity change is reproduced well by the fault model. The smallness of the density implies that highly vesiculated magma or water would have injected into the faults.

Theory on Gravity Change and Crustal Deformation due to Seismic and Volcanic Processes

Sun Wenke and Okubo (1998) presented numerical formulation for computing elastic deformations caused by a dislocation on a finite plane in a spherically symmetric earth. It is based on their previous work for a point dislocation. The formulation enables them to compute the displacement, potential and gravity changes due to an earthquake modelled as spatially distributed dislocations. As an application of the finite-fault dislocation theory, they made a case study of the theoretical and observed gravity changes for the 1964 Alaska Earthquake. The computed results are in excellent agreement with the observed gravity changes during the earthquake. The gravity changes in the near field can reach some hundred microgals which can be easily detected by any modern gravimeter. In a far field it is still significantly large: $|\delta g| > 10$ microgals within the epicentral distance $\theta < 6°$, $|\delta g| > 1$ microgal within $\theta < 16°$, $|\delta g| > 0.1$ microgals within $\theta < 40°$, $|\delta g| > 0.01$ microgals globally.

Refined Crustal Deformation Analysis before the Kobe Earthquake

Zhao detected a high-angle reverse fault was detected in the Shikoku-Kinki region7 southwest Japan through inversion analysis of horizontal displacements observed with GPS during 1990-1994 (Zhao and Takemoto, 1998). The active blind fault is characterized by reverse dip-slip (0.7 ± 0.2 $m \cdot yr^{-1}$ within a layer 17-26 km deep) with a length of 208 ± 5 km, a (down-dip) width of 9 ± 2 km, a dip-angle of 51° ± 2° and a strike direction of 40° ± °(NE). The fact that hardly any earthquakes (M_L >2.0) occurred at depth on the inferred fault plane suggests that the fault activity was largely aseismic. Based on the parameters of the blind fault estimated in their study, they evaluated stress changes in this region. It is found that shear stress concentrated and increased by up to 2.1 $bar \cdot yr^{-1}$ at a depth of about 20 km around the epicentral area of the 1995 January 17 Kobe earthquake (M_L = 7.2, Japan), and that the earthquake hypocentre received a Coulomb failure stress of about 5.6 $bar \cdot yr^{-1}$ during 1990-1994. The results suggest that the 1995 Kobe earthquake could have been induced or triggered by aseismic fault movement.

Secular Gravity Monitoring in a Volcanic Region

After the 1986 eruption of Izu-Oshima volcano, Japan, Okubo's group observed anomalous gravity variations localized at the summit (Watanabe et al., 1998). Based on a vertical cylindrical conduit model, they estimate the time variations of the head of magma in the summit conduit and clarify the magma drain-back process after the 1986 eruption.
They thus demonstrated that it is quite plausible to detect magma movements directly by microgravity observations. Even when it causes only minor deformation in the case of Basalt magma.

Recommendations

We find that recent advances of geodetic measurements including SAR, GPS, Absolute/Relative gravity provides us with an unprecedented opportunity toward better understanding of natural hazards such as earthquakes and volcanic eruptions. Geodetic adjustment/inversion theories also turns out to play important roles in modeling seismic and volcanic processes. We recommend to set up several test fields where those advanced geodetic techniques are applied *in an integrated manner* to monitor and assess potential risks of natural hazards.

Bibliography

Fujiwara S., Rosen PA, Tobita M, Murakami M (1998a): Crustal deformation measurements using repeat-pass JERS 1 synthetic aperture radar interferometry near Izu Peninsula, Japan, J. Geophys. Res., 103(B2): 2411-2426.

Fujiwara S, Yarai H, Ozawa S, Tobita M, Murakami M, Nakagawa H, Nitta K, P.A. Rosen, Werner CL (1998b): Surface displacement of the March 26,
1997 Kagoshima-ken-hokuseibu earthquake in Japan from synthetic aperture radar interferometry, Geophys. Res. Let., 25: 4541-4544.

Kobayashi, S. (1998a): JERS-1 Researches, EORC Annual Report 1997, No. 1, March 1998, 19-27.

Kobayashi, S. (1998b): The Earthquake Remote Sensing Frontier Research (a) Geodetical evaluation of the accuracy of D-InSAR by comparison with GPS,precise gravity measurements and leveling surveys in Omaezaki, central Japan, (b) Criteria for evaluating the accuracy of the D-InSAR technique and its applications to monitoring of volcanic deformation, EORC Annual Report 1997, No. 1, March 1998, 58-59, 1998.

Murakami M, Fujiwara S, Saito T (1995): Detection of Crustal Deformations Associated with the 1995 Hyogoken-Nanbu Earthquake
by Interferometric SAR, J. Geogr. Surv. Inst., 83: 24-27. (in Japanese)

Murakami M, Tobita M, Fujiwara S, Saito T, Masaharu H (1996): Crustal Movements from the 1994 California Earthquake Revealed by Interferometric SAR, J. Geophys. Res., 101(B4): 8605-8614.

Okubo S, Yoshida S, Araya A (1997): Interseismic Gravity Change at a
Subducting Plate Margin: a Paradoxical Observational Result at Omaezaki,
Tokai, Japan, IAG Symposia 117, "Gravity, Geoid and Marine Geodesy", Sep. 30 - Oct. 5, 1996, Tokyo, Japan, Springer-Verlag, 305-309.

Sun Wenke, Okubo S (1998): Surface potential and gravity changes due to
internal dislocations in a spherical earth -- II. Application to a finite fault, Geophys. J. Int., 132: 79-88.

Tobita, M, Fujiwara S Ozawa S, Rosen PA, Fielding EJ, Werner CL, Mas. Murakami, Nakagawa H, Nitta K, Murakami M (1998): Deformation of the 1995 North Sakhalin earthquake detected by JERS-1/SAR interferometry, Earth, Planets and Space, 50: 313-325.

Watanabe H, Okubo S, Sakashita S, Maekawa T (1998): Drain-back process of basaltic magma in the summit conduit detected by microgravity observation at Izu-Oshima volcano, Japan. Geophysical Res. Lett., 25: 2865-2868.

Yoshida S, Seta G, Okubo S, Kobayashi S (1999): Absolute gravity change associated with the March 1997 earthquake swarm in the Izu Peninsula, Japan, Earth Planets Space, 51: 3-12,

Zhao Shaorong, Takemoto S (1998): Aseismic fault movement before the 1995 Kobe earthquake detected by a GPS survey: implication for preseismic stress localization ?, Geophys. J. Int., 135: 595-606.

Special Study Group 5.173

INTERACTION OF THE ATMOSPHERE AND OCEANS WITH THE EARTH'S ROTATIONAL DYNAMICS

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1. Missions

International Association of Geodesy Special Study Group 5.173, 'Interaction of the Atmosphere and Oceans with the Earth's Rotational Dynamics' was established to coordinate studies related to understanding the causes of observed rotational variations and their relationships with oceanic and atmospheric variability over the range of time scales from hours to decades. Understanding these rotational variations requires a combined effort of theory, observation, and numerical modeling of geodetic, oceanographic, and atmospheric processes.

2. Organization

SSG members organized a great variety of special sessions at scientific meetings as noted under the bibliography section, below. Several SSG meetings of opportunity were held at these meetings, and a world wide web site was developed to organize the SSG during its formative year.

As a result of recommendations from the October 1996 workshop, the IERS issued a call for coordinating centers for various geophysical fluids. The extension of IERS missions to include geophysical fluids is directly an effort of members of SSG5.173, and puts in place an organization to advance the study of the interaction of the oceans and atmosphere with the earth's rotation. In effect, the formal development of these geophysical fluid centers is a statement of the success of this SSG, which builds on the work of several related SSG's over the past decade.

The study of the gravity field is the focus of IAG Section III, and the study of the time variations in the gravity field is the subject of Special Study Group 5.174. However, it has become clear that the geophysical sources that change the gravity field also affect the rotation of the earth, and are dominated by the atmosphere and oceans. Thus, forthcoming satellite missions (Germany-CHAMP; NASA-GRACE; ESA-GOCE) that will be capable of observing the gravity field have great importance for the study of Earth rotation changes. They are closely coupled problems, with the focus of earth rotation being the Degree 2 spherical harmonics that influence polar motion and Length of Day. As a means of monitoring variations in mass distribution, earth rotation will retain the advantage of high temporal sampling rates for a limited number of harmonics, and the disadvantage that earth rotation changes measure the sum of mass redistribution and relative angular momentum (wind and current) effects.
Recognizing that earth rotation and gravitational potential problems are closely linked, it is worth noting that members of this SSG have also been engaged in the study of the Earth's geopotential fields, both gravity and magnetic. The principal tool for whole-earth observations is satellite measurement.. Recognition of the next decade (starting in 1999)

as the geopotential field decade was proposed at the IAG Assembly in Rio de Janeiro, in September, 1997. The Executive Committee of IAG has adopted a proposal for the declaration of an International Decade of Geopotential Fields Research, similar to the one adopted earlier by IAGA. The activity related to the time variable gravity field will naturally improve the estimates of the degree 2 spherical harmonic components which are important in the study of earth rotation.

3. Results

The studies of previous Special Study Groups in related areas had established that the atmosphere provides significant forcing of changes in polar motion and length of day, but that there are observable, often large variations in these rotation elements which cannot be explained by the atmosphere. Additionally, it was recongized that the atmosphere and oceans may contribute some influences that would appear as changes in nutation and precession. With improved ability to model and observe the atmosphere, the calculation of atmospheric angular momentum changes has improved steadily within th emeteorological community. Global atmospheric general circulation calculations obtained routinely (every few hours) for weather forecasting purposes are now available, as are reanalysis time series, where the numerical model is held fixed. These atmospheric calculations also provide an estimate of the winds acting on the oceans, and it has become possible to numerically produce time series of oceanic angular momentum variations. Such time series cannot be obtained from observations because the oceans are too poorly observed, but the evidence is that ocean models can be quite effective in estimating changes in earth rotation. The full bibliography below shows the breadth of efforts in this area for both the atmosphere and oceans, and related problems.

Two papers in the bibliography nicely summarize the conclusion that the oceans explain a large part of the remaining variations in the earth's rotation, at periods of a year and less. The paper by Marcus et al (1998) clearly shows that residual non-atmospheric Length of Day changes are of oceanic origin. Similarly, Ponte et al (1998) show a similar result for the case of polar motion. Of course there is a contribution from the storage of water mass on land and in ice, but this appears to be less important at short periods (less than a year), and is probably more important at longer periods. The geophysical fluid centers are organized to address this issue, and others as well. As the bibliography shows, there has also been progress in understanding tidal influences on Earth rotation, and atmospheric and oceanic effects that contribute to apparent nutations.

Overall, the activity of this SSG has made the ocean and atmospheric sciences communities aware of the importance of angular momentum as a diagnostic tool, and the ability of earth rotation observations to determine these quantities for the oceans and atmospheres with high accuracy.

4. Recommendations

The establishment of the Geophysical Fluid Centers activity under the IERS, in 1997, now provides a structure to provide data and to further stimulate research in this area. The SSG recommends that time series which reflect atmospheric, oceanic and other influences on the rotation of the earth be reported in the most fundamental SI units of torques and angular momenta.

Continued study of the effects of the oceans on earth rotation is called for, because the oceans are poorly observed. There is common ground with other important geodetic problems, notably the study of time variable gravity from space, variations in the geocenter, and the study of nutation and precession. These topics span the full range of time scales from hours to decades. Development of a Special Study Group which engages geodetic and oceanographic communities, while strengthening the efforts of the Geophysical Fluid Center for the oceans, is appropriate.

It is clear that there remain some important earth rotation changes that are not fully understood, both in polar motion and length of day, particularly at long periods, beyond a year. Further study of these is warranted. The core is implicated in these longer term variations in LOD, and hydrological mass balance is a suspected contributor to longer term polar motion changes. The data provided by the various Geophysical Fluid Centers working under the IERS should enable further research in these areas.

5. Bibliography

Bizouard Ch., Brzezinski A. and Petrov S. (1997). Variability of nutations: can it be driven by the atmosphere?, Proceedings Journees Systemes de Reference Spatio-Temporels 1997, Astronomical Institute, Academy of Sciences of the Czech R., pp. 73-76.

Bizouard Ch., Brzezinski A. and Petrov S. (1998). Diurnal atmospheric forcing and temporal variations of the nutation amplitudes, Journal of Geodesy, Vol. 72, pp. 561-577.

Black, R.X., D.A. Salstein, and R.D. Rosen, 1996: Interannual modes of variability in atmospheric angular momentum. *J. Climate*, **9**, 2834-2849.

Brosche, P., J. Wünsch, E. Maier-Reimer, J. Segschneider, J. Sündermann. The axial angular momentum of the general circulation of the oceans. Astron. Nachr. 318, 193-199, 1997

Brzezinski A. (1995a). On the interpretation of maximum entropy power spectrum and cross-power spectrum in earth rotation investigations,manuscripta geodaetica, Vol.20, pp. 248-264.

Brzezinski A. (1996a). "Broad band" Liouville equation of polar motion, Publ. Inst. Geophys. Pol. Acad. Sc., Vol. M-18 (273), pp. 173-181.

Brzezinski A. and Petrov S. (1998). Observational evidence of the free core nutation and its geophysical excitation. Proceedings Journees Systemes de Reference Spatio-Temporels 1998, Paris Observatory, in press.
Celaya, M., J. Wahr, and F.O. Bryan, 1999. Climate Driven Polar Motion, J. Geophs. Res., 104, 12813-12830.
Chen, J.L., C.R. Wilson, R.J. Eanes, and R.S. Nerem, Geophysical Interpretation of Observed Geocenter Variations, J. Geophys. Res., Vol. 104, No. B2, 2683 - 2690, 1999.
Chen, J.L., C. R. Wilson, D.P. Chambers, R.S. Nerem, and B.D. Tapley, Seasonal global water mass budget and mean sea level variations, Geophysical Research Letters, 25, 19, 3555-3558, October 1, 1998
Chao, B. F., R. D. Ray, and G. D. Egbert, Diurnal/semidiurnal oceanic tidalangular momentum: Topex/Poseidon models in comparison with Earth's rotation rate, Geophys. Res. Lett., 22, 1993-1996, 1995.
Chao, B. F., J. B. Merriam, and Y. Tamura, Geophysical analysis of zonal tidalsignals in length of day, Geophys. J. Int., 122, 765-775, 1995.
Chao, B. F., Anthropogenic impact on global geodynamics due to water impoundment in major reservoirs, Geophys. Res. Lett., 22, 3533-3536, 1995.
Chao, B. F., R. D. Ray, J. M. Gipson, G. D. Egbert, and C. Ma,Diurnal/semidiurnal polar motion excited by variations in oceanic tidal angular momentum, J. Geophys. Res., 101, 20,151-20,163, 1996.
Chao, B. F., and R. D. Ray, Oceanic tidal angular momentum and Earth's rotation variations, Prog. in Oceanog., 40, 399-421, 1998.
Chao, B. F., and Y. H. Zhou, Meteorological excitation of interannual polar motion by the North Atlantic Oscillation, J. Geodynamics, 27, 61-79, 1998.
Clark, T. A., C. Ma, J. W. Ryan, B. F. Chao, J. M. Gipson, D. S. MacMillan, N.R. Vandenberg, T. M. Eubanks, A. E. Niell, Earth rotation measurement yields valuable information about the dynamics of the Earth system, EOS, Trans. Amer. Geophys. Union, 79, 205-209, 1998.
Dehant, V., Wilson, C. Salstein, D., Chao, B., Gross, R., LeProvost, C, Ponte, R., Study of Earth’s Rotation and Geophysical Fluids Progresses, EOS, Transactions of the American Geophysical Union, 78, 34, p. 357, August 26, 1997.
Dehant V., Bizouard Ch., Legros H., Lefftz M. et Hinderer J., 1996,"The effects of on atmospheric pressure perturbations precession and nutations.", Phys. Earth planet. Inter., 96, 1, pp. 25-40.
Dehant V., C. Wilson, B. Fong Chao, R. Gross, Ch. Le Provost, R. Ponte, et D.Salstein, 1997, "Earth rotation dynamics and geophysical fluids." Report concerning Topic 6 of Workshop of the International Earth Rotation Service,Paris, France, octobre 1996, in: IERS Technical Note, eds. C. Reigberg et N. Capitaine, 22, pp. 31-40.
Dehant V., Feissel M., Defraigne P., Roosbeek F. et Souchay J., 1997,"Could the energy near the FCN and the FICN be explained by luni-solar or atmospheric forcing?", Geophys. J. Int., 130, pp. 535-546.
Desai, S. and J. Wahr, 1995 Empirical Ocean Tide Models Estimated from TOPEX/POSEIDON Altimetry, J. Geophys. Res., 100 (C12), 25205-25228.
Desai, S., J. Wahr, and Y. Chao, 1997.Error Analysis of Empirical Ocean Tide Models Estimated from TOPEX/POSEIDON Altimetry, J. Geophys. Res., 102 (C11), 25157-25172.
Desai, S., and J. Wahr, 1999.Monthly and fortnightly tidal variations of the earth's rotation rate predicted by a TOPEX/POSEIDON empirical ocean tide model",Geophys. Res. Lett., 26, 1035-1038.
DeViron,O., C. Bizouard, D.A. Salstein, and V. Dehant, 1999: Atmospheric torque on the Earth and comparison with atmospheric angular momentum variations, *J. Geophys. Res.,* **104**, 4861-4875.
De Viron O., Bizouard Ch. et Dehant V., 1997, "Calcul des moments de force produits par l'atmosphere sur la Terre solide, effets correspondents sur la nutation annuelle.", in: Proc. Journees Systemes de Reference Spatio-temporels 1996, septembre 1996, Paris, France, ed. N. Capitaine, pp. 189-190.
Dickman, S.R. and Y.-S. Nam, 1995. Revised predictions of long-period ocean tidal effects on Earth's rotation rate, J. Geophys. Res., 100, 8233-8243.
Dickman, S.R. and Y.-S. Nam, 1998. Constraints on Q at long periods from Earth's rotation, Geophys. Res. Lett., 25, 211-214.
Dickman, S.R., 1998. Determination of oceanic dynamic barometer corrections to atmospheric excitation of Earth rotation, J. Geophys. Res., 103, 15127-15143.
Furuya, M., and B. F. Chao, Estimation of period and Q of the Chandler wobble,Geophys. J. Int. 127, 693-702, 1996.
Furuya, M., Hamano, Y., and Naito, I., Quasi-Periodic Wind Signal As a Possible Excitation of Chandler Wobble, J.Geophys.Res., 101,25537-25546, 1996.
Furuya, M., Hamano, Y., and Naito, I., Importance of Wind for the Excitation of Chandler Wobble As Inferred From Wobble Domain Analysis, J. Phys.Earth. 47, 177-188, 1997.
Furuya, M. and Hamano, Y., Effect of the Pacific Ocean on the Earth's seasonal wobble inferred from National Center for Environmental Prediction ocean analysis data}, J. Geophys.Res., 103,10131-10140, 1998.
Gaspar, P., and R.M. Ponte, 1997. Relation between sea level and barometric pressure determined from altimeter data and mode simulations. Journal of Geophysical Research, 102, 961-971.
Gegout P., Hinderer J., Legros, H., Greff M. et Dehant V., 1998, "Influence of atmospheric pressure on the Free Core Nutation, precession and some forced nutational motions of the Earth.", Phys. Earth planet. Inter., 106, pp. 337-351.

Gross, R. S., B. F. Chao, and S. Desai, Effect of long-period ocean tides on the Earth's polar motion, *Prog. Oceanogr.*, **40**, 385ˆ397, 1998.
Gross, R. S., S. L. Marcus, T. M. Eubanks, J. O. Dickey, and C. L. Keppenne, Detection of an ENSO signal in seasonal length-of-day variations, *Geophys. Res. Lett.*, **23**, 3373ˆ3376, 1996.
Gross, R. S., K. H. Hamdan, and D. H. Boggs, Evidence for excitation of polar motion by fortnightly ocean tides, *Geophys. Res. Lett.*, **23**, 1809ˆ1812, 1996
Hide, R., J.O. Dickey, S.L Marcus, R.D. Rosen, and D.A. Salstein, 1997: Atmospheric angular momentum fluctuations in global circulation models during the period 1979-1988. *J. Geophys. Res.*, **102**, 16423-16438.
Hinderer J., Legros, H., Gegout P., Greff M., Dehant V. et Bizouard Ch., 1996, "L'atmosphere peut-elle perturber la pr'ecession de la Terre?", Comptes-rendus de l'Academie des Sciences, Paris, France, Serie Geophysique, Geodynamique, T. 323, Serie IIa, pp. 205-211.
Iskenderian, H., and D.A. Salstein, 1998: Regional Sources of Mountain Torque Variability and High-Frequency Fluctuations in Atmospheric Angular Momentum, *Mon. Wea. Rev*, **126**, 1681-1694.
Johnson, T.J., C.R. Wilson, B.F. Chao. Oceanic Angular Momentum Variability Estimated From The Parallel Ocean Climate Model, 1988-1998, J. Geophysical Res., in press.
Kagan, B.A. and J. Sündermann. Dissipation of tidal energy paleotides and evolution of the Earth-Moon system. Adv. in Geoph. 38, 179-266, 1996
Klosko, S. M., and B. F. Chao, The use of satellite laser ranging and long duration orbital changes to constrain geophysical models, in Dynamics of the Ice Age Earth: A Modern Perspective, ed. P. Wu, Trans Tech Pub., 533-556, 1998
Klosko, S. M., and B. F. Chao, Secular variations of the zonal gravity field,global sea level, and polar motion as geophysical constraints, Physics and Chemistry of the Earth, 23, 1091-1102, 1998.
Kuehne, J., Wilson, C., and Johnson, S., 1996. Estimates of the Chandler Wobble Frequency and Q., Journal of Geophysical Research v. 101, B6, 13573-13580.
Lejenas,h., r.a. madden, and J.J.. Hack,1997: global atmospheric angular momentum and earth-atmosphere exchange of angular momentum simulated in a general circulation model. j.geophys.res.,v102,p1931-1941
Madden,r.a., and P. Speth, 1995: estimates of atmospheric angular momentum,friction, and mountain torques during 1987-1988. j. atmos. sci., v 52, p3681-3694
Madden,r.a., h. lejenas, and j.j. hack,1998: semidiurnal variation in the budget of angular momentum in a general circulation model and in the real atmosphere. j.atos.sci., v55, p2561-2575
Madden, r.a., t.j. Hoar, and r.f. Milliff, 1999: scatterometer winds composited according to the phase of tropical intraseasonal oscillations. tellus, v51a, p 263-272
Marcus, S.L., Y. Chao, J.O. Dickey, P.Gegout, Detection and Modeling of Nontidal Oceanic Effects on Earth's Rotation Rate, Science 281, 1656-1659.
Mireault, Y., J. Kouba, and J. Ray, IGS Earth Rotation Parameters, GPS Solutions, in press 1999.
Nastula, J., and D. A. Salstein, 1999: Regional atmospheric angular momentum contributions to polar motion excitation, *J. Geophys. Res.*, **104**, 7347-7358.
Nastula, J., and R.M. Ponte, 1999. Further evidence for oceanic excitation of polar motion, Geophysical Journal International, in press.
Nastula J.,Short periodic variations of polar motion and hemispheric atmospheric angular momentum excitation functions in the period 1984-1992, Ann. Geophysiace, 13, 217-225, 1995.
Nastula J. , Analysis of the EAAM regional contributions to the polar motion excitation, proceedings of the international conference Journees 1995, Systemes de reference spatio-temporels, Warsaw, Poland, 155 - 158, 1995.
Kolaczek B., M. Nuzhdina, J. Nastula & W. Kosek, El Nino impact on atmospheric and geodetic excitation of polar motion, in printing in JGR-Solid Earth.
Kosek W., J. Nastula & B. Kolaczek, Variability of polar motion oscillations with periods from 20 to 150 days in 1979 -1991, Bulletin Geodesique, 30, 1, 27 - 43, 1995.
Nastula J., W. Kosek and B. Kolaczek, analyses of zonal atmospheric excitation functions nd their correlation with polar motion excitation functions, Annales Geophysicae, Vol. 15, 439 -1446, 1997.
Nastula J. & S. Manabe, Influence of the shallow seas on the pressure terms of the EAAM functions, IAG Symposia, Vol. 117; Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy, Springer-Verlag, 273 - 280, 1997.
Nastula J., The regional atmospheric contributions to the polar motion and EAAM exciatation functions, IAG Symposia, Vol. 117; Segawa et al. (eds.), Gravity, Geoid and Marine Geodesy,Springer-Verlag, 281 - 288, 1997.
Nastula J. & D. A. Salstein, Regional atmospheric angular momentum contributions to the polar motion excitation, IAG Symposia, Vol. 119; Forsberg et al. (eds.), Geodesy an the Move,Gravity, Springer-Verlag, 333 - 338., 1998.
Nastula J., O. Kotreleva, B. Kolaczek, & W. Kosek, Time-frequency characteristics of the pressure term of the EAAM excitation, IAG Symposia, Vol.119; Forsberg et al. (eds.) Geodesy on the Move, Springer-Verlag, 339 -334, 1998. .

Kolaczek B., M. Nuzhdina, J. Nastula & W. Kosek, El Nino impact on atmospheric and geodetic excitation of polar motion, in printing IERS Technical Notes No 26, Paris France.

Petrov S. D., A. Brzezinski & J. Nastula, First estimation of the non-tidal oceanic effect on nutation poceedings of the international conference Journees 1998, Systemes de reference spatio-temporels; Conceptual,conventional and practical studies related to Earth rotation; september 21 - 23, France, Paris, in press.

Petrov S., Brzezinski A., and Gubanov V. (1995). On application of the Kalman filter and the least squares collocation in earth rotation investigations, Proceedings Journees Systemes de Reference Spatio-Temporels 1995, Space Res. Centre, Polish Acad. of Sciences, pp. 125-128.

Petrov S. and Brzezinski A. (1996). On the contribution of the atmospheric normal modes to the polar motion excitation, Proc. of the Russian Conference "Modern Problems and Methods of Astrometry and Geodynamics", 23 – 28 September 1996, St. Petersburg, pp. 308-313.

Petrov S., Brzezinski A. and Gubanov V. (1996). A stochastic model for polar motion with application to smoothing, prediction, and combining, Artificial Satellites, Planetary Geodesy No 26, Vol. 31, pp. 51-70.

Petrov S., Brzezinski A. and Bizouard Ch. (1997). Time domain comparison of the VLBI nutation series and observed changes of the atmospheric angular momentum. Proceedings Journees Systemes de Reference Spatio-Temporels 1997, Astronomical Institute, Academy of Sciences of the Czech R., p. 107.

Petrov S. (1998). Modeling geophysical excitation of Earth rotation: stochastic and nonlinear approaches. Ph.D. Thesis, Polish Academy of Sciences, Space Res. Centre, Warsaw, Poland, 121 pages.

Petrov S., Brzezinski A. and Bizouard Ch. (1998a). Diurnal and semidiurnal variations of the atmospheric angular momentum and Earth orientation parameters, Trudy IPA RAN, wyp.3 "Astrometria i geodinamika", St.Petersburg, pp. 24 - 35, in Russian.

Petrov S., Brzezinski A. and Nastula J. (1998b). First estimation of the non-tidal oceanic effect on nutation. Proceedings Journees Systemes de Reference Spatio-Temporels 1998, Paris Observatory, in press.

Ponte, R.M., 1997. Oceanic excitation of daily to seasonal signals in Earth rotation: results from a constant-density numerical model. Geophysical Journal International, 130, 469--474.

Ponte, R.M., 1997. Nonequilibrium response of the global ocean to the 5-day Rossby-Haurwitz wave in atmospheric surface pressure. Journal of Physical Oceanography, 27}, 2158--2168.

Ponte, R.M., D. Stammer, and J. Marshall, 1998. Oceanic signals in observed motions of the Earth's pole of rotation. Nature, 391, 476--479.

Ponte, R.M., 1999. A preliminary model study of the large-scale seasonal cycle in bottom pressure over the global ocean, Journal of Geophysical Research, 104, 1289-1300.

Ponte, R.M., and P. Gaspar, 1999. Regional analysis of the inverted barometer over the global ocean using TOPEX/POSEIDON data and model results, Journal of Geophysical Research, in press.

Ponte, R.M., and R.D. Rosen, 1999. Torques responsible for evolution of atmospheric angular momentum during the 1982--83 El Nino, Journal of Atmospheric Sciences, in press.

Ponte, R.M., and D. Stammer, 1999. Role of ocean currents and bottom pressure variability on seasonal polar motion, Journal of Geophysical Research, accepted.

Ray, R. D., B. F. Chao, Z. Kowalik, and A. Proshutinsky, Angular momentum of Arctic Ocean tides, J. Geodesy, 71, 344-350, 1997.

Salstein, D.A., 1995: Atmospheric angular momentum and Earth Rotation, Journees 1995, Systemes de reference statio-temporels, Space Research Center, Warsaw, Poland, 139-146.

Salstein, D.A. and R.D. Rosen, 1998: Global Momentum and Energy Parameters from Reanalyses, Proceedings of the first WCRP International Conference on Reanalyses, Silver Spring, MD, 286-289.

Salstein, D. A., 1999: Angular momentum and during the 1997-98 El Niño event., *IERS Technical note 26*, on the Impact Of El Nino And Other Low-Frequency Signals On Earth Rotation And Global Earth System Parameters., in press.

Segschneider, J. and J. Sündermann. Response of a global ocean circulation model to real time forcing and implications to Earth's rotation. J. Phys. Oc. 27, 2370-2380, 1997

Stieglitz, T.C and S.R. Dickman, 1999. Refined correlations between atmospheric and rapid polar motion excitations, Geophys. J. Int., in press.

Thomas, M. and J. Sündermann. Tides and tidal torques of the world ocean since the last glacial maximum. J. Geoph. Res. 104, C2, 3159-3183, 1999

vanDam, T.M., J. Wahr, Y. Chao, and E. Leuliette, 1997.Predictions of Crustal Deformation and of Geoid and Sea Level Variability Caused by Oceanic and Atmospheric Loading, Geophys. J. Int., 129, 507-517.

Vicente, R., and Wilson, C., 1997, On the Variability of Earth Rotation Parameters, Journal of Geophysical Research, 102, B9, 20439-20445.

Wilson, C., and Chen, J., 1996. Discrete Polar Motion Equations for High Frequencies. Journal of Geodesy. v. 70, no. 9.

Wilson, C.R., Oceanic Effects on Earth’s Rotation Rate, Science, 281, 5383, September 11, 1998, 1623-1624.

Xie, L. and S.R. Dickman, 1995. North Sea pole tide dynamics, Geophys. J. Int., 121, 117-135.

Xie, L. and S.R. Dickman, 1996. Tide gauge data analysis of the pole tide in the North Sea, Geophys. J. Int., 126, 863-870.
Xie, B.Q., Zheng, D.W., High frequency excitation of Earth rotation parameter (ERP) from atmosphere, Acta Astronomica Sinica, 37, 2,113-123, 1996
Yu, N.H., Zheng, D.W., Oceanic angular momentum and its excitation tothe Earth rotation variations, Progress in Astronomy, 16, 1, 35-40, 1998
Yu, N.H., Zheng, D.W., and Wu, H.Q., Contribution of new AAM data source change to LOD excitation, Journal of Geodesy, 1998, accepted
Yu, N.H., Zheng, D.W., Earth rotation and it's relations to geophysical phenomena: I. The changes of length of day, Progress in Geophysics,11, 3, 70-81, 1996
Zharkov V. N., S. M. Molodensky, A. Brzezinski, E. Groten and P. Varga (1996). The Earth and its Rotation: Low Frequency Geodynamics, Herbert Wichman Verlag, H¸thig GmbH, Heidelberg, 501 pages.
Zheng, D.W., Y. H. Zhou, N. H. Yu, and B. F. Chao, Improvement of edge effect of the wavelet time-frequency spectrum: Application to the length of day series, in press, J. Geod., 1999.
Zheng, D.W., Chen, J.L., Hua, Y.M., Xiao, N.Y., Preliminary research of the influence of Earth rotation rate on latitude wards changes of sea level, Acta Astronomica Sinica, 37, 1, 97-104, 1996
Zheng, D.W., Zhou, Y.H., Chao, B.F., Variation in NAO and polar motionon decadal time scale, Acta Astronomica Sinica, 38, 2, 204-208, 1997
Zheng, D.W., Yu, N.H., Earth rotation and it's relations to geophysical phenomena: I. The changes of length of day, Progress in Geophysics,11, 2,81-104, 1996
Zhou, Y., D. Zheng, M. Zhao, and B. F. Chao, Interannual polar motion with relation to the North Atlantic Oscillation, Global and Planetary Change, 18,79-84, 1998.
Zhou, Y.H., Zheng, D.W., Application of LSTAR model to improvement of wavelet transform of LOD variation series, Annuals of Shanghai Observatory Academia Sinica, 18, 13-17, 1997
Zhou, Y.H., Zheng, D.W., Wavelet analysis of interannual length-of-dayvariation, El Nino-Southern Oscillation and atmospheric Quasi-Biennial Oscillation, Acta Astronomica Sinica, 38, 2, 209-214, 1997

Scientific Sessions and Meetings List

Fall 1995 AGU, San Francisco, December, 1995 Session G51A: Geodetic and Geophysical Evidence of Global Change; The Interdisciplinary Impact of Earth Rotation Studies: A Tricentennial Commemoration;

Spring 1996 AGU, Baltimore, May, 1996 Session G1: Geodetic Measurements of Past and Present Climate Change Session U41A: Earth System Dynamics From High Frequency to Global Change Time Scales I Session U51A Earth System Dynamics From High Frequency to Global Change Time Scales II;

Spring European Geophysical Society Meeting, The Hague, June 1996 Session SE5/G8 Earth’s Rotation Variabilities at Different Time Scales and Tidal Deformations in memory of Keith Runcorn, Convened by J. Hinderer

IERS Workshop: Future Directions, Paris Observatory, October, 1996 Session on Topic 6: Geophysical Fluids.

VLBI/CORE Workshop, College Park Maryland, November, 1996 Special workshop convened by NASA

Fall 1996 AGU, San Francisco, December, 1996 Session G11A Paleogeodesy: Ice Sheets, Oceans and the Earth's Shape; Session G12C Static and Time-Varying Gravity Field Modeling and Their Application to Climate Change Studies**;** Session G31B Earth System Dynamics: Insights from Earth Rotation Studies

Spring 1997 European Geophysical Society, Vienna, April 1997 Session G13/SE12 Variations in Earth Rotation

Spring 1997 AGU, Baltimore, May, 1997 Session G42B Earth Rotation: Measurements and Models II Posters; Session G42C Earth Rotation: Measurements and Models I

July 1997 IAPSO General Assembly, Melbourne, Australia Session on Angular Momentum Variations in the Oceans

Fall 1997 AGU, San Francisco, California, December 1997; Session G31A Insights Into Earth System Science: Variations in Earth's Rotation and Its Gravitational Field I Posters; Session G41D Insights Into Earth System Science: Variations in Earth's Rotation and Its Gravitational Field II

Spring 1998 European Geophysical Society, Nice, France, April 1998 Session G7 Joint EGS/AGU symposium on geodetic observation and geophysical interpretation of mass movements in the Earth system Part 1 Solid Earth and core, Part 2 Ocean and hydrosphere Part 3 Cryosphere Part 4 Atmosphere Part 5 Interactions between the components of the Earth system

Spring 1998 AGU, Boston, May 1998 Session G21A The Impact of El Nino and Other Low-Frequency Signals on Earth Rotation and Global Earth System Parameters. Session G22A The Impact of El Nino and Other Low-Frequency Signals on Earth Rotation and GlobalEarth System Parameters Posters Session G22BThe Impact of El Nino and Other Low-Frequency Signals on Earth Rotation and Global Earth System Parameters

Western Pacific Geosciences Meeting, Taipei, Taiwan, July, 1998 Session G31A Measuring Global Geodynamics and Mass Transports in Geophysical Fluids

Fall 1998 AGU, San Francisco, California Session G71I Polar Motions From Hours to Decades I; Session G41A Polar Motions From Hours to Decades II Posters

Spring 1999 London Workshop on Ocean Bottom Pressure changes and ocean contributions to time variable gravity;

Spring 1999 EGS Meeting, The Hague, April 1999 Session G16 The impact of global fluids on Earth rotation. Session G16 The impact of global fluids on Earth rotation - Poster Session; Session G18 High frequency and subseasonal oscillations of Earth rotation I and II.

Spring 1999 AGU Meeting, Boston, June, 1999 Session U32 Geodetic Monitoring of the Earth System

IUGG Birmingham Symposium JSG14 July, 1999. Insights into Earth System Science: Variations in the Earth's Rotation and its Gravitational Field.

SPECIAL STUDY GROUP 5.175

INTERANNUAL VARIATIONS OF THE VERTICAL AND THEIR INTERPRETATION

MEMBERSHIP:

M.Barlik, M.Becker, P.Gegout, H.Li, Z.X.Li (Chairman), H.P.Sun, J.Vondrak

1. WHY SUCH A STUDY?

1.1 Efforts of the IAU and IAG since 1991

* Although many astrometric stations (astrolabes, PZT) ceased their activities after 1/1/1988. A recommendation of IAU Commission 19 has been adopted during the XXI IAU General Assembly (1991); IAG endorsed this recommendation. It concerns "Application of optical astrometry time and latitude programs".

The Shanghai Observatory, having established and operating an analysis center for optical Earth rotation data, has been invited to continue to collect optical astrometric data in order to investigate the possibility of deriving long term variations in the deflection of the vertical within the reference frame provided by Hipparcos.

This recommendation involves too that IAG undertakes this project.
After the working of the IAG SSG 5.146: "Processing of Optical Polar Motion Data in View of Plumb Line Variations", Chaired by Professor P.Paquet from 1991 to 1995, the IAG SSG 5.175 was established in the fall of 1995.

* There are also reports of some astronomical observatories from time to time, which locate at seismic areas, on the possible relation between their observed abnormal deflection of the vertical prior seismic events. It has been suggested also to search if deflection of the vertical could be a precursor to seismic events.

1.2 In an historical point of view, the topic of the SSG has long been an interesting problem, but remain unsolved, since the establishment of the IAG and IAU

* In 1924, Dr. Kimura, director of the ILS central bureau, reported in his paper: "A change of vertical amounting to 0.18" must have taken place at Mizusawa", he also related it to the possible "Change in internal distribution of mass underneath the Earth" (Bull. Geod. 1925, p. 535-537).

* At the occasion of IAG General Assembly held at Rome in 1954, Dr.
Cecchini, director of the ILS central bureau, specified the "Variation de la verticale locale" as one of the three possible sources of the latitude changes. Based on his report, the IAG demonstrated again the necessity of the determination of the plumb line variations (Bull. Geod. 1955, p.3).

* In 1961, Dr. Yumi, director of the IPMS, used the term of "Non-polar latitude variation", in which plumb line variation is included (Publi. Int. Lat. Obs. Mizusawa 3, No. 2, 55-120,1961). Since then a numerous of papers have been published by his colleagues, including the two papers recently (Astron. Astrophys. Suppl. Ser.86, 251; Astron. Astrophys. Suppl. Ser. 86,95), in which the possible "variation in the vertical" at the IPMS collaborating stations have been discussed.

1.3 The work of the IAG SSG 5.146 (1991-1995)

It has been stated in the final report of the previous IAG SSG 5.146, "Processing of Optical Polar Motion Data in View of Plumb Line Variations", that "It is quite clear now that there is a component, of which the order is 0.01" at interannual time scales, in latitude residuals which is correlated with the SOI in many cases but with different phase lag at different regions in the world". Further investigation on the interannual variations of the plumb line has been recommended.

1.4 The objectives of the IAG SSG 5.175

The efforts of the IAG SSG 5.175 have been concentrated on the
Following points in the past four years:

* Other than the known tidal variations of the plumb line, are there Non-tidal Plumb Line Variations (PLV) on earth? The SSG intends to have evidences as strong as possible;

* Possible interpretation of the PLV;

* Possible use of the PLV in the studying related to the geoid and the earthquakes.

2. RESULTS

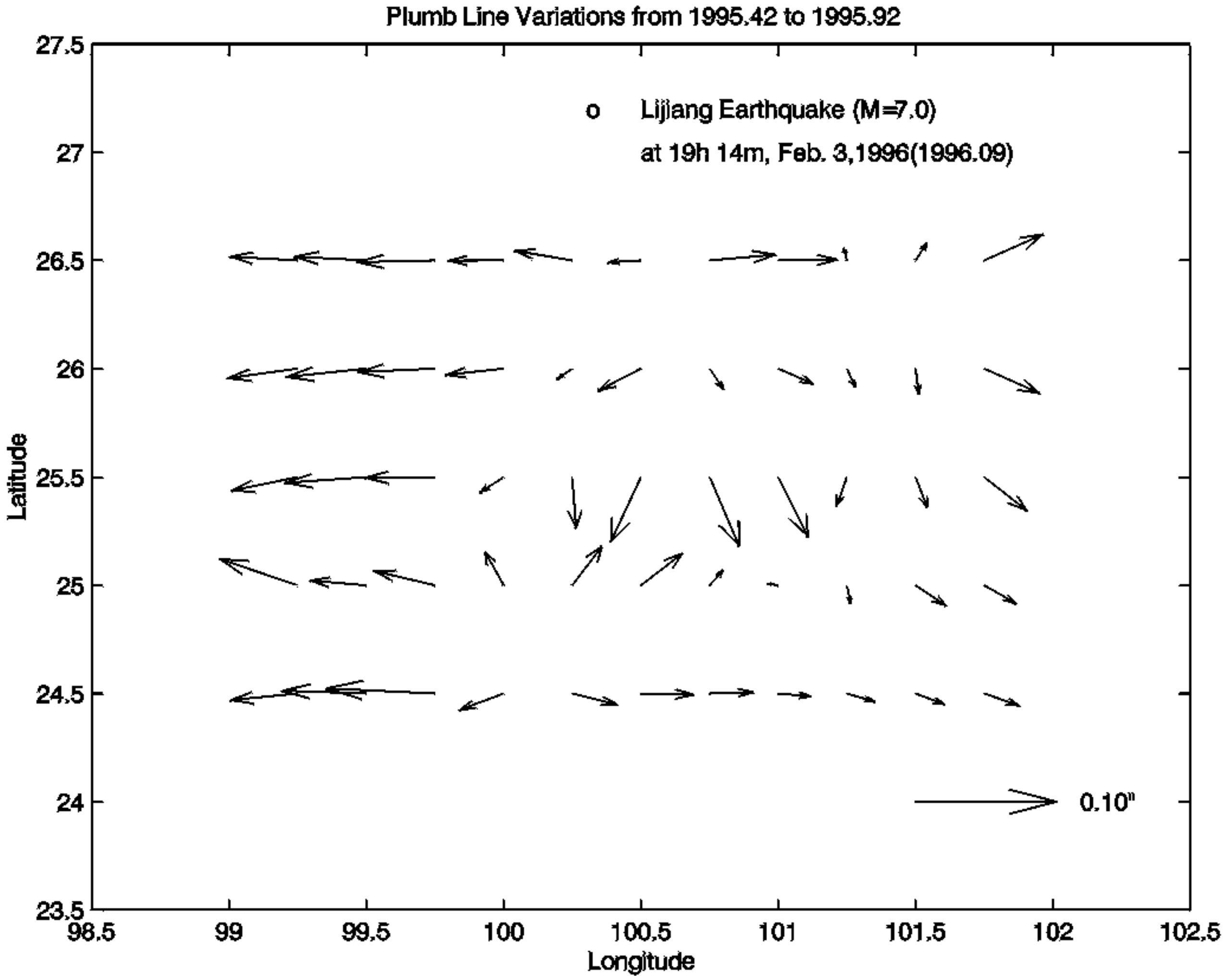

Fig.1 Changing of the PLV in Yunnan before the Lijiang Earthquake

Under the efforts of the members of the SSG, a series of studies have been carried on, which are now described as the following:

2.1 Non-tidal Plumb Line Variations (PLV) and their interpretation in the case of Lijiang Earthquake

The strongest evidence of the existence of PLV on earth obtained by the SSG is the one finished just recently: "Plumb line variations in Yunnan before the Lijiang Earthquake on Feb.3, 1996".

In west Yunnan of China, there is a gravitational network with the size of 300*300 km**2 for which continuous repeated gravimetric measurements have been performed since 1985. The PLV in the whole region have been calculated recently, with which the PLV before and after the Lijiang Earthquake (M=7.0, at 19h 14m, Feb.3, 1996, location: 100.3 (Longitude); 27.2 (Latitude)) have been studied (see Fig.1 and Fig.3).

It is very clear now that PLV with amplitudes in the order of 0.1" emerged even two months before the event of earthquake (see Fig.1), and then disappeared after the earthquake since contrary PLV happened (see Fig.3). In using these PLV data, it is really interested to see the whole process of the deformation of the geoid around Lijiang before and after the earthquake event. Before the event the geoid was going up (see Fig.2). The highest point of the deformed geoid was very near Lijiang, the place where a earthquake of M=7.0 happened two months later; but almost contrary process happened after the earthquake event, the geoid at the same region was coming down (see Fig.4). Thus, the geoid around Lijiang was restoring to the previous situation.

The relationship between the PLV and the Lijiang earthquake has given us a living example in which the existence of the PLV, of which the amplitudes were in the order of 0.1" and the interpretation of the PLV is very clear now. The PLV amounting to 0.1" in this event are caused by the same causes of an earthquake: the inner changing of the earth.

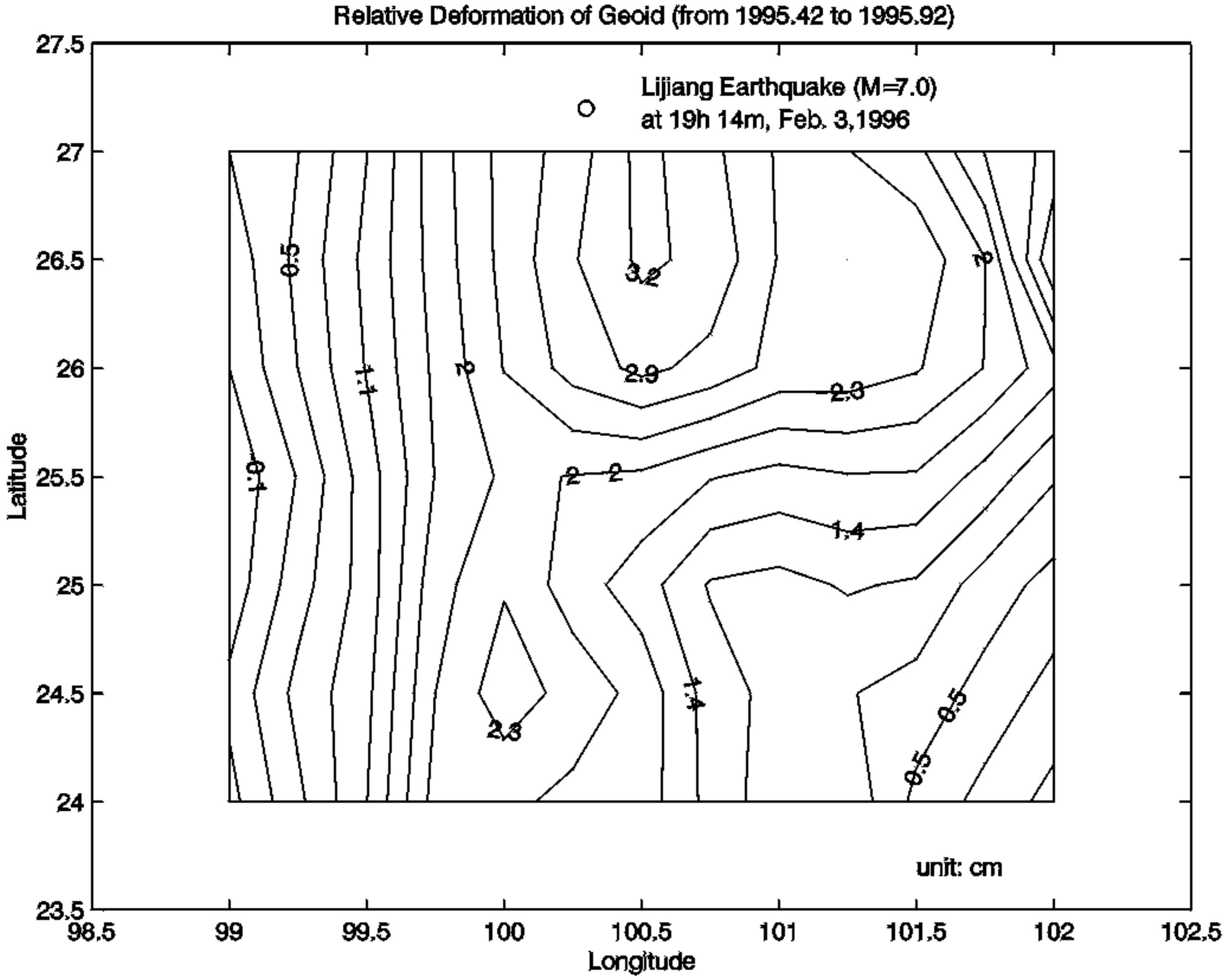

Fig.2 Relative deformation of the geoid in Yunnan before the Lijiang Earthquake

2.2 Interannual PLV found in a comparison between the gravimetric PLV results and the corresponding astronomical observational residuals obtained at the same place

Non-tidal PLV can also be proved by a comparison between the PLV results, derived by gravimetric techniques, and the observational residuals of astronomical techniques at the same location. The astronomical technique is related to the vertical (plumb line) at the observational location but has nothing to do with the non-tidal PLV until now. Due to the remaining star catalog errors in astronomical observations, the comparison is usually done at interannual time scales. From the comparisons made at the three observatories, which are now described in the following, the interannual variations of the plumb line have been studied:

* Direct evidence: comparison done while the gravimetric PLV results have been calculated exactly at the same site where the astronomical instrument install:

- At W-E direction for the case of Beijing Observatory, China (see Fig.5);
- At S-N direction for the case of Jozefoslaw Observatory, Poland (see Astron. Astrophy. Suppl. Ser. 129, 353-355).

* Indirect evidence: the site where the gravimetric PLV results have been calculated is not far away from the astronomical instrument

- At both W-E and S-N directions for the case of Yunnan Observatory of China (see Fig.6).

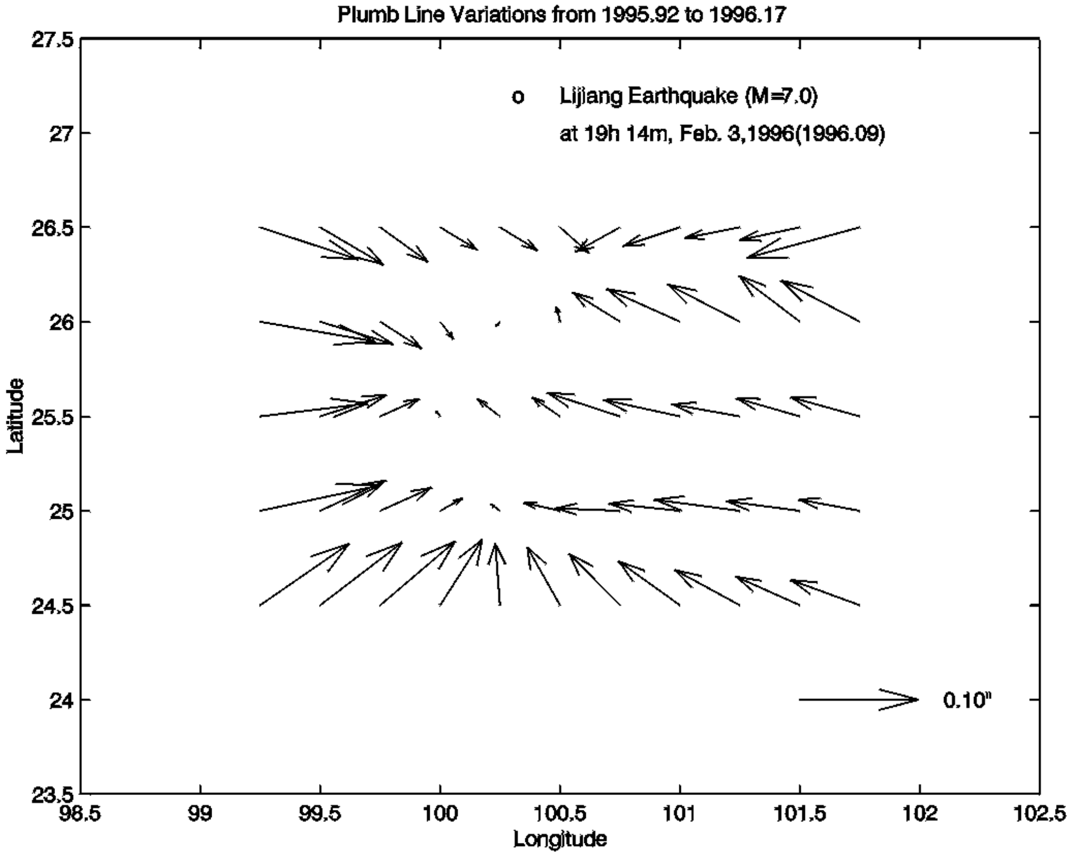

Fig.3 Changing of the PLV in Yunnan after the Lijiang Earthquake

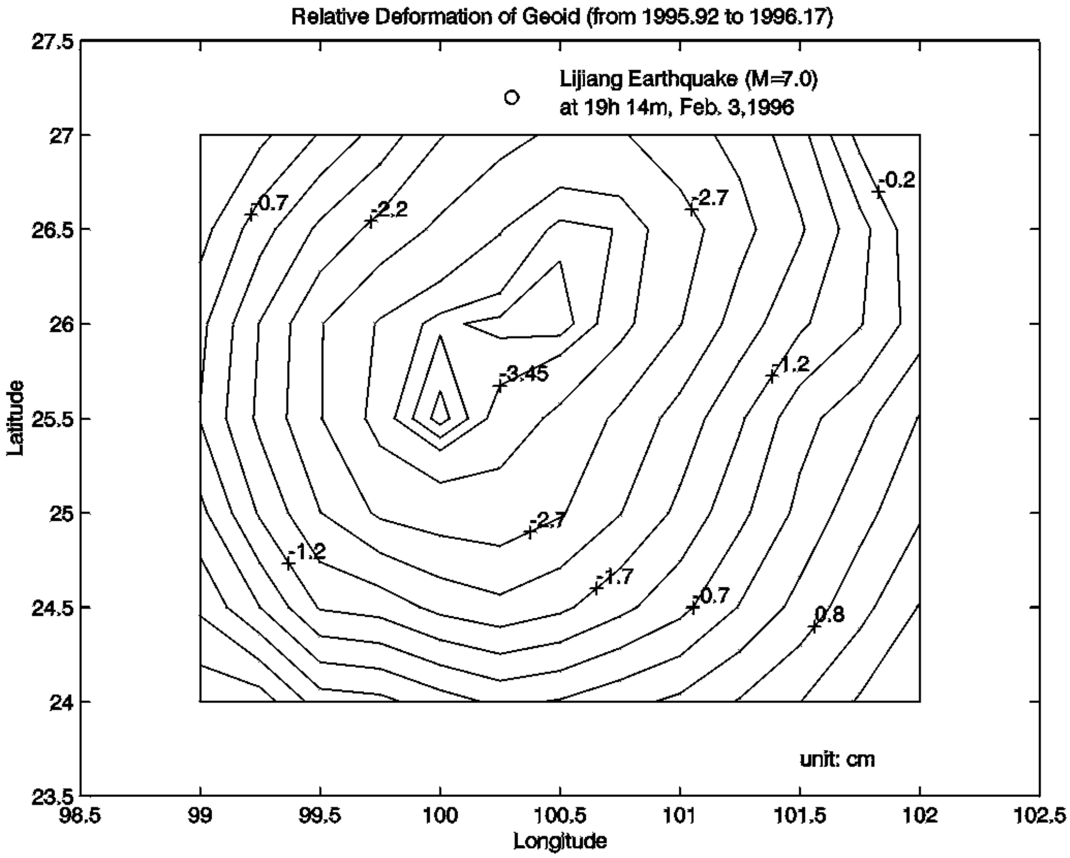

Fig.4 Relative deformation of the geoid in Yunnan after the Lijiang Earthquake

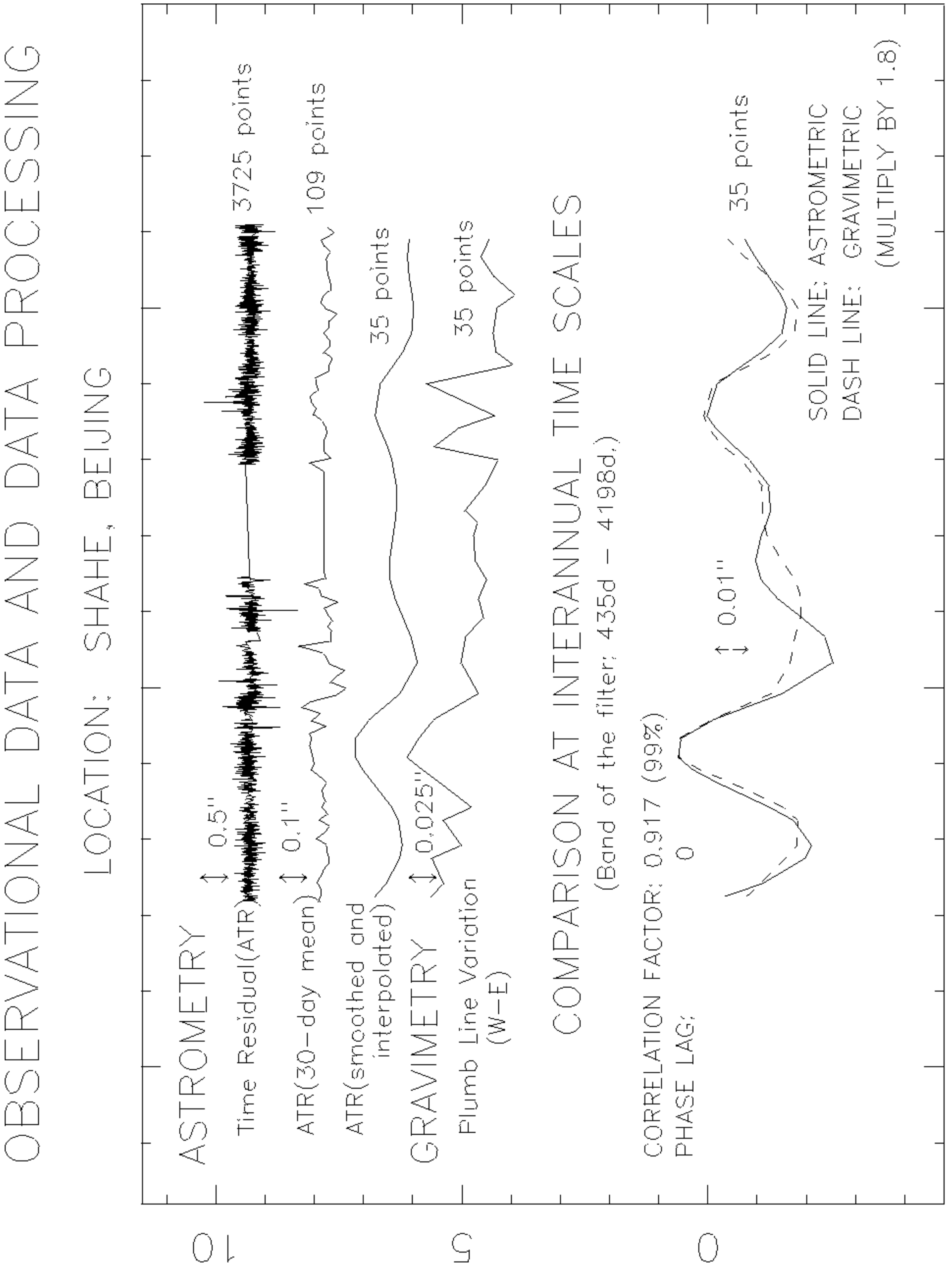

Fig.5 Direct comparison between the PLV (W-E) results of the two techniques at interannual time scales in Shahe

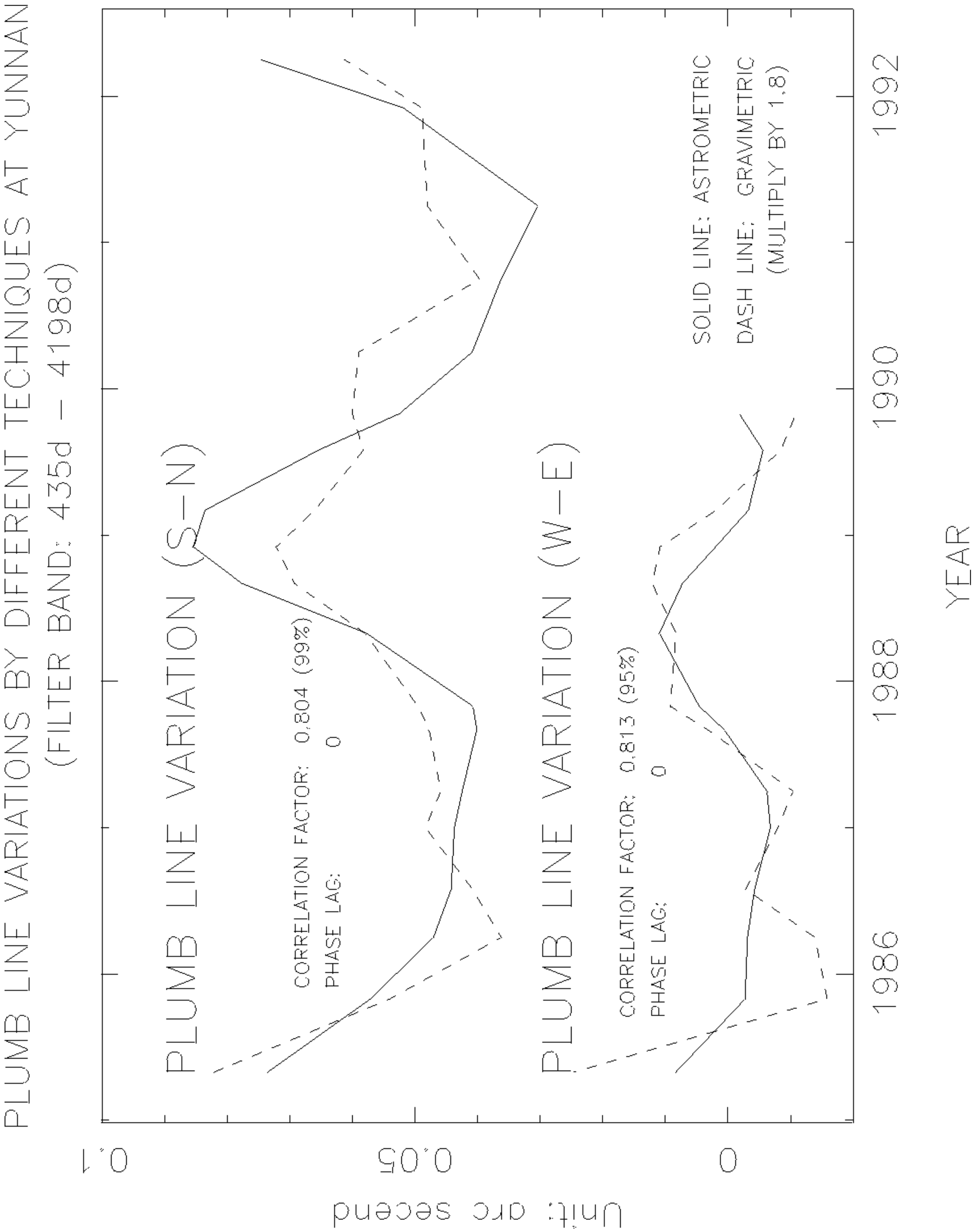

Fig.6 Comparison between the PLV (S-N) and PLV (W-E) results of the two techniques at interannual time scales in Kunming

The correlation at interannual time scales is quite evident between the results of the two different techniques. There may be a scale difference between the results of the two techniques. It can be explained by the size of the gravimetric network used in deriving the gravimetric PLV results (see Astron. Astrophy. Suppl. Ser. 129, 353-355).

The only common component existing in both the astronomical residuals and the PLV from the gravimetric technique is the PLV itself at the observatory. From the correlationship, including the level of significance and zero phase lag between the two time series derived from different techniques, the existence of the interannual PLV, of which the amplitudes are in the order of 0.02", and the ability of the two techniques in measuring them can be concluded.

2.3 Other works

There are also some works in the past four years, mainly:

- Study of anomalous atmospheric refraction in astronomical time and latitude observations (Li, Z.X. and Wilson, C.)
- Possible PLV caused by atmosphere (Shen, H.P. et al.)
- Possible relationship of PLV with ENSO

All the other works also support that the PLV, which we are now talking about, can not be caused by the sources other than the one we have already explained in the Section 2.1: the inner changing of the earth.

Thus, it has been suggested that the PLV may be used as a new observational quantity in the studying related to the geoid and earthquake.

3. Conclusion

(1) Other than the known tidal plumb line variations, there are also detectable Non-tidal Plumb Line Variations (PLV). The amplitudes of the PLV are: 0.02" at interannual time scales; 0.02" - 0.05" at shorter time scales; bigger one are possible when a earthquake is going to take place, for example at least 0.1" in the case of Lijiang Earthquake (M=7.0) on Feb. 3,1996;

(2) Both the gravimetric and astronomical techniques are able to measure the PLV;

(3) Non-tidal variations of plumb line may be used as a new observational quantity in the studies related to the Earth, especially to the deformation of geoid and earthquake.

4. Recommendation

(1) Establish a new SSG: "Deformation of the geoid and earthquakes" in the Section V (Geodynamics) of the IAG;

(2) Or include this special study into an existing Commission of the IAG but with an appropriate name.

5. Bibliography

Chollet, F. et N-E. Najid, 1992, Astron. Astrophy., 262, 341-346.
Chollet, F.1993, Astron. Astrophy., 280, 675-682.
Czechowski,L. and B. Kolaczek,1985, PAGEPH, Vol. 123, 398-406
Ishii, H., Y. Goto and T. Ishikawa, 1990, Astron. Astrophy. Suppl. Ser. 86, 251-257.
Ishii, H., 1973, Publi. Int.Lat.Obs. Mizusawa 9, No 2, 235.
Ishii, H., 1974, Proc. Int. Lat. Obs. Mizusawa 9, No 14, 96.
Kakuta, C., 1981, Publi. Int. Lat. Obs. Mizusawa 14, No 1.
Kakuta, C., 1981, Publi. Int. Lat. Obs. Mizusawa 14, No 15.
Kakuta, C., 1984, Geod. Soc. Japan 30, 307.
Kitago,H.,S. Abe, K. Iwadate, K.-H. Sato and Y. Goto, 1990, Astron. Astroph. Suppl. Ser. 86, 95-102.
Kotlyar, P.E., and Kim V.I., 1990, Irregular constituents of Pole displacement and regional seimicity, Geologiya i Geofizika, Vol.31, No 11, pp 93-98.
Li,Z.S. et al, 1978, Acta Geophysica Sinica, Vol.21. 278-291.
Li,Z.X., 1981, Kexue Tongbao, Vol.26, No 21, 278-291.

Li Zheng-xin, You-Fen Chen and Chang-Xia Qian, 1992, Astrometric Latitude and Time observational Database at Shanghai Observatory, Proceed. IAU Symposium 156, Ed. I.Mueller.
Li,Z.X. et al.,1993a, Possibility of deriving the variations of plumb line from optical astrometric time and latitude observations, Report at IAG General Meeting 1993.
Li,Z.X. et al.,1993b, Evidence of plumb line variations in Europe from optical astrometric latitude observations, Report at IAG General Meeting 1993
Li,Z.X. and Gambis,D., Astron. Astrophy. 290,1001-1004,1994.
Li,Z.X., Qian,C.X., 1995a, Annal of Shanghai Observatory, Academy Sinica, No. 16.
Li,Z.X., 1995b, Acta Astronomica Sinica, Vol.36, No 1, 47-52, 1995.
Li,Z.X., Astron. Astrophy. 309, 313-316 (1996)
Li,Z.X., AStron. Astrophy. Suppl. Ser. 129, 353-355 (1998)
Li,Z.X.,H. Li,H. Hu and G.Y. Fu,1999b, Interannual variations of the plumb line at Beijing, Jozefoslaw and Yunnan by gravimetric and astrometric techniques(to be published).
Li,Z.X. and H.Li,1999a,"Plumb line variations in Yunnan before the Lijiang Earthquake on Feb.3,1996"(to be published).
Meining, M., 1992, One century latitide determinations at Potsdam (personal Communication).
Naito,I. 1973, Proc. Int. Lat. Obs. Mizusawa, No. 13,13
Sugawa, C.1972, Proc. Int. Lat. Obs. Mizusawa, NO12, 176
Sugawa, C.1973, Proc. Int. Lat. Obs. Mizusawa, NO13, 39
Yokoyama,S. 1973,Proc. Int. Lat. Obs. Mizusawa, NO1,1.

INTERNATIONAL CENTRE FOR EARTH TIDES

CENTRE INTERNATIONAL DES MARÉES TERRESTRES

(ICET)

ACTIVITY REPORT

for the period
1995-1999

by

B.Ducarme, ICET Director
ducarme@oma.be

The staff of ICET, which is completely supported by the Royal Observatory of Belgium, is composed as follows:

Prof. B.Ducarme, Director(part time)
Dr. O.Francis, Vice-Director(part time, until November 1998)
Mrs. L.Vandercoilden, technician(full time)
Mr. M.Hendrickx, technician(part time)

The Royal Observatory of Belgium is hosting ICET since 1958 and continues to provides numerous administrative and scientific facilities especially for the publication of the " Bulletin d'Information des Marées Terrestres" and for the tidal data processing.

In November 1998 Dr. O. Francis decided to resign his position of Vice-Director for personal reasons.

1. Previously assigned scientific goals

Quoting Prof. P.Melchior last report as ICET Director in 1995 we can summarise the tasks ascribed to ICET since 1958 as follows:
- *as World Data Centre C, to collect all available measurements on Earth tides;*
- *to evaluate these data by convenient methods of analysis in order to reduce the very large amount of measurements to a limited number of parameters which should contain all the desired and needed geophysical information;*
- *to compare the data from different instruments and different stations distributed all over the world, evaluate their precision and accuracy from the point of view of internal errors as well as external errors;*
- *to help solving the basic problem of calibration by organising reference stations or realising calibration devices;*
- *to fill gaps in information and data;*
- *to build a data bank allowing immediate and easy comparison of earth tides parameters with different Earth models and other geodetic and geophysical parameters ;*
- *to ensure a broad diffusion of the results and information to all interested laboratories and individual scientists.*

Of course these goals have to be continuously reactualised and require a close cooperation with all scientists working in the field of tidal research.

For example tidal data analysis has always been one of the main activities of ICET. In the early days, at the very beginning of the computer technology, it was necessary to provide computing facilities for many scientists involved in tidal research. Nowadays everybody is able to process the tidal data on his own Personal Computer. However ICET has still to reprocess the data before their inclusion in the data bank to be sure that no gross error is left in the received data. For the sake of homogeneity we also prefer to include in the data bank, when it is possible, analysis results reprocessed at ICET. It should be noted that ICET did always accept any input format and developed the necessary conversion software. Now PRETERNA is the most widely used standard exchange format.

The main problem in data preprocessing has always been the correction of spikes and tares. When analog records had to be manually digitised the human eye was able to « smooth » the curves when taking hourly readings. The digital data acquisition systems
require a higher sampling rate, at least one value per minute, and automatic softwares for the data smoothing and jumps correction. Decimation filters are required for extracting the hourly readings for tidal analysis. ICET is currently using different softwares for tidal data preprocessing and analysis.

The data storage and exchange are also drastically modified. Starting from listings that we had to encode on punched cards we are now exchanging by FTP digital data that will be stored on CD-ROM's. The ICET data base has proved to be very useful for the data providers themselves as observations lost or destroyed in their home institution were retrieved at ICET. It is important to note that all data stored have been reevaluated. All analysis results are kept in a special data bank. Its version DB92 included as much as 360 stations for gravity tides and around 50 stations for tilt and strain. For each station we provide not only the tidal factors but also oceanic loading and relevant geophysical parameters. Its content is available on request.

In the last decades ICET brought a significant contribution to tidal gravity observations through the so called « Trans World Tidal Gravity Profiles »(TWP). This effort was launched in close cooperation with the Royal Observatory of Belgium. All participating instruments were intercompared in the Brussels reference station. The 136 stations occupied between 1973 and 1991 form the core of the tidal data bank. This project gave also the opportunity to many scientists to start tidal observations in their own country.

Oceanic loading is the main additional signal from geophysical origin which is perturbing the body tides. Since 1980 ICET adopted the Schwiderski cotidal maps as a working standard. We are now currently using the most recent oceanic models for tidal loading computations. Special attention was paid also to the evaluation of the atmospheric pressure effects.

2. Main Commitments for the future

It appears first that most geodetic measurements are affected by earth tides, as at the centimetric level the tidal displacement of the station is no more negligible. It will thus remain an important task for ICET to provide algorithms for tidal computation or analysis. For example the geophysicists, such as seismologists or volcanologists, who are measuring crustal deformations for natural hazards monitoring, are now conscious of the necessity of dealing properly with the tidal signals. In a similar way absolute gravity measurements require accurate tidal corrections that should take into account the local tidal parameters. These parameters have to be computed including oceanic tidal loading effects or even require in situ tidal gravity observations.

On the other hand the earth tidal scientific community is limited. The last International Symposium on Earth Tides held in Brussels in 1997 brought together only one hundred participants. The groups are always very small and often marginally involved in tidal research. The papers dealing specifically with tidal studies are not fitting so well to international journals. It is thus very important to keep a specialised diffusion and information medium. It is the vocation of the "Bulletin d'Information des Marées Terrestres"(BIM). ICET is publishing two eighty pages issues per year. It has been decided to interrupt the publication of French translations of Russian papers, taking into account the fact that the Russian scientists are now able to publish in English.

Finally ICET will continue to welcome trainees or guest scientists as there is a steady demand.
Besides this basic activity, which is the scientific challenge for the future ?

The mathematical modelisation of the astronomical tidal forces as well as of the elastic response of the Earth made recently decisive progress. Two new high precision tidal developments have been published by Hartmann & Wenzel in 1995 and Roosbeek in 1996. It is thus now possible to model the astronomical tidal forces to within 5 nanogal in the time domain. The different mathematical techniques for the evaluation of the tidal response of the Earth do agree now to better than 0.1%. The most recent models include anelasticity in the mantle.

The last problems to be solved are linked to the fluid elements of our planet: liquid core resonance, oceanic loading, meteorological effects, underground water.

Among the ground based observations only gravity tides are able to give informations valid at the regional level. The other components(tilt, strain, volume change) are heavily depending of the local parameters of the crust, including cavity or topography effects. These observations should be mostly used to monitor tectonic deformations after removing the tidal phenomena.

Tidal gravity observations are able to provide constrains on the liquid core resonance by means of very precise observations in selected sites. The same is valid also for the selection of the most realistic model for the elastic or inelastic response of the Earth. For that purpose it is essential to improve the calibration methods in order to achieve a 0.1% accuracy in amplitude and a 0.01^o accuracy in the phase determination. The determination of the amplitude factor of the polar motion effect on gravity will constrain the Earth viscosity at low frequency.
To achieve these goals it will be necessary to tackle three main questions: tidal loading, atmospheric pressure effects, underground water. It is only possible through a coordinated effort.

3.New prospects

These objectives are now directly addressed by the "Global Geodynamic Project"(GGP). A network of seventeen cryogenic gravimeters is in operation since July 1997, using a similar hardware and the same procedures for data acquisition. This observation campaign will continue during six years.

A complementary objective of GGP is to study the residues after elimination of the tidal contribution in order to detect inertial accelerations such as free oscillations of the Earth core and mantle with periods larger than 50 minutes, which are difficult to observe by means of conventional seismometers. In fact the cryogenic gravimeters are extra-large band instruments covering phenomena with period ranging from one second to more than one year(figure 1).

As the study of tiny signals in gravimetric records requires an effective elimination of the dominant phenomena it is absolutely necessary to carefully model the tidal and barometric effects. It is a unique opportunity to improve the techniques of evaluation of the barometric effects and to obtain high quality well calibrated tidal observations. It is a reason why ICET has been interested to support this project since its beginning and finally became the GGP « Data Centre ». His task will be not only to archive the raw and preprocessed data from all the contributing stations but also to provide his expertise for the preprocessing and analysis of the raw data. To insure the homogeneity and the quality of the archived data ICET will treat the raw data in a standard way.

A new integrated software for tidal data preprocessing has been developed by Dr. P.Vauterin[1998] from the Royal Observatory of Belgium. Based on a remove restore procedure TSOFT is fully interactive(figure 2

One of the conclusions of the TWP is that the accuracy of the observations, comprised between 0.5% and 1%, was essentially limited by the accuracy of the calibration of the instruments. Moreover, excepted for the cryogenic gravimeters, the sensitivity is time dependant. To solve efficiently this question a Working Group on Calibrations has been set up inside the Earth Tides Commission during the Brussels Symposium.

On the other hand the interpretation of the observed tidal factors is strongly limited by the accuracy of the tidal loading evaluation. Even the most recent oceanic tidal models incorporating altimetric data are not globally better for tidal loading computations than the, now by many aspects obsolete, Schwiderski model. The reason is probably that there exists for each model areas where it fits better than in others. To investigate more closely this fact it is important to install accurately calibrated gravimeters in areas where noticeable disagreements do exist between different models. The atlantic coast of Western Europe has been selected as a first test area. Gravimetric tidal stations will be selected at distances from the coast ranging between 50 and 100 kilometers. To insure a maximum of accuracy it is recommended to record with two different instruments, carefully intercompared, during a six month period to allow the separation of the eight principal tidal waves in diurnal and semidiurnal bands. The measurements are performed by colleagues from Brussels and Madrid. We hope to extend this project to the Pacific coast of Russia in collaboration with russian colleagues.

[1] *Crossley D., Hinderer H.:* GGP Newsletter 5, September 1997
[2] *Vauterin H.P.* : Tsoft : Graphical and Interactive Software for the Analysis of Earth Tides Data. Proc. 13th Int. Symp. On Earth Tides, Observatoire Royal de Belgique, Série Géophysique, Brussels, 1998, 447-454

4. Activities

The “Bulletin d’Information des Marées Terrestres”(BIM) is printed in 300 copies. From March 1995 until May 1999 the issues numbered from 121 to 131 have been published with a total number one thousand three hundred pages.

ICET welcomed more than 15 visitors. Besides visitors coming only for a short stay we must consider also guest scientists and trainees.
The guest scientists bring their own know how or data to work at ICET during several weeks. They will either , as Prof. A.P. Venedikov (Bulgaria), prepare new softwares or, as Dr. G.Casula(Italy), H.P.Sun(China) and Dr. V.Timofeev(Russia), perform data analysis using the ICET data bank or computing facilities.
Younger scientists are coming to received intensive training on earth tide data processing and analysis, mainly with the TSOFT and ETERNA packages. Since 1997 we welcomed trainees from Argentina, Brazil, Great Britain, Italy, Spain and USA.

It should be noted that several visitors are not at all specialists in earth tides. It is an indication of a renewed interest with respect to tidal phenomena.

We receive regularly requests for information.
The most common requests concerns tidal predictions or general information. We receive more or less one request per week.

Several Institutes continue to send regularly earth tides data to ICET. *All data received have been checked and recompiled*. Among the recently participating countries we should mention : Belgium, China, Czech Republic, France, Germany, Hungary, Indonesia, Italy, Grand Duchy of Luxembourg, Poland, Russia and Spain. Most of the tidal recording activity is devoted to gravity tides. This tendency is even more striking if we consider the GGP activities

The status of the GGP data bank on July first 1999 is given in the following table. All the original minute sampled data have been carefully preprocessed at ICET using TSOFT. The data are corrected for tares and spikes. The data are then decimated to one hour and analysed. This is the main task of Mrs.L.Vandercoilden. The analysis results are directly communicated to the data owners. This follow up is required to detect quickly the anomalies that could affect the data sets and insure their homogeneity

The archiving of the data is rather complex as the data are only released according to a strict time table. The data are sent to ICET only one year after their production. It is why in the table most of the stations sent their data only until April 98. During one additional year the data are only available to the GGP members and can be freely accessed only after two years. The software provided for the gestion of this data bank by the GeoForschungZentrum Potsdam is now fully operational. The implementation of this software required to purchase new informatic equipments. Although he resigned his position in ICET, Dr. O. Francis from the Royal Observatory of Belgium agreed to continue to supervise the data archiving until the end of the project. The routine work is assumed by Mr. M.Hendrickx.

The one minute sampled raw data of each gravimeter represents 1.6 Mbytes per month. For fifteen operational stations we have thus 24 Mbytes per month or 300 Mbytes per year. It represents only one CD-ROM. We do also archive the preprocessed minute data ready for tidal analysis.

5. Conclusions

The reason why it is important to keep an International Centre for Earth Tides is that Earth tidal Scientific Community is very scattered. On one hand there are no large scientific teams working on that subject. On the other hand most of the Geodetic community members are confronted to tidal phenomena, when working on Earth deformations. In a similar way the Seismologists or Volcanologists getting acquainted with modern geodetic techniques have to learn about the perturbing effects on ground displacement measurements, such as earth tides, tidal loading, barometric effects,…. Scientists who know already the tidal phenomena can easily produce tidal analysis on their own personal computer, but for the new tidalists training sessions are the best way to get acquainted with the data reduction and analysis, which remain a delicate procedure. It stresses also the importance of keeping the “Bulletin d’Information des Marées Terrestres”, where experienced people can share their know how with the newcomers. Nowadays beside very specialised projects such as GGP for which a dedicated infrastucture is required there is an increasing demand for a basic knowledge in tidal data processing to remove properly these effects from various signals.

GGP Data Bank

99/07/01

BA	Bandung, Indonesia		failure
BE	Brussels, Belgium	97/07/01-99/05/01	
BO	Boulder, USA	97/07/01-98/08/01	
BR	Brasimone, Italy	97/07/01-98/04/01	
CA	Cantley, Canada	97/07/01-98/03/31	
CB	Canberra,Australia	97/07/01-98/03/31	
ES	Esashi, Japan	97/07/01-98/04/30	
KY	Kyoto, Japan		
MA	Matsushiro, Japan	97/07/01-98/06/30	
MB	Membach, Belgium	97/07/01-99/03/03	
ME	Metsähovi, Finland	97/07/01-98/04/30	
PO	Potsdam, Germany	97/07/01-99/03/03	South Africa
ST	Strasbourg, France	97/07/01-98/04/30	
SY	Syowa, Antartica		not due
VI	Vienna , Austria	97/07/01-98/04/30	
WE	Wettzell,Germany	97/07/01-98/09/27	
WU	Wuhan, China	97/07/01-98/12/31	

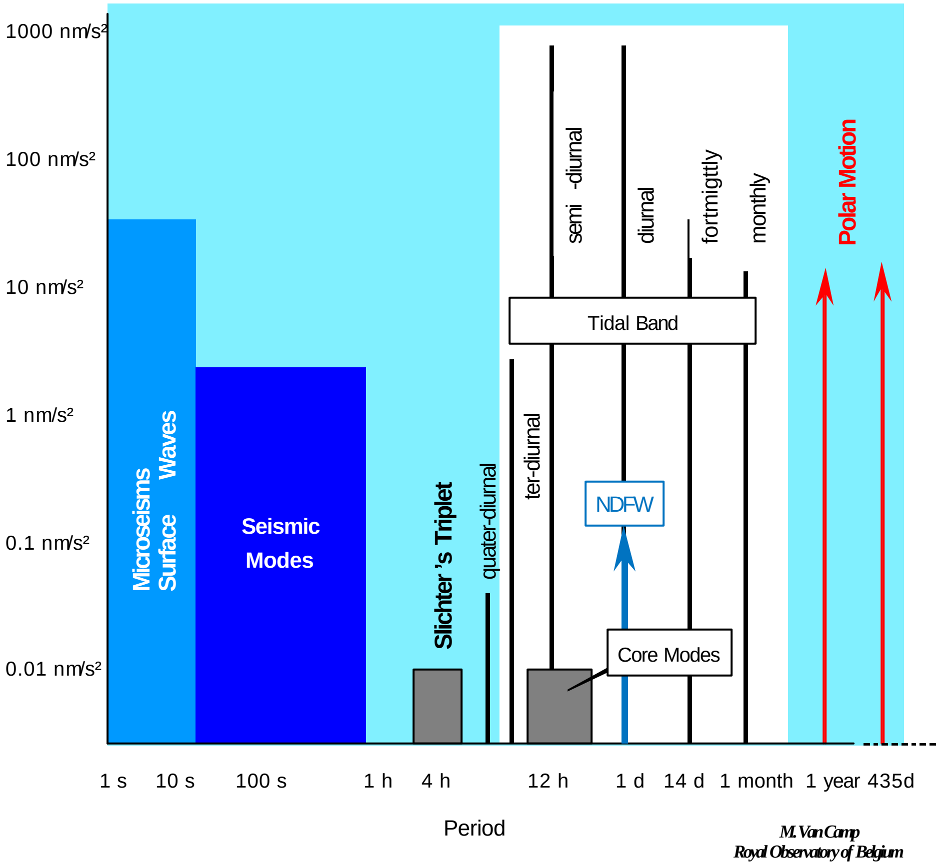

Figure 1: Spectrum of phenomena recorded by A Cryogenic Gravimeter

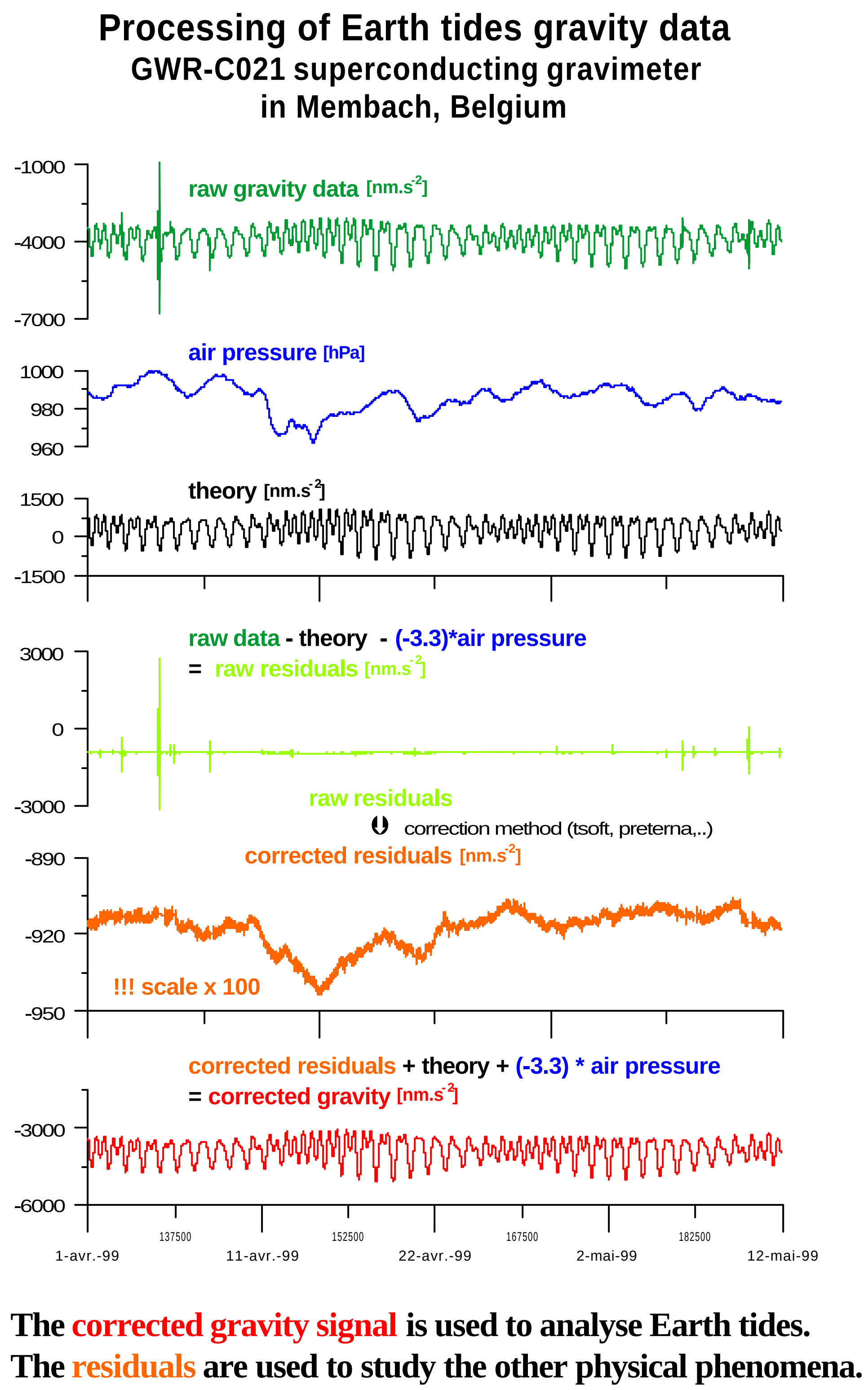

Figure 2: Reduction Procedure for Tidal Gravity Data

THE INTERNATIONAL EARTH ROTATION SERVICE
1995 TO 1999

REPORT TO THE INTERNATIONAL ASSOCIATION OF GEODESY
SECTION V

BUREAU CENTRAL DE L'IERS
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ACTIVITIES OF THE IERS

The IERS was created in 1987 by the IAU and the IUGG, replacing the Bureau International de l'Heure (BIH) and the International Polar Motion Service (IPMS), as a result of the ten-year international MERIT Campaign. The IERS started its activities in January 1988.

IERS was given the missions to define and maintain a terrestrial reference system based on the most precise space geodesy techniques at this time, to define and maintain a celestial reference system based on the directions of extragalactic radio sources and its tie to other celestial reference frames, and to monitor the Earth's orientation, i.e. the parameters that connect the terrestrial and the celestial reference systems as a function of time.

When operation began, the observational techniques available for these tasks where Very Long Baseline radio Interferometry (VLBI), Lunar Laser Ranging (LLR) and Satellite Laser Ranging (SLR). The Directing Board included representatives of the Coordinating Centres for these observing techniques, of the Central Bureau, and of IUGG, IAU and FAGS (Federation of Astronomical and Geophysical Data Analysis Services).

According to the Terms of Reference of the service, "the Directing Board exercises general control over the activities of the service, including modifications to the organisation and participation that would be appropriate to maintain efficiency and reliability, while taking full advantage of the advances in technology and in theory". The main decisions of the Directing Board in the first eight years of activity were the setting up of permanent monitoring of global atmospheric dynamical parameters in 1989, the adoption of the Global Positioning System (GPS) as an additional observing technique in 1989-93 and of DORIS (Doppler Orbitography by radio positioning integrated on satellite) in 1994-96, and the redefinition of the VLBI contributions in 1995-96.

In 1995, the IERS had achieved its primary missions, by providing globally distributed terrestrial and celestial references and the Earth's orientation with an accuracy equivalent to about one centimeter on the surface of the Earth.

After the initial IERS observing techniques reached maturity, new and powerful techniques were introduced. The environnement in Earth sciences - including funding aspects - evolves rapidely. The consideration of expectations and frustrations as well as the recognition of achievements led the Directing Board to organize a general public evaluation of the service, that would encompass a review of current operation, and advice on possible extensions to better meet new and future needs for global references. In December 1995 they decided that the 1996 IERS Workshop would be dedicated to this review, after a period of preliminary discussion. The discussion was organized under six topics, each analyzed by Topic Coordinators helped by a small group. The Topics were as follows.

1: Assessment of current missions
2: Astronomical reference frames
3: Vertical references, incl. geoid, sea level, etc.
4: Topography and crustal deformations
5: Unification of regional reference systems
6: Earth rotation dynamics and geophysical fluids

The Topic Coordinators prepared draft reports with recommendations and distributed them in advance to the IERS Workshop. The latter took place at Paris Observatory, 14-16 October 1996, with program and participants as given at the end of this volume. The draft reports and recommendations were discussed in detail during the workshop and then finalized by the Topic Coordinators, taking into account the results of the discussions. The final texts are those published in this volume.

The lively discussions that took place in this context were extremely productive in that a number of important aspects were put forward or given increased emphasis. While some extensions of activities in the fields of astronomy, geodesy and geophysics were recommended, the Workshop also recognized the success of IERS in providing timely and accurate data on Earth rotation, and in the establishment and maintenance of accurate terrestrial and celestial reference frames.

The IERS Directing Board started to work on the implementation of the recommendations, at and between the two DB meetings already held in October and in December 1996. The major aspects of the foreseen evolution are as follows.

Maintaining the International Celestial Reference Frame (ICRF) based on VLBI-derived directions of extragalactic radio sources, and of the tie of the Hipparcos galactic reference frame, as will be recommended by the IAU Working Group on Reference Frames to the 1997 IAU General Assembly. This activity will be performed in concertation with an IAU Working Group on reference frames.

Coordinating the use of astronomical observations for tying the Solar System reference frames to the ICRF.

Monitoring the global geophysical fluids that influence both the ground measurements and the Earth's rotation, an extension of the current activity on atmospheric data.

Monitoring the motion of the Earth's centre of gravity.

Fostering the provision of global vertical terrestrial references and of global horizontal references for the monitoring crustal deformations, in close cooperation with the International Association of Geodesy.

Enhancing the role of Coordinators and extending their field of responsability to general themes of importance to IERS.

Getting organized to interact with the Working Groups set up by IAU, IAG and IUGG on topics relevant to IERS missions.

Strengthening the development and maintenance of the IERS Conventions.

Developing or improving technical abilities for the global combination of products from analyses of the various observing techniques, and fostering internal competition within IERS on this aspect.

Extending formally the Directing Board membership to better represent all components of IERS activities.

Polling the IERS distribution lists to check the various types of users and their specific requirements.

The whole endeavour of reviewing IERS and making it evolve owes much to the dedication of the scientists that accepted to work on the requested evaluations and then took account of the input of the Workshop participants to finalize the documents in this volume. The IERS Directing Board is most thankful to these colleagues for their strong contributions.

IERS DIRECTING BOARD

Chairman and IUGG representative	C. Reigber, Germany
IAU representative	B. Kolaczek, Poland
FAGS representative (until September 1998)	O.B Andersen, Denmark
FAGS representative (since October 1998)	H.G. Wenzel
Central Bureau representative	
(until December 1997)	M. Feissel, France
(since January 1998)	D. Gambis, France
VLBI Coordinating Centre representative	C. Ma, USA

LLR Coordinating Centre representative	P.J. Shelus, USA
GPS Coordinating Centre representative	W.G. Melbourne, USA.
SLR Coordinating Centre representative	B.E. Schutz, USA.
DORIS Coordinating Centre representative	P. Willis, France.
SBBAM representative (until December 1997)	D. Salstein, USA
MGGF Coordinating Centre representative (since 1 January 1998)	B.F. Chao, USA.
Central Bureau, TRF representative	C. Boucher, France
Central Bureau, CRF representative	F.E. Arias, Argentina
Sub-bureau for rapid service and predictions	D.D. McCarthy, USA

PUBLICATIONS

All global IERS results are available under anonymous ftp and World Wide Web (see the back cover of this volume). IERS also maintains a series of publications, with Bulletins devoted to the Earth's rotation, Reports and Technical Notes for general results.

- **Sub-Bureau for Rapid Service**

  - Twice weekly Bulletin A — Earth orientation parameters (x,y,UT1,d ,d): Rapid Service, prediction. *Available electronically only.*

- **Central Bureau of IERS**

  - Monthly Bulletin B — Earth orientation parameters (x,y,UT1,d ,d) combined solution and individual series. Information on UTC time scale. *First issue in January 1988.*
  - EOP(IERS) C 04 — Earth orientation parameters (x,y,UT1,d ,d) combined solution. Updated twice weekly. *Available electronically only.*
  - Annual Report — Activities of the coordinating centres and bureaus. Results and analyses concerning the Earth orientation and the terrestrial and celestial frames of the IERS reference system. *First issue, Report for 1988.*
  - Special Bulletin C — Announcement of the leap seconds in UTC.
  - Special Bulletin D — Announcement of the value of DUT1 to be transmitted with time signals.
  - Technical Notes — Reports and complementary information of relevance to the work of IERS.
  - IERS Gazette — General information on IERS. *Available electronically only.*

IERS TECHNICAL NOTES

This series of publications gives technical information related to the IERS activities, e.g., reference frames, excitation of the Earth rotation, computational or analysis aspects, models, etc. It also contains the description and results of the analyses performed by the IERS Analysis Centres for the Annual Report global analysis. The technical Notes published over the period 1995-1999 are:

No 21: D.D. McCarthy (ed.). IERS Conventions (1996)

No 22: C. Reigber and M. Feissel (eds.). IERS missions, present and future. Report on the 1996 IERS Workshop

No 23: C.Ma and M. Feissel (eds.). Definition and realization of the International Celestial Reference System by VLBI Astrometry of Extragalactic Objects

No 24: C. Boucher, Z. Altamimi, P. Sillard (eds.). Results and Analysis of the ITRF96

No 25: J. Ray (ed.). Analysis Campaign to Investigate Motions of the Geocenter

No 26: D. Salstein, B. Kolaczek, D. Gambis (eds.). The impact of El Niño and other low-frequency signals on Earth rotation and global Earth ssystem parameters

No 27: C. Boucher, Z. Altamimi, P. Sillard (eds.). The 1997 International Terrestrial Reference Frame (ITRF97)

POLL PERFORMED IN 1996

A polling of IERS users needs was done in 1996. The tables hereafter summarize some preliminary results about the domain of application of IERS results, the type of use and the importance in the users work.

Domains

Astronomy	32%
Space Geodesy	49%
Navigation	22%
Geodesy	32%
Earth Sciences	23%
Time	21%

IERS results

	Celestial Reference Frame	Terrestrial Reference Frame	Earth Orientation Parameters
Type of use(%)			
Comparison	20	45	18
Conventional refer	28	43	29
Accurate reference	54	66	54
Research	35	43	43
Information	30	30	26
Importance of results for the user(%)			
Marginal	8	2	5
Useful	24	14	20
Very useful	27	31	35
Indispensible	41	53	40

The sum of percentages and in the domain are larger than 100%, as most users have a multidisciplinary activity. It is also the case for the type of use: in the mean, the users need two types results, which is a clear confirmation of the relevance of the main mission of IERS which is to provide global references.

IERS CORRESPONDING MEMBERS

B. Ambrosius
B. Archinal
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G. Beutler
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Y. Bock
A. Brzezinski
P. Brosche
J. Campbell
T. Clark
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J. Williams
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W.H. Wooden
P. Woodworth
Y. Yatskiv
K. Yokoyama
T. Yoshino
T. Yunck
Zhu.
J.F. Zumberge

ELECTRONIC ACCESS TO IERS BUREAUS AND PUBLICATIONS

CENTRAL BUREAU

e-mail address:	iers@obspm.fr		
World Wide Web:	http://hpiers.obspm.fr		

EARTH ROTATION AND CELESTIAL FRAME

e-mail addresses	Earth rotation:	gambis@obspm.fr	
	Celestial frame:	iers@obspm.fr	
Anonymous ftp:	hpiers.obspm.fr		145.238.100.28
World Wide Web:	http://hpiers.obspm.fr		

TERRESTRIAL FRAME

e-mail address	boucher@ensg.ign.fr	
Anonymous ftp:	lareg.ensg.ign.fr	192.33.147.230
World Wide Web:	http://lareg.ensg.ign.fr/ITRF	

IERS CONVENTIONS

e-mail address	dmc@maia.usno.navy.mil	
Anonymous ftp:	maia.usno.navy.mil	192.5.41.22
	cd conventions	

SUB-BUREAU FOR RAPID SERVICE AND PREDICTIONS

e-mail address:	ser7@maia.usno.navy.mil	
Anonymous ftp:	maia.usno.navy.mil	192.5.41.22
World Wide Web:	http://maia.usno.navy.mil	

SUB-BUREAU FOR ATMOSPHERIC ANGULAR MOMENTUM (until December 1997)

e-mail address:	salstein@aer.com
Anonymous ftp:	nic.fb4.noaa.gov
	ftp.aer.com
World Wide Web:	http://www.aer.com

COORDINATING CENTER FOR MONITORING GLOBAL GEOPHYSICAL FLUID

e-mail address:	chao@denali.gsfc.nasa.gov
World Wide Web:	http://cddisa.gsfc.nasa.gov/926/mggf

REPORT BY THE PERMANENT SERVICE FOR MEAN SEA LEVEL (PSMSL)

for the period 1995-99

Philip L. Woodworth
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Birkenhead, Merseyside CH43 7RA, United Kingdom

1. Introduction

This report reviews briefly the work of the Permanent Service for Mean Sea Level (PSMSL) during 1995-99. In this period, the PSMSL has data banked a record amount of sea level information, has taken a major role in the development of the Global Sea Level Observing System (GLOSS), and has contributed to important international working groups on climate change and geophysics.

The PSMSL is operated at the Proudman Oceanographic Laboratory (POL), Bidston Observatory under the auspices of the International Council of Scientific Unions, and is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). The PSMSL reports to the International Association for the Physical Sciences of the Ocean Commission on Mean Sea Level and Tides (IAPSO/CMSLT) and has an Advisory Board consisting of scientists expert in each area of sea level research. Annual reports on the work of the PSMSL are circulated each year to the International Association of Geodesy (IAG), the Intergovernmental Oceanographic Commission (IOC), IAPSO, FAGS, and other relevant bodies and are available publicly via the web at:

http://www.pol.ac.uk/psmsl/psmsl.info.html

This same web page also serves as a source of PSMSL data and ancillary information. Copies of PSMSL data can also be provided via ftp and on CD-ROM and other media.

2. PSMSL Data Receipts for 1995-99

On average, approximately 2000 station-years of data were entered into the PSMSL database during each year of the period. This compares well to rates obtained in previous years. It is particularly gratifying that receipts are now obtained routinely from virtually every corner of the globe, thanks to a large extent to GLOSS and World Ocean Circulation Experiment (WOCE) activities, but also thanks to the generally improving ease of worldwide communications. Figure 1 indicates the locations from which data were received during 1995-99.

3. GLOSS Activities

The Global Sea Level Observing System (GLOSS) is an IOC project, one of the aims of which is to improve the quality and quantity of data supplied to the PSMSL. GLOSS can be considered as one of the first components of the Global Ocean Observing System (GOOS). The PSMSL has taken the lead role in the development of GLOSS with the PSMSL Director (first Dr. David Pugh then Dr. Philip Woodworth) also being GLOSS Chairman. Two major GLOSS Experts meetings (in Pasadena, USA in 1997 and Toulouse, France in 1999) were organised during the period with 'mini-GLOSS meetings' in between.

A particularly important task during the period was the construction of a new Implementation Plan for GLOSS prepared by the PSMSL with contributions from many sea level scientists. The Plan was subsequently presented for endorsement by the 19th Session of the IOC Assembly at UNESCO House in Paris in July 1997, and was printed and circulated by IOC in 1998.

3.1 GLOSS Status

Each year the PSMSL has provided a summary of the status of GLOSS from its viewpoint, the most recent of which can be inspected via:

http://www.pol.ac.uk/psmsl/gloss.info.html

In brief, GLOSS can be considered approximately two-thirds operational, if one uses data receipts by the PSMSL as a guide to operational status. However, the overall status is somewhat better than that. At some gauge locations (e.g. Tristan da Cunha and some Antarctic sites), the gauges take the form of simple pressure transducers which provide useful information for oceanography (e.g. for WOCE) but which do not supply MSL data, as conventionally defined, which can subsequently be submitted to the PSMSL. This situation is understandable and tolerable if there are good environmental or technical reasons for such a choice of technology. At other locations, while a perfectly good gauge might exist and be providing data of some kind, the expertise or facilities or manpower do not exist in order to process those data routinely and deliver them to the international community. This situation is not an acceptable one, as it clearly requires some kind of investment in hardware, software or training. The job of IOC/GLOSS and of the PSMSL is to remedy such situations as far as possible and to improve GLOSS status as far as possible.

3.2 GLOSS Training Courses, Training Materials and Training Placements

The PSMSL took the lead in the organisation of four GLOSS training courses in this period at Dehra Dun, India (1995), Buenos Aires, Argentina (1996), POL, UK (1997) and Cape Town, South Africa (1998). A further course is planned for Sao Paulo, Brazil in late 1999. Each of these course concerned themselves with background sea level science (climate change, oceanography), the need for related geodetic measurements, and ‘hands on training sessions’ (HOTS).

The widely-used PSMSL/POL Tidal Analysis Software Kit (TASK) was extended and updated during 1998, particularly with regard to year 2000 compliance. The package is available free to any university or research institute scientist, with a small fee charged to commercial users.

Training materials continued to be made available to the community by means of CD-ROM, and a training web page is planned for 1999, accessible from the same pages as given above.

In 1996, the British Council funded an Indian scientist (Mr. C.Biswas of the Survey of India) to visit and study tide gauge techniques at POL. This successful visit followed that of another Indian scientist (Dr. Antony Joseph) from the National Institute of Oceanography the previous year. Consultations have taken place with colleagues from Viet Nam and Ghana with regard to collaborative gauge installations in those countries.

3.3 GLOSS Newsletters

The PSMSL publishes a newsletter for the GLOSS community called the *GLOSS Bulletin* which can found on the web at:

http://www.pol.ac.uk/psmsl/gb.html

An updated two page brochure advertising GLOSS has also been produced by the PSMSL. Two thousand copies were printed for circulation in the UK and we hope that GLOSS National and Regional Contacts will arrange for printing in their own countries. Copies of the files which make up the brochure (Corel Draw files) may be sent to anyone interested who can edit and adapt them according to local interests.

3.4 GLOSS Handbook and the WOCE Sea Level CD-ROM

In preparation for the International WOCE Conference in Halifax, Canada in May 1998, the PSMSL and the British Oceanographic Data Centre (BODC) published a new CD-ROM containing WOCE Sea Level Centre data sets together with an updated version of the GLOSS Handbook product and the PSMSL data set. Copies have been distributed widely. In addition, the updated GLOSS Handbook can be inspected via the above GLOSS web page.

4. Geodetic Fixing of Tide Gauge Benchmarks

A major development with regard to tide gauge benchmark fixing has been the establishment of the International GPS Service for Geodynamics (IGS). In March 1997, a meeting on tide gauge benchmark fixing was held at the Jet Propulsion Laboratory, prior to a meeting of the GLOSS Experts. This meeting was organised jointly by the IGS

Central Bureau (Director, Dr. Ruth Neilan), the PSMSL and IOC/GLOSS and resulted in an excellent workshop report on the use of GPS at gauge sites for measuring long term changes in vertical land movements and for altimeter calibration. In May 1999, a follow-up meeting was held at Toulouse, France, also alongside a GLOSS meeting, with plans for a Manual on 'How to Operate GPS at Gauges' put in place for probable publication in 1999.

5. Scientific Study Groups

5.1 Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report

The third scientific assessment of the Intergovernmental Panel on Climate Change (IPCC) commenced with a meeting in Bad Munstereifel, Germany at the end of the June 1998 and with a first drafting session in Paris in December. At the Bad Munstereifel meeting, there was considerable discussion as to whether there should be a dedicated sea level chapter and working group, as for the second assessment. In the end, the conclusion was that there should be, and the following people were eventually delegated to act as Lead Authors:

John Church	CSIRO Marine Research, Australia (Joint Coordinator)
Jonathan Gregory	Hadley Centre, UK (Joint Coordinator)
Philippe Huybrechts	Free University of Brussels, Belgium
Michael Kuhn	University of Innsbruck, Austria
Kurt Lambeck	Australian National University
Dahe Qin	Chinese Academy of Sciences
Philip Woodworth	Proudman Oceanographic Laboratory, UK and PSMSL

The latter's role in this is, of course, to provide some linkage to GLOSS and the PSMSL. The December IPCC meeting was followed by the first International CLIVAR (Climate Variability and Prediction) Conference, also held in Paris.

5.2 Tidal Science '96

A meeting entitled Tidal Science '96 was held at the Royal Society in October of that year to celebrate Dr. David Cartwright's seventieth birthday and also the major advances in global tide modelling during the last decade, largely thanks to the availability of TOPEX/POSEIDON data. Papers stemming from the meeting were published in a special issue of Progress in Oceanography (Volume 40, Numbers 1-4) during 1998 with Dr. Richard Ray (Goddard Space Flight Center) and Dr. Philip Woodworth (PSMSL Director) acting as editors.

5.3 Altimetry and Gravity Field Activities

Participation has continued in European and US altimeter working groups with PSMSL-related scientists becoming Principal Investigators for the JASON (TOPEX/POSEIDON Follow On) mission during the period, and Co-Investigators for the Envisat mission of the European Space Agency (ESA). PSMSL-related scientists have also become members of the Mission Advisory Group (MAG) of the ESA Gravity Field and Steady State Ocean Circulation Experiment (GOCE) mission, which is now at the end of the Phase-A development stage, and of the US/German Gravity Recovery And Climate Experiment (GRACE). The provision of a more precise model of the Earth's gravity field and geoid is of great importance to a range of oceanographic and geophysical studies which impact on sea level research.

6. After GLOSS: GLOUP

Many people interested in tide gauges and altimetry will also be interested in bottom pressure measurements. Dr. Chris Hughes from POL has recently taken a lead in trying to get global bottom pressure measurements and data sets on a better footing, providing potentially a component of GOOS parallel to GLOSS. He calls this activity GLOUP. For more information, see:

http://www.pol.ac.uk/psmslh/gloup/gloup.html

It is intended that this activity will be discussed at a business meeting of the IAPSO/CMSLT during the IUGG General Assembly . If approved, this activity will formally be managed by the PSMSL and will encompass the data collection of pelagic tidal constants which the PSMSL has been responsible to the Commission for during the last decade.

7. UK and European Projects

During the period, POL and PSMSL contributed strongly to a UK proposal for a large 'thematic' programme of research into sea level changes. This proposal was highly graded by the UK Natural Environment Research Council with decisions on ultimate funding expected later in 1999.

A European Union (EU) funded sea level study called SELF-2 for the Mediterranean took place during the period with POL participation, with concentration at POL on mean sea level changes, storm surge modelling, absolute gravity and tidal loading. Consultations and site visits also took place with colleagues in Greece with regard to collaborative upgrading of the Greek tide gauge sites. The EU EOSS project (formerly called NOSS) aims to enhance sea level (tide gauges) and land level (GPS) monitoring, and associated data exchange, in Europe primarily by sets of bilateral (i.e. no new cost) agreements. First activities in this five year project have centred around the North Sea, where most of the countries which have so far signed up to the project commitments are located. Mr. Philip Axe from POL has taken the lead in informing the EOSS group of the activities in PSMSL and GLOSS and in leading Work Package 5 which is associated with data exchange issues. Philip has also attended all twice-yearly Management Meetings. In addition, several other PSMSL-related POL staff have contributed to EOSS activities during the period. It is to be hoped that EOSS will result in the more reliable provision of sea and land level information from the European region. More information on EOSS can be obtained at:

http://www.pol.ac.uk/psmsl/eoss/eoss.html

8. Publicity

The PSMSL has endeavoured to publicise sea level data and their use as often as possible through brochures, web pages, newspaper and TV articles, seminars etc. Open Days took place at POL (including PSMSL) on several occasions during the period, attended by approximately 2000 members of the public on each occasion, as well as local dignitaries and Members of Parliament.

9. PSMSL/WOCE Centre Staffing

The PSMSL was joined at the start of 1997 by Mr. Philip Axe from the University of Plymouth. Philip has recently finished his Ph.D studies on coastal processes in the south of England. His main duties at the PSMSL and WOCE Centre include the bringing up to date of several WOCE-related sea level data sets, overlaps with the various European and global GPS/tide gauge activities, and of course scientific analysis of the data.

10. Meetings and Visitors

Many scientific meetings have been attended over the period and a large number of scientists and others interested in sea level research have visited the PSMSL. Summaries of meetings and visitors each year can be found in the PSMSL Annual Reports.

Summary

It can be seen that 1995-99 has been a further active period with regard to important workshops and conferences, and a busy one with regard to data acquisition and analysis.

Particular thanks as usual go to Elaine Spencer who has been PSMSL Technical Secretary since 1974. The PSMSL is very much her data set. Unfortunately, both Elaine and her husband Bob, who will be well known to a number of PSMSL/GLOSS people though his deployments of tide gauges and bottom pressure recorders, decided to take early retirement in May 1999. I am sure that the sincere thanks and best wishes of the sea level community will be extended to them both.

P.L.Woodworth (July 1999)

Distribution:

Prof. Paul Paquet, President Federation of Astronomical and Geophysical Data Analysis Services (FAGS)
Dr. Niels Andersen, Secretary FAGS
Dr. Patricio Bernal, Secretary Intergovernmental Oceanographic Commission (IOC)
Dr. Colin Summerhayes, Director GOOS Office IOC
Dr. Thorkild Aarup, GLOSS Technical Secretary IOC
Prof. Jacquie McGlade, Director Centre for Coastal and Marine Sciences (CCMS)
Dr. Ed Hill, Director CCMS Proudman Oceanographic Laboratory (POL)

Dr. Christian Le Provost, President IAPSO Commission MSL and Tides
Dr. Martine Feisel, Institut Geographique National, France (for IAG)
PSMSL Advisory Group:

- Dr. Ruth Neilan, Jet Propulsion Laboratory, USA
- Dr. Gary Mitchum, University of South Florida, USA
- Prof. Bruce Douglas, University of Maryland, USA
- Dr. Richard Warrick, University of Waikato, New Zealand
- Dr. David Pugh, Southampton Oceanography Centre, UK
- Dr .Georges Balmino, Bureau Gravimetrique International , Toulouse, France

REPORT OF THE BIPM TIME SECTION 1996-1999

Gérard Petit
Report first presented at the 14th meeting of the CCTF, 20 April 1999

Over the three years covered by this report, the work of the BIPM time section has been guided by the need to incorporate into TAI the present and expected improvements in the timing data. In this respect, the major facts relating to the clocks and primary frequency standards are discussed in section 1, while those relating to the time links are discussed in section 2. Section 3 addresses other research work that has been carried out to investigate the implications of the progresses in the metrology of time in such fields as general relativity, space-time references, pulsars and dynamical time scales, and atom interferometry.

1 International Atomic Time (TAI) and Coordinated Universal Time (UTC)

The reference time scales TAI and UTC have been regularly computed and published in the monthly *Circular T* and in the successive volumes of the *Annual Report of the BIPM Time Section* (Volume 11 for 1998). The definitive results of the Annual Reports have been also made available in the form of computer-readable files on the BIPM Time section Internet anonymous ftp site and the BIPM Web site (http://www.bipm.fr). The results of 1998 were made available electronically on March 5, 1999.
Since January 1996, access to TAI and UTC has been provided for the Modified Julian Days (MJDs) ending in 4 and 9, which corresponds to an update period of 5 days instead of the 10 days used previously. Thanks to the efficient electronic transmission of data and subsequent improvements in data processing at the BIPM, the results for month *n* have for several years been regularly published between the 13 and the 16 of month *n+1*. The efficiency and reliability of the calculation and diffusion of TAI and UTC are continuously kept under review.
Research concerning time scales mainly includes studies which aim to improve the long-term stability of the free atomic time scale EAL (the first step in the calculation of TAI) and the accuracy of TAI.

1.1 EAL stability

Two main facts have influenced the stability of EAL in recent years. First, the replacement of clocks of older design by new ones of type HP 5071A has continued; some 75% of the clocks are now either commercial caesium clocks of the new type or active, auto-tuned hydrogen masers, and together they contribute 89% of the total weight with consequent improvement in the stability of EAL.
Second, since 1st of January 1998, the weighting method in the ALGOS algorithm has been changed [8,9] adopting a relative maximum weight of a clock, and the calculation interval of TAI has been reduced from two months to one month. Initially, the maximum relative weight that can be attributed to a clock has been set to 0.7%
Following these changes, the medium-term stability of EAL, expressed in terms of the Allan standard deviation σ_y, is now estimated to be 1.3×10^{-15} for averaging times of about 40 days. This improves the predictability of UTC for averaging times between 1 and 2 months [1,2], a duration considered of fundamental importance for institutions in charge with the dissemination of real-time time scales.

1.2 TAI accuracy

Introduction of new primary frequency standards has also improved the accuracy of TAI. Most of these are “classical” caesium beam standards, some of them using optical techniques for the excitation and detection of the atoms. The first results of a primary standard using cold atoms in a fountain geometry were submitted in 1995 but only a few results from this primary standard have been submitted since 1996. This is a first step towards using a larger number of primary frequency standards, and using standards of different designs, as recommended on several occasions in the past by the CCTF (e.g. CCDS Recommendation S1 (1996)). In the future, we hope to receive data from a larger number of primary frequency standards using cold atoms. If these standards only operate intermittently and over limited periods in time, it will be necessary to develop specialised frequency comparison techniques to compare them with each other and to transmit their accuracy to TAI. More generally, the reduced uncertainties of such standards and their increasing number will require a more detailed understanding of their operation in order to optimise their use in TAI.
To characterize the accuracy of TAI, estimates are made of the relative departure, and of its uncertainty, of the duration of the TAI scale interval from the SI second on the geoid as realized by primary frequency standards. Since 1996, individual measurements of the TAI frequency have been provided by up to eight primary frequency standards:

- LPTF-FO1 is the caesium fountain developed at the BNM-LPTF, Paris (France). In the period covered by this report, it provided three measurements in May 1996 and one measurement in November 1997. For the most recent measurement the type B uncertainty of LPTF-FO1 has been stated by the LPTF at 0.22×10^{-14} (1σ).

- NIST-7 is the optically pumped primary frequency standard developed at the NIST, Boulder (Colorado, United States). In the period covered by this report, it provided ten measurements made over periods of 10 or 30-35 days. The type B uncertainty of NIST-7 is stated by the NIST as $1\times 10^{\;14}$ (1).
- NRLM-4 is the new optically pumped primary frequency standard developed at the NRLM, Tsukuba (Japan). Seven measurements over 5-day or 10-day periods have been made in 1998. The type B uncertainty of NRLM-4 is stated by NRLM as $2.9\times 10^{\;14}$ (1).
- PTB CS1, CS2 and CS3 are classical primary frequency standards operating continuously as clocks at the PTB, Braunschweig (Germany). Frequency measurements have been taken continuously, over two-month periods until December 1997 and over one-month periods since January 1998. Measurements have been available since July 1998 for PTB CS1, over the whole period covered by this report for PTB CS2, and since July 1996 for PTB CS3. The published evaluation of their type B uncertainties (1) are $0.7\times 10^{\;14}$, $1.5\times 10^{\;14}$ and $1.4\times 10^{\;14}$, respectively.
- CRL-01 is an optically pumped primary frequency standard jointly developed by the NIST and the CRL at the NIST. Its first measurement covers a 25-day period in July-August 1998, and its type B uncertainty has been stated by the CRL as $1\times 10^{\;14}$ (1).
- SU MCsR 102 is a classical primary frequency standard operated at the VNIIFTRI, Moscow, Russia. Three measurements over one-month periods have been performed in 1996 and its type B uncertainty has been stated by the VNIIFTRI as $5\times 10^{\;14}$ (1).

Although the number of available measurements and the number of the primary standards has increased over the period 1996-1998, the situation is by no means ideal. Particularly the uncertainty of the measurements of some primary standards is difficult to evaluate rigorously. Work has been initiated in the framework of the CCTF working group on the expression of uncertainties in primary frequency standards [10] to develop a better understanding between laboratories that evaluate the accuracy of their primary frequency standards and the BIPM which uses the measurements provided by these standards

The global treatment of individual measurements [6,7] led to a relative departure of the duration of the TAI scale unit from the SI second on the geoid decreasing from about $2.4\times 10^{\;14}$ for 1996 (with an uncertainty of about $0.7\times 10^{\;14}$) to about $-0.4\times 10^{\;14}$ at the end of 1998 (with an uncertainty of $0.4\times 10^{\;14}$). This result suggests that the procedure for compensating the discrepancy due to uniform application of the correction for the black-body radiation frequency shift in 1995 [3] has fulfilled its task. It consisted of cumulative frequency steering corrections, each of relative amplitude $1\times 10^{\;15}$ to $2\times 10^{\;15}$ and applied at each 2-month interval (1-month interval in 1998). It was applied starting March 1995 for a total correction of $-2.7\times 10^{\;14}$ until March 1998 when it was decided to abandon it. The relationship between the frequencies of EAL and TAI has then been fixed until February 1999. It may of course be changed again in the future to ensure the accuracy of TAI.

2 Time links

Since the beginning of 1995, the GPS common-view technique has been the sole means of time transfer used for TAI computation. Nevertheless, the BIPM Time section continues to study any other time comparison method which has the potential for nanosecond accuracy. Over the period covered by this report, this concerns in particular the techniques of common views on GLONASS satellites and of the two-way time transfer via geostationary satellites. Most recently, commercial receivers have been developed that allow simultaneous reception and processing of signals from both GPS and GLONASS so that the distinction, still used in this report, between these two satellite systems is becoming somewhat arbitrary. In the future, it may be necessary to treat as a whole all Global Navigation Systems used for time and frequency comparisons.

2.1 Global Positioning System (GPS)

Since GPS common view is the standard technique used for TAI [26], the BIPM issues, twice a year, GPS international common-view schedules. Rough GPS data are collected and treated regularly following well-known procedures: The international network of GPS time links used by the BIPM is organized to follow a pattern of local stars within a continent, together with two long-distance links, NIST-OP and CRL-OP, for which data is corrected to take account of on-site ionospheric measurements and post-processed precise satellite ephemerides. Only strict common-views are used in order to overcome effects due to the implementation of Selective Availability on satellite signals.

The BIPM also publishes an evaluation of the daily time differences [*UTC – GPS time*] in its monthly *Circular T*. These differences are obtained by smoothing data taken at the OP from a selection of satellites observed with an angle of elevation greater than 30°. The standard deviation of the daily results is about 10 ns, as the procedure does not fully eliminate Selective Availability.

An important part of our current work is to check the differential delays between GPS receivers which operate on a regular basis in collaborating timing centres or, on special request, in other laboratories. The results are published in BIPM reports [48,49,50,51,52,53]. As a result of these calibrations experiments, a differential delay for a pair of laboratories may be applied by the Time section in the regular TAI computation if its value is found to be significant and consistent over different evaluations. Alternatively, the internal delay of a receiver may be changed by a laboratory. Presently such a differential delay is applied for four GPS links in the TAI computation. It should be noted that the absolute calibration of GPS receiver delays still relies on old measurements and that it would be desirable to obtain new measurements. Although the differential calibration method is, in principle, perfectly suited to maintain consistency, absolute calibrations would provide an independent check of the overall consistency of the TAI links.

Several studies have been carried out with a view to extending the classical common-view time transfer technique to multi-channel receivers [11,23]. Present results show that, in general, the uncertainty in the time transfer measurements is decreased as expected from the statistics. Since such data are obtained from several commercially available receivers, it would be desirable to pass this technique into regular use for TAI computation. In addition to yielding a better stability, it would also suppress the need for the common view schedules and result in a more efficient operation at the BIPM and in laboratories.

GPS time and frequency transfer may be carried out using dual-frequency carrier-phase and code measurements. It is expected that an uncertainty of one part in 10^{15} in frequency transfer will be obtained over a period of one day [29]. An Ashtech Z12-T receiver has been acquired for this purpose and has been operated at the BIPM since December 1997. A close collaboration has been initiated with the BNM/LPTF, which owns a similar receiver, and a detailed study of the two receivers operating side by side in zero- or short-baseline has been carried out [32,33,35]. Clock comparisons over longer baselines are also being carried out [30].

One main purpose is to demonstrate the performance of this technique for frequency comparison and then to apply it to the comparison of primary frequency standards. In addition, absolute calibration of the receiver delays, which would allow its use for time transfer as well, is being studied. These studies are being conducted in the framework of the newly created IGS/BIPM Pilot Project to study accurate time and frequency comparisons using GPS phase and code measurements [36], which organized its first meeting at the BIPM on 22 and 23 June 1998.

The dual-frequency capability of the Ashtech Z12T receiver allows its use for measurements of the ionospheric delay of GPS signals. Such measurements were used to complement and recalibrate (after a failure in March 1998) ionospheric delay measurements obtained from an older Nitzuki 7633 unit which is routinely used at the BIPM to obtain the on-site ionospheric corrections for OP. In the near future, it is planned that ionospheric models produced by the International GPS Service for Geodynamics (IGS) will be routinely used to compute all long-distance time links used for TAI, an improvement needed in view of the coming maximum in ionospheric activity (2000-2001). These computations are being carried out in parallel with the regular TAI procedures since March 1999.

Technical directives, agreed in 1993 for the standardization of GPS time receiver software, are now widely implemented. In March 1999, most of the timing centres contributing to TAI provided data according to the new data format. Within the CCTF sub-group on GPS and GLONASS time transfer standards, the BIPM is working to reduce the sensitivity to outside temperature of some types of receiver currently in operation. Following preliminary experiments in which temperature-controlled ovens built at the BIPM had been used to protect antennas, a commercial temperature-stabilized antenna is now available from 3S Navigation [20]. Three units are available at the BIPM and are used for GLONASS or GPS+GLONASS receivers.

The BIPM is also conducting studies on low-cost multichannel receivers: software which fulfils all standards agreed for accurate time transfer is being developed for one of these, the Motorola Oncore 8-channel receiver [18,22,27,28].

2.2 Global Navigation Satellite System (GLONASS)

As is done for the GPS, GLONASS international common-view schedules are also established twice a year by the Time section. Rough GLONASS data taken by eight time laboratories are collected and studied at the BIPM, but are not yet used in the current TAI computation.

Since January 1997, the BIPM has published an evaluation of the daily time differences [*UTC – GLONASS time*] in its monthly *Circular T*. These differences are obtained by smoothing data, taken at the NMi-VSL, from a selection of satellites at high elevation. The standard deviation of the daily results is about 5 ns. This value is smaller than that obtained for the daily time differences [*UTC – GPS time*] mainly because GLONASS signals are not affected by intentional degradation such as the Selective Availability of GPS. However, the combined standard uncertainty of the daily values [*UTC - GLONASS time*] is not better than several hundred nanoseconds as there are no absolutely calibrated GLONASS time receivers.

The BIPM is equipped with four GLONASS and GPS/GLONASS time receivers from the 3S Navigation company: a two-channel P-code single-frequency GLONASS unit, and three multichannel GPS/GLONASS receivers with P-code double-frequency channels for GLONASS observation together with twelve channels for C/A-code single-frequency GPS or GLONASS observation. Results from these receivers make it possible to conduct research on the use of GPS and GLONASS for international time transfer in single and multichannel modes [13,21]. A recent study has demonstrated a stability gain between one-channel GPS observations and multichannel GPS and GLONASS observations for all averaging times [12,25].

Within the CCTF sub-group on GPS and GLONASS time transfer standards, the BIPM has helped to adapt the standard GPS data format for use in dual-system, dual-frequency, dual-code observation [24].

The first differential calibration of GPS/GLONASS multichannel dual-code receivers was carried out in the period from August to November 1997 [51]. This involves 3S Navigation, the NMi-VSL and the BIPM. The second part of this exercise began in February 1998. Results for the parts of the receivers involving GPS and GLONASS C/A code are similar to those usually obtained with ‘classical’ single-channel C/A code GPS receivers, and preliminary results for

GLONASS P code seem to indicate a significant improvement in stability [13,14]. This should be confirmed by further investigation.

One of the 3S Navigation receivers in operation at the BIPM, which has the capability to provide GLONASS phase measurements, provides data to the International GLONASS Experiment, IGEX'98, organized by the IAG, the IGS and the ION since October 1998. The objective of this project is, among others, to produce post-processed precise GLONASS satellite ephemerides as has been done for several years for GPS satellites. This is a necessary step in view of using GLONASS for long distance time transfer in the TAI computation.

2.3 Two-way time transfer

The CCTF working group on two-way satellite time transfer met four times, the last meeting was in San Fernando (Spain) on 29-30 October 1998. Other more technical meetings of representatives of the participating two-way stations were held, the last one on 3 December 1998 in Reston (Virginia), during the 30th PTTI. At these meetings the main topics were: routine operation, station calibration problems, the new format for reporting data, discussion on the comparison of two-way and GPS common-view data. Regular TWSTT sessions began on 20 January 1997 using the INTELSAT 706 satellite on a commercial basis [15]. The first months of operation were dedicated to testing. The BIPM has begun in February 1998 collection of two-way data from six operational stations and undertaken treatment of some two-way links. The BIPM ensures the secretariat of the working group and is also involved in the calibration of two-way time transfer links by comparison with GPS [50,52,53].

3 Other research studies

3.1 Application of general relativity to time metrology

A summary of the research on general relativity and the metrology of time carried out over the last four years in the BIPM Time section was published in the form of a doctoral thesis by P. Wolf. It was presented and accepted for the degree of Ph.D. at Queen Mary and Westfield College (University of London) on 30 March 1997 [44]. This work was also published as a *BIPM Monographie* [55].

A novel test of special relativity has been carried out using data from clock comparisons between hydrogen maser clocks on the ground, and caesium and rubidium clocks on 25 GPS satellites [40,45,46]. The clocks were compared via carrier-phase measurements of the GPS signal using geodetic receivers at a number of stations of the IGS spread world-wide. In special relativity synchronisation of distant clocks by slow clock transport and by Einstein synchrony (using the transmission of light signals) is equivalent in any inertial frame. A violation of this equivalence can be modelled using the parameter c/c, where c is the round-trip speed of light and c is the deviation from c of the observed velocity of a light signal travelling one-way along a particular spatial direction with the measuring clocks synchronised using slow clock transport (sometimes referred to as the anisotropy of the one-way speed of light). In special relativity $c/c = 0$. Experiments can set a limit on the value of c/c along a particular spatial direction. The results presented set an upper limit on the value of $c/c < 5\mathrm{x}10^{-9}$ when considering all spatial directions and $c/c < 2\mathrm{x}10^{-9}$ for the component in the equatorial plane. These are the most stringent limits for this parameter reported up to date.

3.2 Space-time references

Studies have been initiated to unify the work on space-time references being carried out at the BIPM, previously within the CCDS working group on the application of relativity to metrology, and in working groups within the IAU, the IUGG, and the IERS. With this aim, the IAU and the BIPM created in 1997 the BIPM/IAU Joint Committee on general relativity for space-time reference systems and metrology under the chairmanship of G. Petit.

The membership has been established and the Joint Committee started its work in 1998. After an initial work of specifying the tasks, notably with the IAU Working Group on Relativity in Celestial Mechanics and Astrometry, the first issues raised concern the realization of barycentric and geocentric coordinate times at the present and foreseeable levels of uncertainty [41]. A first step in this work is to draw the conclusions of these studies in the form of Recommendations to be proposed to the IAU General Assembly and to the CIPM in 2000.

A Web site has been established [http://www.bipm.fr/WG/CCTF/JCR/welcome.html] that contains general information on the Joint Committee as well as the main headlines of the work, which are regularly published in Circulars.

3.3 Pulsars

Millisecond pulsars can be used as stable clocks to realize a dynamical time scale by means of a stability algorithm [37,38]. Collaboration is maintained with radio-astronomy groups observing pulsars and analysing pulsar data. Each year in February, the Time section provides these groups with the latest version of its post-processed realization of Terrestrial Time TT(BIPMxx), where xx stands for the last two digits of the year.

A new technique to be used at radio observatories to obtain pulsar data has been developed in collaboration with the Centre National d'Études Spatiales, CNES (France) and the Observatoire Midi-Pyrénées, OMP (France). The use of this technique to search for new pulsars in a sky survey has been the subject of the doctoral work of B. Rougeaux [42]. The complete chain of hardware and software has been validated by observations of known pulsars [43] and a program of survey observations, covering a small area on the sky, has been started at Nançay (France). The processing of these observations, started at the BIPM, will be pursued at the OMP.

3.4 Atom interferometry

Recently atomic interferometers using laser cooled Cs atoms in a fountain geometry have been used to measure the acceleration of gravity, *g* (as well as its gradient) with uncertainties that are competitive with those obtained using the best classical instruments. Such instruments are very similar to fountains used as primary frequency standards and, at least in principle, existing instruments can be used for both purposes. A theoretical investigation of some systematic effects in the gravimetric measurements has been carried out [47] giving explicit expressions for the corresponding corrections and showing that they are not negligible when considering the most recent experimental uncertainties.

3.5 Clocks in space

The BIPM time section follows with interest the progress towards any highly stable and/or accurate clock in space, like e.g. the ACES (Atomic Clock Ensemble in Space) project, expected to consist of a hydrogen maser and a cooled atom Cs clock (PHARAO) onboard the international space station (ISS). The clocks will be linked to ground clocks via a laser system (Time Transfer by Laser Link, T2L2) and a microwave time and frequency transfer system (yet to be specified). The PHARAO primary frequency standard with an absolute uncertainty expected to be below that of ground based standards and the ACES time and frequency transfer systems are of potential interest for the calibration of TAI and for the verification of existing time transfer methods.

4. Publications

4.1 External publications on Section 1 (time scales)

1. THOMAS C., Stability and Accuracy of International Atomic Time, *Proc. 10th EFTF,* 1996, 520-527
2. THOMAS C., Impact of New Clock Technologies on the Stability and Accuracy of the International Atomic Time, *IEEE Trans. Ultras. Fer. Freq. Cont.*, 1997, **44**, 696-700
3. THOMAS C., Impact of international decisions on TAI generation, *Proc. 28th PTTI*, 1996, 25-36.
4. THOMAS C., TAVELLA P., Time Scales, *Selection and Use of Precise Frequency and Time Systems*, ITU Handbook, Chapter VI, Geneva, 1997, 119-149.
5. THOMAS C., The CCDS Working Groups, *Proc. 28th PTTI*, 1996, 327-330.
6. THOMAS C., The accuracy of the international atomic time TAI, *Proc. 11th EFTF,* 1997, 283-289.
7. THOMAS C., The accuracy of TAI, *Proc. 29th PTTI,* 1997, 19-26.
8. THOMAS C., AZOUBIB J., TAI Computation: Study of an Alternative Choice for Implementing an Upper Limit of Clock Weights, *Metrologia*, 1996, **33**, 227-240.
9. THOMAS C., AZOUBIB J., Proposal for Updating TAI Algorithm, *Proc. 29th PTTI*; 1997, 7-17.
10. DOUGLAS R., THOMAS C., The CCTF working group on the expression of uncertainties in primary frequency standards, *Proc. 29th PTTI,* 1997, 85-95.

4.2 External publications on Section 2 (time links)

11. AZOUBIB J., LEWANDOWSKI W., DE JONG G., A new approach to common-view time transfer using ‘All-in-view’ multi-channel multi-code GPS and GLONASS observations, *Proc. 29th PTTI,* 1997, 299-308.
12. AZOUBIB J., LEWANDOWSKI W., DE JONG G., A New Approach to International Time Transfer : Multi-channel and Multi-Code GPS+GLONASS Common-View Observations, *Proc. 12th EFTF*, 1998, 87-93.
13. AZOUBIB J., LEWANDOWSKI W., A test of GLONASS P-Code time transfer, *Proc. ION GPS'98*, 1998, 1729-1735.
14. AZOUBIB J., LEWANDOWSKI W., A test of GLONASS Precise Code for high precision time transfer, *Proc.30th PTTI*, 1998, in press.
15. AZOUBIB J., KIRCHNER D., LEWANDOWSKI W., HETZEL P., KLEPCZYNSKI W., MATSAKIS D., PARKER T., RESSLER H., SOERING A., DE JONG G., BAUMONT F., DAVIS J., Two-way satellite time transfer using Intelsat 706 on a regular basis: status and data evaluation, *Proc. 30th PTTI*, 1998, in press.
16. JALDEHAG K., THOMAS C., AZOUBIB J., Use of a Dual-frequency Multi-channel geodetic GPS Receiver for the Estimation of Ionospheric Delays applied to Accurate Time Transfer, *Proc. 12th EFTF*, 1998, 499-504.
17. LEWANDOWSKI W., DANAHER J., KLEPCZYNSKI W.J., GLONASS Common-View Time Transfer Between North America and Europe and its Comparison with GPS, *Proc. 10th EFTF*, 1996, 388-392.
18. LEWANDOWSKI W., MOUSSAY P., GUERIN P., MEYER F., VINCENT M., Testing Motorola Oncore GPS Receiver and Temperature-Stabilized Antennas for Time Metrology, *Proc. 28th PTTI*, 1996, 387-396.
19. LEWANDOWSKI W., AZOUBIB J., GEVORKYAN A.G., BOGDANOV P.P., DE JONG G., HAHN J., First Results From GLONASS Common-View Time Comparisons Realized According to the BIPM International Schedule, *Proc. 28th PTTI*, 1996, 357-366.
20. LEWANDOWSKI W., MOUSSAY P., DANAHER J., GERLACH R., LEVASSEUR E., Temperature-Protected Antennas for Satellite Time Transfer Receivers, *Proc. 11th EFTF*, 1997, 498-503.
21. LEWANDOWSKI W., AZOUBIB J., WEISS M., ZHANG V., HANNS V., GEVORKYAN A.G., BOGDANOV P.P., TUTOLMIN N., DANAHER J., DE JONG G., HAHN J., MIRANIAN M., GLONASS Time Transfer and Its Comparison with GPS, *Proc. 11th EFTF*, 1997, 187-193.

22. LEWANDOWSKI W., MOUSSAY P., GUERIN P., MEYER F., VINCENT M., Testing Motorola Oncore GPS receiver for Time Metrology, *Proc. 11th EFTF*, 1997, 493-497.
23. LEWANDOWSKI W., AZOUBIB J., DE JONG G., NAWROCKI J., DANAHER J., A New Approach to International Satellite Time and Frequency Comparisons: 'All-in-View' Multichannel GPS+GLONASS Observations, *Proc. ION GPS'97*, 1997, 1085-1091.
24. LEWANDOWSKI W., AZOUBIB J., GEVORKYAN A.G., BOGDANOV P.P., KLEPCZYNSKI W.J., MIRANIAN M., DANAHER J., KOSHELYAEVSKY N.B., ALLAN D.W., A Contribution to the Standardization of GPS and GLONASS Time Transfers, *Proc. 28th PTTI*, 1996, 367-383.
25. LEWANDOWSKI W., AZOUBIB J., GPS+GLONASS : Toward Subnanosecond Time Transfer, *GPS World*, **9, 11**, 30-39, 1998.
26. LEWANDOWSKI W., AZOUBIB J., KLEPCZYNSKI W.J., GPS: Primary Tool for Time Transfer, *IEEE Proc*., **27, 1**, 163-172, 1999.
27. NAWROCKI J., LEWANDOWSKI W., AZOUBIB J., Time transfer with GPS multi-channel Motorola Oncore receiver with CCDS standards, *Proc. 29th PTTI*, 1997, 319-328.
28. NAWROCKI J., LEWANDOWSKI W., AZOUBIB J., GPS multi-channel common-view time transfer using Motorola Oncore receiver with CCTF standards, *Proc. 12th EFTF*, 1998, 510-515.
29. PETIT G., THOMAS C, GPS frequency transfer using carrier phase measurements, *Proc. 50th IEEE FCS*, 1996, 1151-1158.
30. PETIT G., Frequency Comparison Using GPS Carrier Phase: Some Experimental Results, *Proc. 11th EFTF*, 1997, 336-340.
31. PETIT G., THOMAS C., MOUSSAY P., DAVIS J.A., MIRANIAN M., PALACIO J., Multi-Channel GPS Common-View Time Transfer Experiments: First Results and Uncertainty Study, *Proc. 29th PTTI*, 1997, 309-318.
32. PETIT G., THOMAS C., JIANG Z., UHRICH P., TARIS F., Use of GPS Ashtech Z12T receivers for accurate time and frequency comparisons, *Proc. IEEE FCS*, 1998, 306-314.
33. TARIS F., UHRICH P., THOMAS C., PETIT G., JIANG Z., Stability characterization of two multi-channel GPS receivers for accurate frequency transfer, *Journées 1998 Systèmes de Référence Spatio-Temporels*, 1998, in press.
34. THOMAS C., AZOUBIB J., Proposal for updating TAI algorithm, *Proc. 29th PTTI*, 1997, 7-17
35. THOMAS C., Accurate time and frequency transfer using GPS phase measurements, *Journées 1998 Systèmes de Référence Spatio-Temporels*, 1998, in press.
36. RAY J., THOMAS C., The IGS/BIPM Pilot Project to study accurate time and frequency comparisons using GPS phase and code measurements, *Proc. 30th PTTI*, 1998, in press.

4.3 External publications on Section 3 (other research studies)

37. PETIT G., TAVELLA P., Pulsars and Time Scales, *Astron. Astrophys.* **308**, 290-298, 1996.
38. PETIT G., The stability of atomic time scales versus millisecond pulsars, *Pulsar timing, general relativity and the internal structure of neutron stars*, Elsevier, 1998, in press.
39. PETIT G., WOLF P., Computation of the Relativistic Rate Shift of a Frequency Standard, *IEEE Trans. Instrum. Meas.* **46**, 201-204, 1997.
40. PETIT G., WOLF P., Tester la Relativité sans Quitter son Fauteuil, *La Recherche*, April 1997, 38-39.
41. PETIT G., Importance of a common framework for the realization of space-time reference systems, *Proc. IAG symposium IGGOS*, 1998, in press.
42. ROUGEAUX B., *Une recherche de pulsars millisecondes à courte période et grande dispersion*, to be presented for Ph.D. thesis, Université Paul Sabatier, 1999, 181 p.
43. ROUGEAUX B., PETIT G., FAYARD T., DAVOUST E., A survey for very fast and dispersed millisecond pulsars, *Exp. Astron.* , 1999, submitted.
44. WOLF P., *Relativity and the Metrology of Time*, Ph.D. Thesis, Queen Mary and Westfield College, University of London, 1997, 169 p.
45. WOLF P., PETIT G., A Test of Special Relativity Using the GPS System, *Proc. 11th EFTF*, 1997, 298-302.
46. WOLF P., PETIT G., Satellite test of special relativity using the global positioning system, *Phys. Rev. A* **56**, 4405-4409, 1997.
47. WOLF P., TOURRENC P., Gravimetry using atom interferometers: Some systematic effects, Phys. Lett. A **251**, 241-246, 1998.

4.4 BIPM publications

48. LEWANDOWSKI W., MOUSSAY P., Determination of the differential time correction between GPS time equipment located at the Observatoire de Paris, Paris, France, and the United States Naval Observatory, Washington DC, U.S.A., *Rapport BIPM*-96/10, 1996, 9 p.
49. LEWANDOWSKI W., MOUSSAY P., Determination of the differential time corrections between GPS time equipment located at the Observatoire de Paris, Paris, France, the National Measurement Laboratory, Sydney, Australia, the Orroral Geodetic Observatory, Belconnen, Australia, the Measurement Standards Laboratory, Lower Hutt, New Zealand, and the Communications Research Laboratory, Tokyo, Japan, *Rapport BIPM*-97/1, 1997, 11 p.

50. LEWANDOWSKI W., MOUSSAY P., Determination of the differential time corrections between GPS time equipment located at the OP, NPL, VSL, DTAG, PTB, TUG, IEN and OCA, *Rapport BIPM*-97/5, 1997, 14 p.
51. AZOUBIB J., DE JONG G., LEWANDOWSKI W., Differential Time Corrections for Multi-Channel GPS and GLONASS Time Equipment Located at 3S Navigation, BIPM and VSL, Part 1, *Rapport BIPM*-97/6, 1997.
52. LEWANDOWSKI W., MOUSSAY P., Differential time corrections for GPS time equipment located at the OP, CH, SP, VSL, DTAG, PTB, NPL, TUG, IEN and OCA second evaluation, *Rapport BIPM*-98/1, 1998, 31 p.
53. LEWANDOWSKI W., MOUSSAY P., Differential time corrections for GPS time equipment located at the OP, VSL, NPL, DTAG, PTB, TUG, IEN, ROA, IPQ and OCA third evaluation, *Rapport BIPM*-98/7, 1998, 30 p.
54. THOMAS C., Weighting factors attributed to measurements of primary frequency standards in estimating the accuracy of TAI, Rapport BIPM-98/2, 1998, 22 p.
55. WOLF P., Relativity and the metrology of time, *BIPM Monograph* 97/1, 1997, 169 p.

REPORT 1999 OF THE WG ON 'NON RIGID EARTH NUTATION THEORY', JOINT IAU/IUGG WG

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June 1999

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The last nutation model adopted by the IAU (International Astronomical Union) in 1980 is the nutation series built, on the one hand, on Wahr's transfer function for the nutations of an oceanless elastic Earth (Wahr, 1981), and on the other hand, on Kinoshita's rigid-Earth precession-nutation series (Kinoshita, 1977; Kinoshita et al., 1979). The adopted model is expressed for the Celestial Ephemeris Pole (CEP) as defined by Seidelmann (1982). The resulting non-rigid Earth nutation series have been used since that time and have been compared with observations. The IAU adopted nutations in longitude and obliquity have been compared with Earth's orientation parameters derived from modern astronomical observations, mainly from very accurate VLBI (Very Long Baseline Interferometry). This comparison shows residuals of the order of 10 milliarcsecond (mas) and has led to a re-evaluation of the ability of the models to describe the observations. The WG aims at obtaining a new theoretical nutation series which could be used for giving the Earth's orientation in space to practical users who want high accuracy, especially for geophysical studies.

The WG on Non rigid Earth nutation theory has mainly been working by e-mail exchanges in which various important issues were discussed. We have separated the discussions into six different levels and examined a series of questions for each level.

The **first level** concerns the seismic input models used for computing the Earth's transfer function for nutations. The main points examined are the validity of the PREM model and the consideration of violation of the hydrostatic equilibrium in order to reconcile the computed and observed moments of inertia, the dynamical flattening and the boundary flattenings (in particular the flattening of the Core-Mantle Boundary (CMB)).

The **second level** concerns the Earth's transfer function for nutations. These transfer functions are based on new models for the Earth's interior, with changes in the boundary shapes due to the non-hydrostatic equilibrium, changes in the density which provide the observed hydrodynamical flattening and changes in the elastic parameters in order to incorporate the effects of mantle inelasticity. One particular transfer function incorporates additionally an electromagnetic torque at the core-mantle boundary and at the inner core-outer core boundary (see below).

The **third level** concerns the rigid Earth nutation theories and discusses the differences between these theories. This discussion and comparison has led to a convergence of the series; the mutual differences are less than tens of microarcseconds in the frequency domain when effects including second order terms as the J2-tilt effect, the direct and indirect effects of the planets etc are taken into account.

The **fourth level** concerns the convolution between the transfer function (level 2) and the rigid Earth nutation series (level 3). We discussed the coherency between the constants used in the transfer function and the rigid Earth nutation series and the accuracy of the results of this convolution.

The **fifth level** concerns the ocean and atmospheric effects on nutation. Two approaches are used: (1) the angular momentum approach in which the variations of the angular momentum of the Earth are calculated from the equal and opposite variations of the angular momentum of the ocean and the atmosphere, and (2) the torque approach in which the pressure, gravitational and friction torques on the Earth due to the ocean and atmosphere are computed. The advantages and disadvantages of the two approaches have been discussed. We have also considered the indirect effects of the atmosphere, which are the effects of the oceans on the Earth in response to the atmospheric forcing. We have pointed out the necessity to have atmospheric data models that give a correct estimation in the diurnal frequency band in the terrestrial frame and to have a dynamic ocean model in the same frequency band.

The **sixth level** concerns the comparison with the observations. We have stressed the necessity to have continuous VLBI observations and the importance of these data which can be used to build a nutation theory as done by Mathews et al. (1998, 1999).

We have published the questions and answers discussed at the different levels, in Celestial Mechanics (paper of 65 pages, in press). Additionally, we have organized joint discussions at the IAU and special sessions at the Journees Systeme de Reference.

One of the main conclusions of this work is that the precision of the rigid Earth nutation theory is high enough to meet the accuracy of the observations. The three accurate rigid Earth nutation series presently available are:

1. SMART97 rigid Earth nutation series of Bretagnon et al. (1997, 1998),
2. REN2000 rigid Earth nutation series of Souchay and Kinoshita (1997), and
3. RDAN97 rigid Earth nutation series of Roosbeek and Dehant (1998).

From the comparison with the observations it has been concluded that interchange of these three rigid Earth nutation series does not change the residuals of the non-rigid Earth nutation series at the observational level.
On the other hand, the choice of the transfer function is found to be fundamental in the sense that observable differences still exist between these functions. Models of the Earth are available for computing the transfer function for non-rigid Earth nutations:

1. The model of Dehant and Defraigne (1997). This model is based on a numerical integration method and includes the effects of mantle inelasticity and of non-hydrostatic equilibrium (steady-state mantle-convection is considered at the equilibrium state). The non-hydrostatic equilibrium hypothesis induces changes in the global Earth dynamical flattening and in the core flattening. The model is the next generation of Wahr's nutation model (it uses an upgraded version of the same program) but still suffers from a lack of dissipation in the core with associated lack of Free Core Nutation (FCN) damping (remaining difference in the out-of-phase part of the retrograde annual nutation of about 0.4 mas.

2. The model of Mathews et al. (1998 and 1999). This model includes the effects of electromagnetic coupling at the CMB and at the ICB, the ocean effects, mantle inelasticity effects, atmospheric effects and changes in the global Earth dynamical flattening and in the core flattening. It is based on a semi-analytical method in which several adjustable parameters are fitted from the observations. The parameters include for example the core flattening. The theoretical nutation amplitudes are obtained from a dynamical system of four coupled linear differential equations, and a least-quares fit to nutation amplitudes is determined using VLBI. The model is an extension of Mathews et al. (1991a and 1991b) with the following modifications: (1) magnetic couplings are included by introducing additional terms in the relevant matrix elements, the coupling strengths are represented by complex parameters which are estimated along with the other parameters by the least-squares fit; (2)anelasticity is included by making appropriate complex increments (based on some model of the dependence of mantle Q on frequency) to the compliances;(3) ocean tide effects are included through frequency dependent increments to the relevant compliances. The frequency dependence is given by an empirical formula involving constant parameters which are determined beforehand on the basis of Chao et al.'s (1996) ocean angular momentum data.

3. The model of Schastok (1997) The effects of the atmosphere on the nutations can be computed from either the torque approach or the angular momentum approach as described here above. Besides these two methods Schastok (1997) has developed a global approach; he has included the oceans and atmosphere via outer surface boundary conditions in his integration inside the ellipsoidal Earth. This coupling between the solid Earth, the atmosphere and ocean could be important for the determination of the eigenfrequencies such as the Chandler Wobble (CW) and FCN frequencies. Schastok has additionally computed all the second-order effects which have allowed him to

evaluate the Free Inner Core Nutation (FICN), in addition to the other classival modes such as the FCN and the CW.

The hydrostatic flattening of the CMB does not match the value derived from the observed FCN period (deduced from observations of tides and VLBI nutations); an increase of the core flattening corresponding to an extra difference between the equatorial and the polar radii of about 500 metres could resolve this discrepancy (Herring, 1995). This 500 metre extra-difference is computed from the observed FCN period by considering the CMB coupling as being due to the core dynamic pressure on the CMB flattening only. Non-hydrostatic models exist which allow this difference. An additional electromagnetic torque at that boundary would reduce this extra-difference to 375 metres as shown in Mathews et al. (1998 and 1999). The flattening of the fluid core would need to be known to below 2.5m to match the precision of the nutation data if the electromagnetic torque is ignored or correctly modeled.

The models of Schastok (1997) and of Dehant and Defraigne (1997) suffer from a neglect of dissipation in the core. The model of Dehant and Defraigne (1997) suffers additionally from a non-modeling of the ocean and atmosphere effects, which can however always be taken from elsewhere (they are thus corrections computed by other scientists). The non-hydrostatic state considered in the model of Schastok (1997) does not correspond to a mantle convection state but rather is constructed from Clairaut's equation for the flattening profile constrained to match the observed FCN (or CMB flattening) and the observed global dynamical flattening.

Herring (1995) has provided the users with a resonance formula of which the parameters are derived from the observations and from the rigid Earth nutation amplitudes of Kinoshita and Souchay (1990) (see the IERS Conventions McCarthy, 1996, for the nutation amplitudes). The resonance parameters cannot be interpreted in terms of geophysical parameters.

The model provided by Mathews et al. (1999) is a good compromise between a complete numerical integration incorporating all the effects which influence the nutation at the tenths of *mas* level (such as Dehant and Defraigne, 1997, if it would model dissipation at the CMB), and a model fitted to the observations. Indeed, while it is based fitting on the observations, the parameterisation is chosen to have a physical meaning.

An important next geophysical step in the theoretical computation of the Earth's transfer function is better modeling of the core in the models using the integration method. Indeed, the core influences not only the values of the displacement field induced by an external forcing, but also the eigenfunctions throughout the whole Earth and the eigenfrequencies, in particular. Constraints from nutation observations on core dynamics at diurnal time scale is a very promising topic.

Important efforts are still needed in the computation of the oceanic and atmospheric effects on nutations. In particular, the models used for the atmosphere and the associated indirect effects of the oceans are still not perfect. There are important differences in the diurnal atmospheric forcing derived from different sets of data as shown in de Viron et al. (1999). Large efforts are thus still needed in this area.

The members and correspondents of the WG have also discussed the possibilities to redefine the CEP to account for the subdiurnal motion of the pole in the terrestrial frame as well as for the subdiurnal motion in the celestial frame. In the present CEP definition, the subdiurnal motions do not appear so that the astrometric Earth orientation parameters can be assumed constant over one day. But the present-day precision of VLBI and the better observation campaign schedule and coordination make the observation of such motions possible. However certain geophysical phenomena related to the ocean and atmosphere or to the luni-solar attraction on a triaxial Earth have periods in these frequency bands and should be taken into account. Various new definitions are being studied and the final choice still needs some simulations. Last but not least, the adoption of the new International Celestial Reference System (ICRS) and its realisation, the International Celestial Reference Frame (ICRF) has pushed scientists to work on the consequences for the precession/nutation series. To that aim, a sub-group, chaired by Nicole Capitaine, of the IAU WG on the ICRF has been created. These two last topics are thus still under discussion.

References

Bretagnon P., Rocher P. and Simon J.-L., 1997, Theory of the rotation of the rigid Earth., Astron. Astrophys., 319, pp. 305-317.

Bretagnon P., Francou G., Rocher P. and Simon J.-L., 1998, SMART97: a new solution for the rotation of the rigid Earth., Astron. Astrophys., 329, pp. 329-338.

Capitaine N., 1998a, Overview, formulation and current situation for precession-nutation., XXIIIrd General Assembly of IAU, Kyoto, invited paper JD 3 on 'Precession-nutation and astronomical constants for the dawn of the 21st century', Kluwer Academic Publ., Highlights of Astronomy, Vol. 11, pp. 153-157.

Capitaine N., 1998b, Formulation of precession and nutation for precise astrometric data., Proc. Journ ees Syst emes de Reference Spatio-temporels 1997, Prague, Czech Rep., eds. J. Vondrak and N. Capitaine, pp. 83-90.

Chao B.F., Ray R.D., Gipson J.M., Egbert G.D. and C. Ma, 1996, Diurnal/semidiurnal polar motion excited by oceanic tidal angular momentum., J. Geophys. Res., 101, B9, pp. 20151-20163.

Dehant V. and Defraigne P., 1997, New transfer functions for nutations of a non-rigid Earth., J. Geophys. Res., 102, pp. 27,659-27,688.

de Viron O., Bizouard Ch., Salstein D. and Dehant V., 1999, Atmospheric torque on the Earth rotation and comparison with atmospheric angular momentum variations., J. Geophys. Res, 104, B3, pp. 4861-4875.

Guinot B., 1979, in 'Time and the Earth's Rotation', eds. D.D. McCarthy and J.D. Pilkington, D. Reidel Publishing Company, pp. 7.

Herring T.A., 1995, {\it A priori} model for the reduction of the nutation observations., invited paper at JD19 on `Nutation', in: Proc. XXIst GA of IAU 1994, The Hague, The Netherlands, ed. I. Appenzeller, Kluwer Academic Publ., Highlights of Astronomy, Vol. 10, pp. 222-227.

Kinoshita H., 1977, Theory of the rotation of the rigid Earth., Celest. Mech., 15, pp. 277-326.

Kinoshita H., Nakajima K., Kubo Y., Nakagawa I., Sasao T. and Yokohama K., 1979, Note on nutation in ephemerides., Publ. Int. Lat. Obs. Mizusawa, 12, pp. 71-108.

Kinoshita H. and Souchay J., 1990, The theory of the nutation for the rigid Earth model at the second order., Celest. Mech., 48, pp. 187-265.

Mathews P.M., Buffett B.A., Herring T.A. and Shapiro I.I., 1991a, Forced nutations of the Earth: Influence of inner core Dynamics. I. Theory., J. Geophys. Res., 96, B5, pp. 8219-8242.

Mathews P.M., Buffett B.A., Herring T.A. and Shapiro I.I., 1991b, Forced nutations of the Earth: Influence of inner core Dynamics. II. Numerical results and comparisons., J. Geophys. Res., 96, B5, pp. 8243-8258.

Mathews P.M., Buffett B.A. and Herring T.A., 1998, Earth rotation and core modeling: Couplings of the mantle, outer core, and inner core., EGS, Session G12: 03 Effects of the core, Nice, France, April 1998.

Mathews P.M., Buffett B.A. and Herring T.A., 1999, The magnetic coupling contribution to nutation., in: Proc. Journ es Syst emes de R ef erence 1998, Paris, France, in press.

McCarthy D.D., 1996, IERS Conventions., IERS Technical Note 21.

Roosbeek F. and Dehant V., 1998, RDAN97: an analytical development of rigid Earth nutation series using the torque approach., Celest. Mech. Dynamical Astron., 70, pp. 215-253.

Schastok J., 1997, A new nutation series for a more realistic model Earth., Geophys. J. Int., 130, pp. 137-150.

Seidelmann P.K., 1982, 1980 IAU Theory of Nutation: the final report of the IAU working group on Nutation., Celest. Mech., 27, pp. 79-106.

Souchay J. and Kinoshita H., 1996, Corrections and new developments in rigid Earth nutation theory: I. Lunisolar influence including indirect planetary effects., Astron. Astrophys., 312, pp. 1017-1030.

Souchay J. and Kinoshita H., 1997, Corrections and new developments in rigid Earth nutation theory: II. Influence of second-order geopotential and direct planetary effect. Astron. Astrophys., 318, pp. 639-652.

Wahr J.M., 1981, The forced nutations of an elliptical, rotating, elastic and oceanless Earth., Geophys. J. R. astron. Soc., 64, pp. 705-727.

Present statutes and by laws are shown in black
Suggestions by the Cassinis committee are shown as uncerlined text

Because of the ongoing discussion on the IAG structure, it was decided that the Cassinis Committee report would be presented to the Council at Birmingham for information but not for immediate adoption. It would be considered as a base for the continuing discussions on the IAG structure and will be incorperated in the proposal to the Council meeting following Birmingham.

STATUTES AND BY-LAWS

I- *Definition and objectives of the International Association of Geodesy*

1. The *International Association of Geodesy*, hereafter called the Association, is one of the constituent associations of the *International Union of Geodesy and Geophysics*, hereafter called the *Union*.

<u>Unchanged</u>

2. The *objectives* of the Association are :

a) to promote the study of all scientific problems of geodesy and encourage geodetic research;

<u>a) to promote the study of all scientific problems of geodesy, to encourage geodetic research, and to further the education of young researchers,</u>

b) to promote and coordinate international cooperation in this field, and promote geodetic activities in developing countries;

<u>b) to promote and coordinate international cooperation in geodesy and to provide international services,</u>

c) to provide, on an international basis, for discussion and publication of the results of the studies, researches and works indicated in paragraphs a) and b) above.

<u>c) to encourage and support geodetic activities in developing countries,</u>

<u>d) to provide an international forum for the discussion and publication of results which originate from the activities mentioned above</u>

3. To achieve these objectives, the Association shall comprise a small number of Sections, each of which deals with a distinct part of geodesy.

Commissions, Special Commissions and Special Study Groups may be formed as provided in the By-Laws.

<u>Commissions, Special Study Groups, and Services may be formed as provided in the By-Laws. They are normally assigned to one Section. Committees may be appointed according to the By-Laws.</u>

4. Every country adhering to the Union *(Member Country)* may be represented by Delegates to the Association.

a) Scientists may become *Affiliates* of the Association, either as *Fellows* or *Associates*, as provided in the By-Laws.

<u>a) Sientists from member countries may become Affiliates of the Association, either as Fellows or Associates, as provided in the By-Laws. Each member country, through its Adhering Body, shall appoint National Delegates to the Association from the Association Affiliates.</u>

II- *Administration*

5. The *General Assembly* of the Association shall consist of the Delegates of the Member Countries duly accredited by the corresponding Adhering Bodies, as defined in the Statutes of the Union.

<u>The General Assembly of the Association shall consist of the Affiliates.</u>

6. The ***Council*** of the Association shall consist of the *Delegates*, known as Council Delegates, designated for meetings of the Council and formally accredited by the Adhering Body of Member Countries on the basis of one Delegate for each Member Country. Each Council member shall be an Associate or a Fellow of the Association.

<u>The Council of the Association shall consist of the National Delegates, formally accredited by the Adhering Body of the Member Contries, on the basis of one Delegate per country.</u>

No member of the Bureau of the Association shall serve as a Council Delegate of a country. The President of the Association shall preside over the Council meetings, without vote, except in the case of a tie as provided in article 16 hereafter.

7. Responsibility for the direction of the Association affairs shall be vested in the Council of the Association. Decisions of the Council shall be reported to the General Assembly. In the case that the majority of those present at a General Assembly meeting disagrees with the decisions of the Council, the Council shall reconsider the question, and make a decision, which shall be final.

<u>Unchanged</u>

8. Between meetings of the Council , the direction of the affairs of the Association shall be vested in the *Bureau* and the *Executive Committee*, the respective composition and responsabilities of which are defined hereafter.

<u>Unchanged</u>

9. The ***Bureau*** of the Association shall consist of the *President*, the *First Vice-President* and the *Secretary General*, all of whom shall be elected by the Council. The duties of the Bureau shall be to administer the affairs of the Association in accordance with these Statutes and By-Laws and with the decisions of the Council and the Executive Committee.

<u>The ***Bureau*** of the Association shall consist of the *President*, the *Vice-President* and the *Secretary General*, all of</u>

whom shall be elected by the Council. The duties of the Bureau shall be to administer the affairs of the Association in accordance with these Statutes and By-Laws and with the decisions of the Council and the Executive Committee.

10. The ***Executive Committee*** shall consist of the *Bureau*, the *immediate past President* and the *Second Vice-President* of the Association, and the *Presidents of the Sections*.

The Honorary Presidents and the Honorary General Secretaries of the Association, the Presidents of Commissions, the Secretaries of the Sections, the Assistant Secretaries of the Association and the Chief Editor of the Bulletin Geodesique may attend any meeting of the Executive Committee of the Association, with voice but without vote.

The duties of the Executive Committee shall be to further the scientific objectives of the Sections and other scientific bodies of the Association through effective coordination and through the formulation of general policies to guide the scientific work of the Association.

The members of the Executive Committee shall attend meetings of the Council, with voice but without vote.

The Executive Committee shall consist of the Bureau, the past President and the Presidents of the Sections.

The Honorary Presidents and Honorary General Secretaries, the Presidents of the Commissions, the Directors or an appointed representative of the Services, the Chief Editor of the Journal of Geodesy, and the Assistant Secretaries of the Association may attend any meeting of the Executive Committee, with voice but without vote.

The duties ...

III- Voting

11. A Council Delegate may represent only one Member Country.

A Member Country which is not represented at a Council meeting may vote by correspondence on any specific question, provided that matter has been clearly defined on the final agenda distributed in advance to the Member Countries and that the discussion thereon has not produced any significant new considerations or changed its substance, and provided that the said vote has been received by the President prior to the voting.

Unchanged

12. In order that the deliberations of the Council shall be valid, the number of the Council Delegates present must be at least half of the Member Countries represented at the General Assembly of the Union.

Unchanged

13. On questions not involving matters of finance, the voting in Council shall be by Member Countries, each Member Country having one vote, provided that its Union subscriptions shall have been paid up to the end of the calendar year preceding the voting.

Unchanged

14. On questions involving finance, the voting in Council shall be by Member Countries, with the same provision that a voting country shall paid its Union subscriptions up to the end of the calendar year preceding the voting in Council. The number of votes allotted to each Member Country shall then be equal to the number of its category of membership as defined by the Union.

... a voting country shall have paid ...

15. Before a vote in a Council meeting, the President shall decide whether or not the matter under consideration is financial in character and whether the procedure of voting by correspondence applies.

Unchanged

16. Decisions of the Council shall be taken by a simple majority, except as otherwise specified in these Statutes. If a tie should occur in a Council vote, the President shall cast the decisive vote. Simple and two-thirds majorities are determined by the proportion of affirmative votes to the sum of all votes (affirmative, negative and abstention). Bank and invalid ballots and votes not cast by delegates present are counted as abstentions.

Unchanged

IV- General

17. Proposals for a change of any article of the Statutes of the Association must reach the Secretary General at least six months before the announced date of the Council meeting at which it is to be considered. The Secretary General shall notify all Member Countries of any proposed change at least four months before the announced date of the Council meeting.

. ...(to add:) The Cassinis Committee, appointed every 8 years for one period by the Executive Committee in its first meeting after the General Assembly, shall review the Statutes and By-Laws of the Association to ensure an up-to-date structure of its scientific organisation.

18. The Statutes of the Association may not be modified except by the approval of a two-thirds majority of votes cast at a Council meeting.

These Statutes or any further modification of them shall come into force at the close of the Council meeting at which they are approved.

Unchanged

19. The Council shall have the power to adopt By-Laws within the framework of the Statutes of the Association.

These By-Laws may not be modified except by a simple majority of votes cast at a Council meeting.

These By-Laws or any further modification of them shall come into force at the close of the Council meeting at which they are approved.

Unchanged

20. In the event of the dissolution of the Association, its assets shall be ceded to the Union.
Unchanged
21. Conduct of meetings : Except as otherwise provided in the Statutes or By-Laws, business meetings shall be conducted according to Robert's Rules of Order.
Unchanged
22. These Statutes and By-Laws of the Association are set out in French and in English.
The validity of these rules shall not be vitiated by any error of a formal or accidental nature.
Unchanged

II- BY-LAWS

I- Structure

1. The scientific work of the International Association of Geodesy is allocated to *Sections*, the respective responsabilities of which are decided by the Council on recommendation of the Executive Committee. The structure of these Sections shall be reviewed every eight years (two periods) by a committee, called the Cassinis Committee, which shall make proposals to the Executive Committee. Because of the complex interrelations among various activities of the Association, interactions between the individual sections are implied.

The scientific work ... the respecitve responsibilities ... on recommendation of the Executive Committee. Because of the complex interrelations ...

There are at present ***five sections*** which are the following :

- **Section I** : *Positioning*.
. high precision horizontal and vertical networks;
. satellite and spatial positioning;
. inertial positioning;
. kinematic positioning;
. geodetic astronomy;
. marine positioning;
. refraction.

Section 1: Positioning
- terrestrial reference frames
- fiducial and control networks
- crustal deformation networks
- positioning by space and inertial techniques
- marine positioning
- engineering applications of geodesy

- **Section II** : *Advanced Space Technology*.
. development of space techniques for geodesy, such as: satellite radio-tracking techniques, radio-interferometric techniques, satellite and lunar laser ranging, satellite altimetry, satellite-to-satellite tracking, satellite gradiometry, geodetic measurements from space;
. orbital computations;
. direct results of such techniques;
. planetary and lunar geodetic techniques.

Section 2: Advanced space techniques
- development of space methods
- orbital computations
- atmospheric investigations from geodetic space techniques
- planetary and lunar geodesy.

- **Section III** : *Determination of the gravity field.*
. absolute and relative terrestrial gravity measurements;
. non tidal gravity variations;
. determination of the external gravity field and the geoid from gravimetry, gradiometry, geodetic astronomy, space and inertial techniques;
. reduction and estimation of gravity field quantities.

Section 3: Determination of the gravity field
- absolute and relative gravity measurements
- determination of non-tidal g ravity variations
- determination of the external gravity field and its representation, e.g. geoid
- reduction and estimation of gravity field quantities
- planetary and lunar gravity fields.

- **Section IV** : *General Theory and Methodology*.
. General mathematical models for geodesy;
. statistical and numerical analysis;
. data processing and management;
. optimization methods;

. least squares methods;
. differential and integral theories of the gravity field;
. theory of estimation, approximation and representation of the gravity field.
Section 4: Theory and methods
- mathematical methods in geodesy
- statistical and numerical analysis
- estimation and prediction methods
- differential and integral theories of the gravity field
- inverse problem theory.
- **Section V** : *Geodynamics.*
. reference systems;
. monitoring and study of time-dependent phenomena: polar motion, Earth rotation, Earth tides, recent crustal motions, variations of gravity, sea surface topography and mean sea level;
. geodetic aspects of international geodynamic projects;
. planetary and lunar dynamics;
. geophysical interpretation of gravity and related data.
Section 5: Geodynamics
- reference systems
- investigation of global time-dependent phenomena such as earth rotation, earth tides, ice and crustal motions, gravity variations, ice and sea-surface
topography, mean sea level
- planetary and lunar dynamics
- geophysical interpretation of gravity with other data.

1A- Each Section shall set up a ***Steering Committee*** consisting of the Section President, the Secretaries, the Presidents of Commissions and Special Commissions within the Section, and such other persons, who have participated in the work of the Section, as are coopted to the Committee, on the recommendation of the Section President.

1A. Each Section shall set up a Steering Committee, consisting of the Section President, the Presidents of the Commission, the Directors or Representatives of the Services, and the Chairpersons of the Special Study Groups.

2. ***Commissions*** may be formed for activities for which close international cooperation or organization is necessary, in particular for long term problems or activities relating to large regions.
Every Member Country of the Union is entitled to nominate one representative to each Commission, except those dealing with specific geographical areas; to the latter Commissions, only Member Countries of the Union in the geographical area in question are entitled to nominate one representative each.
A Commission is normally assigned to one Section.
Each Commission may be organized according to its own requirements in compliance with the Statutes and By-Laws of the Association and subject to approval by the Executive Committee, for instance through the formation of regional Sub-Commissions.
Commissions may be formed for studying scientific problems and for large-scale activities of long-term character, which require close international cooperation or organization. A Commission is normally assigned to one Section.
Every Member Country is entitled to nominate, through its Adhering Body, one National Representative to each Commission. Members of the Commission are the National Representatives and other scientists
A Commission may be organized according to its own requirements,in compliance with the Statutes and By-Laws of the Association, and subject to the approval by the Executive Committee. This includes the selection of the Commission members, the election of the commission officers except the commission President, the formation of Sub-Commissions for studying dedicated problems or for regional activities, and the establishment of Working Groups for specialized tasks.
Each Commission shall set up a Steering Committee, consisting of the Commission President and the other commission officers.

2A- ***Special Commissions*** may be formed to study scientific problems of a long term character which require close cooperation between specialists from different countries.
A Special Commission is normally assigned to a particular Section. Each Special Commission may be organized to its own requirements in compliance with the Statutes and By-Laws of the Association and subject to the approval by the Executive Committee, for instance through the formation of special Sub-Commissions to study defined aspects in its fields.
Delete

3. ***Special Study Groups*** may be formed to study specific scientific problems of limited scope which require close cooperation between specialists from different countries.
A Special Study Group is normally assigned to a particular Section.
. ... A Special Study Group is normally assigned to a particular Section. Inter-Section Special, Study Groups may be formed, but should be allocated to one leading Section

3A. Committees may be appointed for limited time, for specific tasks or questions of scientific, educational or administrative character. The Committees report to the Executive Committee.

3B. The Association may set up or participate in dedicated Services, which collect, analyze and provide data or information relevant to geodesy. The scientific management of the Service shall be ensured by a Director, under the generalsupervision of a Board. The FAGS rules are applied for a Service being a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).The rules for other IAG Services are given by the By-Laws. A Service is normally assigned to a particular Section.

4. The setting-up and dissolution of the Commissions, the Special Commissions and the Special Study Groups are decided by the Executive Committee which also specifies whether the Commission, the Special Commission or the Special Study Group is to be placed under the direct authority of the Association or of one of its Sections.

The list of Commissions, Special Commissions and Special Study Groups shall be published in the Geodesist's Handbook after each General Assembly.

Setting-up and sissolution of the Commissions, the Special Study-Groups, the Committees and the non-FAGS-IAG-Services are decided by the Executive Committee, which also identifies the internal allocation of these bodies.

5. The Association may also participate in joint scientific bodies with other Associations of the International Union of Geodesy and Geophysics, or, representing this Union with other Unions. These bodies shall be administered according to specific rules proceeding from their relations with other agencies, but they shall report on their scientific work at each General Assembly of the Association.

The Executive Committee of the Association shall decide whether the relationship with any such common body is to be placed under the responsibility of the Association or of one specific Section. This responsibility includes the appointment of representatives to these common bodies as well as participating in the planning of their future activities.

The Association may participate in joint bodies of the Union and other scientific organizations, especially those belonging to the International Council of Scientific Unions (ICSU). These bodies shall be administered according to their specific rules. Their relationship with the Associations will be placed under the responsibility of either the Executive Committee or a specific Section, and handled by the IAG Representatives.

5A. The list of Commissions, Special Study Groups, Committees, Services and joint bodies shall be published in the Geodesist's Handbooks after each General Assembly.

II- Elections.

6. Elections shall take place in the Council during each Ordinary General Assembly of the Association.

The President in office, after taking advice from members of the Executive Committee, shall appoint a *Nominating Committee* consisting of a Chairman and three other members. The Nominating Committee, after taking advice from the Adhering Bodies of the Member Countries and officers of the Association, shall propose a candidate for each position to be filled by election in the Council. Candidates shall be asked to signify their acceptance of nomination and to prepare a resume, maximum 150 words, outlining their position, research interests and activities relating to the Association. The delegates shall be informed of these nominations and the resumes, early in the General Assembly, and a notice posted allowing for submission, over a period of at least 48 hours, of further nominations. Such nominations shall be in writing, shall be supported by at least two members of the Council, and shall be submitted with resumes as described above to the Secretary General. Delegates shall be informed of these further nominations and resumes and of their supporters.

Elections shall be by secret ballot.

No person may hold more than one of the following offices at the same time : President of the Association, Vice-President, President of a Section and President of a Commission and a Special Commission.

Unchanged

7. The time interval between the closures of two successive Ordinary General Assemblies of the Association is called here *a period*.

Unchanged

8. The ***President*** of the Association is elected for one period. He may not be re-elected to this office, but the Council may appoint him as *Honorary President*.

Unchanged

9. The ***First*** and ***Second Vice-President****s* are elected for one period and may not be immediately re-elected to the same office.

Unchanged

10. deleted.

11. The ***Secretary General*** is elected for one period initially. He may be re-elected for two additional single periods.

Unchanged

12. The same rules as in Art. 11 apply to ***Assistant Secretaries***, other than the Assistant Secretary appointed under Art. 37A.

Unchanged

13. A member of the Bureau or of the Finance Committee of the Union may not occupy the post of *President*, of First *Vice-President* or of *Secretary General* of the Association.

Unchanged

14. Should the position of President become vacant in the interval between two Ordinary General Assemblies, his duties devolve to the First Vice-President until the closure of the next Ordinary General Assembly. In the same way the duties of the First Vice-President then devolve on the Second Vice-President.
Should the post of Secretary General become vacant, the President shall arrange without delay for the Executive Committee to elect a replacement by correspondence so as to ensure the continuity of the work of the Central Bureau. This election has effect until the closure of the next Ordinary General Assembly.
... delete from "in the same way ... Second Vice-President.
15. The ***Presidents of Sections*** are elected for one period and may not be immediately re-elected to the same office.
Unchanged
16. The ***Secretaries of Sections*** are elected for one period but may be re-elected for one further period.
The President of each Commission which is in a Section shall be a Secretary of that Section. The maximum number of Secretaries in a Section shall be two, except where the number of Commissions in a Section is greater than one, the number of Secretaries shall then equal the number of Commissions plus one.
Deleeted
17. Should the position of President of Section become vacant between two Ordinary General Assemblies, the Executive Committee shall appoint an interim member to take office until the closure of the next General Assembly. Should other vacancies occur, the Executive Committee may make interim appointments.
Unchanged
18. The ***Presidents of Commissions*** and ***Special Commissions*** are elected by the Council of the Association for one period and may be immediately re-elected for one further period.
The Presidents of Commissions are elected for one period and may be immediately re-elected for one further period.
19. The ***Chairman of a Special Study Group*** is appointed by the Executive Committee for one period only.
add
19A. The Chairperson of a Committee is appointed by the Executive Committee for one period and may be immediately reelected for one further period.
19B. The director of a non-FAGS IAG-Service is appointed for one period and may be reelected.

20. A person may be President or Chairman at the same time of no more than one of the bodies referred to in Arts. 18 and 19.
A person may be President, Chairperson or Director at the same time of no more than one of the bodies refered to in Arts. 18 and 19.
III- General Assemblies.
21. The Association shall hold its own Ordinary General Assemblies in conjunction with the Ordinary General Assemblies of the Union, at the same time and in the same country.
Unchanged
22. Before any General Assembly, a detailed agenda is prepared by the Bureau of the Association. As far as the scientific work is concerned, the agenda is drawn up by the Executive Committee. This agenda is sent to the member countries and to all the officers of the Association so as to reach them at least two months prior to the Assembly. In principle, only matters on the agenda may be considered during the sessions, unless a decision to do otherwise is passed by a two-thirds majority in the Council or in the Executive Committee.
Unchanged
23. At each General Assembly, the President of the Association shall present a detailed report on the scientific work of the Association during his tenure. The Secretary General shall present a detailed report on the administrative work and on the finances of the Association for the same period. They both should submit proposals regarding work to be undertaken during the coming period, within the limits of expected resources.
These reports are handed to the delegates attending the General Assembly before the opening of the Assembly.
... within the limits of expected resources. These reporty are published in "The Geodesist's Handbook".
24. The scientific meetings generally take place Section by Section, but the study of some questions may require joint meetings of several Sections or Symposia under chairmen appointed by the Executive Committee.
Joint Symposia covering topics interesting two or more Associations within the Union may be arranged.
Unchanged
25. At each General Assembly, the work of each Section shall be reported by its President assisted by his Secretaries. Similarly, the work of each Commission, Special Commission or Special Study Group shall be reported by its President or Chairman.
At each General Assembly, the work of each Section shall be reported by its President. The work of each Commission, Special Study Group and Service shall be reported to the Section where it is assigned to. The reports of the Committees and the IAG Representatives are given to the Executive Committee.
26. The inclusion on the agenda of scientific papers for presentation at sessions of the General Assembly is decided by a committee consisting of one member of the Bureau and the Presidents of Sections.
A Screening Committee will be set up by the IAG President in due time, in order to decide about the acceptance of scientific papers for presentation at the Genral Assembly. The Committee consists of one member of the Bureau and the Presidents of Sections

27. Individual authors are responsible for the reproduction of their scientific papers. These papers are distributed to the delegates by the Central Bureau prior to the meeting where they are presented. They may be published in the Bulletin Géodésique subject to its editorial policy.
... They may be published in the IAG Symposia Proceedings or in the Journal of Geodesy...

IV- Publications.

28. The Association's journal is the **Bulletin Géodésique**, hereinafter referred to as the journal. The journal is published at regular intervals, through an agreement between the Association and a publishing company, or by other arrangement approved by the Executive Committee. The terms of any agreement for publication of the journal shall be negotiated by the President and ratified by the Executive Committee.
There shall be one or more *Editors-in-Chief* for the journal, hereinafter referred to as the *Editor.* The Editor shall be advised and assisted by a *Board of Editors*, hereinafter referred to as the *Board*.
The Editor shall be responsible for the scientific content of the journal. All scientific manuscripts shall be subject to a refereeing process and the Editor shall make the final decision on whether a manuscript is accepted for publication. The Editor shall keep the Association informed of the activities and status of operations of the journal.
The Association's official journal is the Journal of Geodesy, ...
The journal is published monthly, ...
The journal publishes peer-reviewed papers, covering the whole range of geodetic science, and contains the IAG Newsletter.
There shall be one Editor-in-Chief for the journal, hereinafter referred to as the Editor. He may be assisted by an Assistant Editor-in-Chief. The Editor shall be advised ...
The IAG Newsletter is under the editorial responsibility of the IAG Central Bureau.
28A. At the time of each General Assembly, the Editor shall, in consultation and agreement with the President of the Association, recommend candidates for membership of the new Board, which is to hold office for the next period. During the Assembly, the current Board shall elect the members of the new Board from those recommended. After taking office, the new Board shall elect one, or more, Editors(s) for the next period. The nomination of the Editor(s) shall be approved by the Executive Committee.
The Editor and the members of the Board, shall each hold office for one period, but shall be eligible to be elected for one further period.
Unchanged
28B. After each General Assembly, a special issue of the Bulletin Géodésique shall be published under the name of ***"Geodesist's Handbook"***. This issue aims at providing detailed information on the Association, its structure and scientific activities, and other relevant technical and administrative information.
28B. After each General Assembly, a special issue of the Journal of Geodesy shall be published under the name of "The Geodesist's Handbook". This issue provides the actual information on the Association, including the reports of the President and Secretary General presented at the previous General Assembly, the resolution taken at that Assembly, and the Associations' structures for the running period, as well as relevant scientific and administrative information.
29. After each General Assembly, a collection of the reports presented by the Sections, Commissions and Special Study Groups shall be published in the ***"Travaux de l'Association Internationale de Géodésie"***. This publication is supplied free of charge to the Officiers of the Association and to the Adhering Body of each Member Country.
Unchanged
30. The Association also issues ***special publications*** which contain information on recommended standards in geodesy.
Delete
30A Proceedings of the Association's Symposia may be published in the International Association of Geodesy Symposia Series. The Series Editor is the President of the Association, with the Symposia Convenors acting as Editors. All manuscripts are subject to a refereeing process, and the Editor shall make the final decision on whether a manuscript is accepted for publication.
31. At every General Assembly each Member Country of the Union is invited to supply an adequate number of copies of its National Report on geodetic work done since the previous General Assembly. These **National Reports**, as far as available, are distributed by the Central Bureau of the Association in the same manner as the "Travaux de l'Association Internationale de Géodésie".
Unchanged

V- Administration.

32. The ***Council*** of the Association shall :
a) examine questions of general scientific policy or administration in the business of the Association and appoint such Committees as may, from time to time, be deemed necessary for this purpose;
b) elect the members of the Bureau and of the Executive Committee, the Assistant Secretaries of the Association, the Secretaries of Sections, the Presidents of Commissions and of Special Commissions;
c) receive reports from the Secretary General and consider for approval the decisions or actions taken by the Bureau and the Executive Committee since the last Council meeting;
d) appoint the three members of the ad hoc committee created for examining the finances of the Association, consider its recommendations and adopt the final budget;
e) consider proposals for changes in the Statutes and By-Law;

The Council is convened by the President of the Association. It shall normally meet during the Ordinary General Assemblies.
The Council of the Association shall
a) examine questions of general scientific policy or administration, and propose actions deemed necessary;
b) ... delete: "The Secretaries of Sections" ... "and of Special Commissions".
c) - e) unchanged.

33. The ***Executive Committee*** of the Association shall :
a) initiate actions and issue guidelines, as required, to guide the Association towards the achievement of its scientific objectives;
b) fill vacancies occuring between General Assemblies, in accordance with the present Statutes and By-Laws;
c) set up and dissolve Commissions, Special Commissions and Special Study Groups;
d) appoint Chairmen of Special Study Groups, and approve the election of the Editor(s) in Chief of the Bulletin Géodésique;
e) appoint members of the Cassinis Committee;
f) make recommendations to the Council on matters of General policy of the Association and on the implementation of its objectives;
g) on the recommendation of the Bureau, appoint Fellows and Associates of the Association. Past officers of the Association, including those of the Commissions and sub-Commissions, shall be eligible for appointment as Fellows and shall be invited to become Fellows of the Association. Persons elected as officers of the Association or nominated as members of Commissions, Special Commissions of Special Study Group, shall automatically become Associates of the Association. Persons from Member Countries who apply, indicating previous participation in Association activities, or providing a recommendation from their national Adhering Body or a recommendation from an officier or a Fellow of the Association, shall be eligible to become Associates, and shall be recommended by the Bureau.
The Executive Committee is convened by the President of the Association, it shall meet at General Assemblies and its members shall attend the meetings of the Council, with voice but without vote. It shall also meet normally at least once betwen General Assemblies, one year ahead of the General Assembly, in order to prepare the scientific agenda and the time-table during the next General Assembly.
At a meeting of the Executive Committee, no member may be represented by any other person, except a President of a Section who may be represented by a Secretary of his Section. In order that the deliberations of the Executive Committee shall be valid, half at least of its members must be present or represented.
The agenda for each meeting of the Executive Committee shall be prepared by the Bureau and sent to the members at least three months prior to the meeting.
The Executive Committee of the Association shall:
a) unchanged
b) unchanged
c) set up and dissolve Commissions, Special Study Groups, Committees, and IAG-Services, and approve their internal structure;
d) appoint the Chairperson of the Special Study Groups, the Committees and the Directors of the non-FAGS IAG-Services; the members of the Cassinis Committee, and the IAG representatives to joint bodies, the latter shall be appointed for one period and may be reappointed for one further period;
e) approve the election of the Editor-in-Chief of the Journal
f) unchanged
g) ... including those of the Commissions and IAG-Services, shall be ... persons elected as officers of the Association or nominated as members of commissions, Special Study Groups and Committees shall automatically ... next General Assembly.
The Executive Committee has the right, to establish a Fund (IAG Fund) for supporting specific IAG activities as defined in the Fund Rules, to be published in the Geodesist's Handbook. The Fund is under the direct responsibility of the President, the Fund fortune is administerd by the Secretary General.
The Executive Committee may establish awards for outstanding contributions to geodesy and distinguished service to the Association. The Rules for the awards are published in the Geodesist's Handbook.
At a meeting of the Executive Committee, no member ... except a President of Section who may be represented by the President of a commission assigned to his Section ...
34. The ***Bureau*** of the Association shall :
a) draw up the agenda of the meetings of the Council and Executive Committee;
b) ensure the adequate administration of the Association. It shall normally meet before each meeting of the Executive Committee.
Unchanged
35. The ***President*** of the Association shall :
a) be the representative of the Association in its dealing with National or International Organizations or Institutions;
b) convene and preside over the General Assembly and over all meetings of the Council, Executive Committee and Bureau;

c) submit a report to the General Assembly on the scientific work of the Association during his tenure;
He is a member of the Executive Committee of the Union. In case of his absence, the *First Vice-President* shall act.
delete: "He is a member of the Executive Committee of the Union"
36. The ***Secretary General*** shall :
a) serve as secretary of the General Assembly, the Council, the Executive Committee and the Bureau: arrange for meetings of these bodies, prepare and distribute promptly the agenda and the minutes of all their meetings;
b) be the Director of the Central Bureau;
c) manage the affairs of the Association, attend to correspondence, preserve the records;
d) circulate all appropriate information related to the Association;
e) prepare the reports on the Association's activities, especially report to the General Assembly on the administration and the finance of the Association during the current period;
f) perform such other duties as may be assigned to him by the Bureau.
Unchanged
37. To assist the Secretary General in the performance of his duties to the Association, the Association establishes a permanent agency, the Central Bureau, including a variable number of employees paid out of Association funds.
The Secretary General is also assisted by a small number of *Assistant-Secretaries*, one of whom is located in the same office as the Secretary General. All these functions are unpaid and only expenses incurred in connection with them are repayable.
To assist the Secretary General, the Association established the Central Bureau, after invitation from the host country.
37A. An additional *Assistant Secretary* to be known as the *Assembly Secretary* may also be appointed by the Council on the recommendation of the Adhering Body of the country in which the next General Assembly takes place. If this procedure is not feasible then the Council may delegate the appointment to the Bureau.
In cooperation with the Central Bureau, this Assistant Secretary has responsibilities for liaison with the organizers working on the preparation of the General Assembly. This Assistant Secretary shall be appointed for one period only.
Assistant Secretaries may be appointed by the Executive Committee ...

IV- Activities of Sections, Commissions, Special Commissions and Special Study Groups.

38. The ***President of a Section*** is responsible for the scientific development within the area of his Section and is the representative of his Section on the Executive Committee of the Association. Working closely with the Steering Committee he shall encourage, guide and coordinate the work of the Commissions, Special Commissions and Special Study Groups within his Section, and in particular keep the officers of his Section as well as the Bureau of the Association informed of the Section's activities, on an annual basis.
It is desirable the the President of a Section, or else one of the Secretaries of the Section, should attend each of the Symposia related to the section.
Before each General Assembly the President of a Section shall receive the reports of the Commissions, Special Commissions and Special Study Groups within his Section and, assisted by the Steering Committee, prepare a report on the activities of the Section to be presented at the General Assembly.
He shall receive suggestions for new Special Study Groups, and suggestions for continuation of existing Special Study Groups under Art. 43, and, after consulting his Section Steering Committee, shall coordinate them and transmit his recommendations to the Executive Committee.
Each ***Section Steering Committee*** shall meet at least once during each Ordinary General Assembly and on at least one other occasion during the period. At the General Assembly meeting, or on some other appropriate occasion, the Steering Committee shall review the activities of Commissions, Special Commissions and Special Study Groups over the past period, and for those which will be recommended for continuation, review their programmes for the forthcoming period.
The ***Section Secretaries*** assist the Section President in his duties.
. ... coordinate the work of the bodies assigned to his Section, and in particular ...
He prepares the Terms of Reference for his Section, to be published in The Geodesist's Handbook.
It is desirable that either the President or a Commission President of a Section attend the Symposia related to the Section.
Before each General Assembly ... reports of the bodies assigned to his Section, and prepare a report on the Section's activities to be presente at the GeneralAssembly.
He shall receive suggestions for new Commissions, Special Study Groups and Services, and suggestions for ...
The Section Steering Committee shall meet at least once during each GeneralAssembly ... At the General Assembly, or on some other ... review the activities of the bodies assigned to the Section over the past period, and ... delete: "The Section Secretary assists the Section President in his duties."
39.The ***President of a Commission*** is responsible for initiating and directing its work and selecting its members, apart from those representatives of Member Countries appointed under Art. 2.
The President of each Commission shall issue a brief description of the work to be performed and a list of members, to be published in the Geodesist's Handbook after each General Assembly.
To assist communication and cooperation within each Commission, members should be informed, on an annual basis, of results achieved and of outstanding problems.
The President of a Commission working closely with the Steering Committee, is responsible for initiating and directing

its work, for the formation of Sub-Commissions and Working Groups, and for selecting its members apart from the National Representatives appointed according to Art. 2. The number of selected Commission members should not exceed 30.
The president ...
The Commission Steering Committee should work in an analogous way asdescribed for the Section Steering Committees under Article 38.
39A. The ***President of a Special Commission*** is responsible for initiating and directing its work and selecting its members. Special Commission membership should be balanced so as to reflect international cooperation in the subject and shall be limited to a member not exceeding 30.
The President of each Special Commission shall issue a brief description of the work to be performed and a list of members, to be published in the Geodesist's Handbook after each General Assembly.
To assist communication and cooperation within each Special Commission, members should be kept informed, on an annual basis, of results achieved and of outstanding problems.
Delete
40. The ***Chairman of a Special Study Group*** is responsible for initiating and directing its work and appointing its members. Special Study Group membership should be balanced so as to reflect international cooperation in its subject and shall be limited to a number exceeding 20.
The Chairman of each Special Study Group shall issue a brief description of the work to be performed and a list of members, to be published in the Geodesist's Handbook after each General Assembly.
To assist communication and cooperation within each Special Study Group, members should be kept informed, on an annual basis, of results achieved and of outstanding problems
The Chairperson of a Special Study Group ... a number not exceeding 20.Corresponding members may be selected
40A. new: The Chairperson of a Committee is responsible for directing its work and selecting its members, except for the Committee where according to the Statutes and By-Laws, the members are selected by other IAG bodies.
The Chairperson of the Committee should keep the Executive Committee of the Association informed on the Committee's activities, on a biannual basis. The Chairperson shall prepare a report to be presented at the
40B. new: The Director of a Service is responsible for directing its work according to the Service rules. He should keep the responsible Section informed on the Service activities, on a biannual basis. The Director should prepare a report to be presented at the General Assembly.
41. The President of the Association, the Central Bureau and the President of the relevant Section should receive copies of all official correspondence and of notices to members of Commissions, Special Commissions and Special Study Groups.
The Central Bureau should receive copies of all relevant correspondence of Sections, Commissions, Special Study Groups, Committees and Services.
42. The reports of each Commission, Special Commission and Special Study Group should reach the President of each relevant Section at least three months before each General Assembly. These reports and the reports of the Sections are published in the "Travaux de l'Association Internationale de Géodésie".
The reports of Commissions, Special Study Groups and Services should reach the President of the relevant Section at least three months ... The reports of Committee should reach the President of the Association at least three months before each General Assembly, if not otherwise stated, these reports and the reports of the Sections are published in ...
43. The period of work of each Special Study Group normally ends at an Ordinary General Assembly. In the exceptional case that a continuation of the work is deemed necessary, the Special Study Group Chairman shall submit in writing a well-grounded proposal, including a suggestion for his successor, to his Section President, at least three months before the General Assembly. The Section President shall then make a recommendation to the Executive Committee.
Unchanged
44. Commissions, Special Commissions and Special Study Groups not assigned to one Section shall be under the responsibility of the President of the Association.
Delete
45. Commissions, Special Commissions and Special Study Groups are free to hold workings of their members. If they wish to arrange scientific Symposia, these are subject to the usual approval procedure for Symposia of the Association. Symposia should be arranged only if the topic transcends the frame of one Commisson, one Special Commission or one Special Study Group.
Commissions, Special Study Groups and Committees are free to hold scientific meetings. Scientific Symposia are subject to the approval procedure of the Association. A scientific Symposium has to be sponsored by one or more Commissions or by at least two Special Study Groups.

VII- Symposia.

Articles 46-50 have to be revised completely, in connection with the Rules for IAG Scientific Meetings, published in The Geodesist's Handbook pp. 866-868.
46. The Association may organize scientific Symposia to study particular questions of wide interest.
See remark above article 46

The Executive Committee is responsible for a balanced selection of Symposia, to ensure a representative coverage of subjects and a good geographical distribution and to avoid duplication, overlap and undue frequency.
Symposia sponsored by the Association shall be freely open to all scientists, in accordance with ICSU regulations.
47. Normally applications for Symposia to be held in the period between two Ordinary General Assemblies should be submitted by the Host Organization to the Secretary General before the General Assembly preceding that period.
During this General Assembly other applications may be submitted to the Secretary General at least two days before the last meeting of the Council.
The Council, on recommendation of the Executive Committee, shall decide whether the Symposium in question will be sponsored by the Association.
In exceptional cases, the Executive Committee may approve late applications. Such applications must be submitted at least 18 months before the proposed date for the Symposium.
See remark above article 46
48. The Symposium Organizer must send an official announcement of the Symposium to the Bulletin Géodésique at least one year in advance or immediately after the approval by the Association; the announed date of the Symposium must not be changed later.
See remark above article 46
49. Within three months after, the Symposium Organizer shall provide a report to be published in the Bulletin Géodésique. This report should indicate whether, where, and when the Proceedings will be published. A Copy of the Symposium Proceedings, or else one copy of each paper presented at the Symposium, shall be sent to the Central Bureau of the Association.
See remark above article 46
50. Sponsorship by the Association means only official recognition and does not imply financial support.
See remark above article 46

VIII- International Sientific Cooperation.

51. The Association may undertake directly, supervise or cooperate in scientific work of an international or interdisciplinary character. As a matter of principle, the Association should be represented at Congresses, International Meetings, General Assemblies, etc... of scientific organizations whose activities are connected with its own. The President of the Association or its designate will be the representative of the Association at these meetings.
Travelling and accommodation expenses of the Delegate of the Association may be charged, in whole or in part, to the Association. The Delegate shall prepare a report of the meeting, including the discussions relating to geodesy, which may be published, in whole or in part, in the Bulletin Géodésique.
The Association may also represent the Union in inter-Union Commissions or special joint Committees dealing with topics that are related to its own studies.
Elections of Association or Union geodetic representatives to those permanent bodies shall be made by the Executive Committee. These representatives shall be elected for one period and may be re-elected for one further period.
The Association should initiate and cooperate in scientific work of international and interdisciplinary character. This includes the adequate participation in international programs and projects and the representation at scientific Congresses, Symposia etc. of organizations with related activities. The President of the Association decides on the proper participation or representation.
The Representatives to international programs and projects should keep the IAG President informed on the activities, on a biannual basis. The Representatives shall prepare a report to be presented at the General Assembly. The Representatives to scientific Congresses etc. shall prepare a report to be published in the Journal of Geodesy.

IX- Finance.

52. The *funds* of the Association derive from :
a) the contributions of the member countries of the Union of which a proportion, determined by the Council of the Union on recommendation of its Finance Committee, is paid to the Association by the Treasurer of the Union;
b) the sale of publications;
c) any other source (including grants, donations, interest, funds remaining after a symposium, etc...).
Unchanged
53. The Secretary General is responsible to the Bureau of the Association and to the Council for managing the funds in accordance with the Statutes and By-Laws, with the decisions of the Council and with the recommendations of the Finance Committee of the Union.
The Secretary General alone shall responsible for control of the financial operations of the Association; however for each bank account of the Association, there shall be one Assistant Secretary who shall also have access to the account.
. ... the Secretary General alone shall be responsible for ...!
54. At each Ordinary General Assembly of the Association the budget proposal for the ensuing period shall be presented by the Secretary General and submitted for approval to the Council.
The budget as approved by the Council shall be implemented by the Secretary General.
During the next Ordinary General Assembly, the Council shall examine all expenditures to ensure that they were in accordance with the proposals previously approved. The Council shall appoint an *ad hoc* committee for carrying out this examination in detail.

In addition, these accounts shall be audited by a qualified accountant and shall then be reported to the Treasurer of the Union, as prescribed in Art. 20 of By-Laws of the Union.
<u>Unchanged</u>

GALOS

by B.G.Harsson, Norway

GALOS (Geodetic Aspect of the Law of the Sea) is a committee organized under IAG. As expressed in the name, the committee is working on geodetic subjects related to the United Nations Law of the Sea.

GALOS was formal established as a Special Study Group in IAG, Edinburgh 1989, with Petr Vanicek, Canada, as chairman.

1995 - The 4th technical meeting with IUGG General Assembly in Boulder, Colorado, USA; GALOS becomes a Committee of IAG, with the mandate of looking into Geodetic Aspects of the Law Of the Sea (GALOS). These aspects consist of positioning, datum considerations, uncertainties and time variations in position, i.e., they are encountered in maritime boundary delimitations and enforcement. Close cooperation with the International Hydrographic Organization (IHO) has been sought right from the beginning and put in place already in 1990.

1996 - Bali II. 2nd International Conference, Putri Bali Hotel. Nearly 100 participants from 20 countries. Lawyers, geodesists, hydrographers and oceanographers presented 34 papers.

1997 - The 5th technical meeting with IAG Scientific Assembly in Rio. Bjørn Geirr Harsson, Norway, succeeded to the chairmanship after Petr Vanicek.

1998 - The 6th technical meeting in Fredericton, Canada.

1999 - GALOS is given responsibility for one session under the ABLOS conference in Monaco 9 - 10 September 1999. Papers to be presented at GALOS session in the conference is already filled up.

REPORT OF THE IAU/IAG/COSPAR WORKING GROUP ON CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS OF THE PLANETS AND SATELLITES: 1994

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(Received: 22 November 1995; accepted: 22 December 1995)

Abstract. Every three years the IAU/IAG/COSPAR Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites revises tables giving the directions of the north poles of rotation and the prime meridians of the planets, satellites, and asteroids. Also presented are revised tables giving their sizes and shapes.

Key words: Cartographic coordinates, rotation axes, rotation periods, sizes, shapes

This working group has terminated and the rest of this document is available in
Celestial Mechanics and Dynamical Astronomy 63: 127-148, 1996.

M. Bursa

REPORT TO IUGG ON ANTARCTIC GEODESY 1995-1999

International cooperation in Antarctic Geodesy is principally coordinated by the Scientific Committee on Antarctic Research (SCAR) through its Working group on Geodesy and Geographic Information (WG-GGI). Membership consists of representatives of all SCAR Antarctic nations and the WG-GGI has two programs :

- Geographic Information
- Geodesy

Geodesy is implemented through the Geodetic Infrastructure of Antarctica (GIANT) program. Details of the GIANT work program are available on the WG-GGI web site http://www.scar-ggi.org.au/geodesy/giant.htm. The main geodetic activities in Antarctic in the four-year period 1995-99 were :

- Increase in number of permanent GPS sites transmitting data back by satellite and submitting this data to the IGS.
- Adoption of ITRF and GRS80 as reference standards
- Continued epoch campaigns for geodynamics and to densify the ITRF
- Establishment of Absolute gravity stations
- Re activation of VLVBI facilities at Syowa
- Installation of several new tide gauges
- Technological developments in support of continuous GPS tracking at remote sites

In 1995 Germany took over coordination responsibility from Australia for the summer epoch campaigns beginning with the GAP95 survey. This principally focused on the geodynamics of the Antarctic Peninsula and sites occupied are shown in Figure 1.

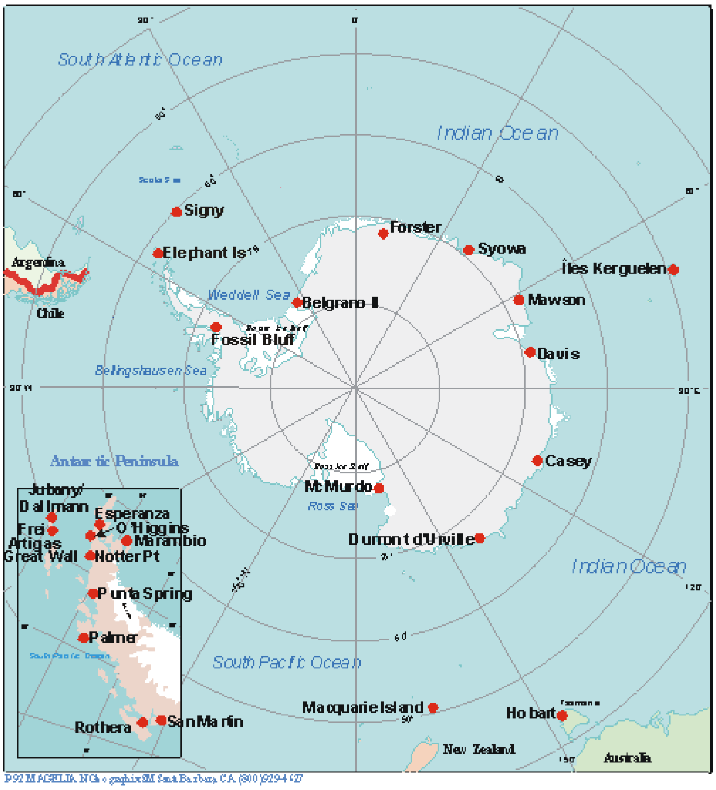

Figure 1. GAP95 Observational Sites

Germany has continued to coordinate the ongoing summer epoch campaigns since that time . The sites occupied in each operational phase are summarised in Table 1below.

4-ID	Station name	Station owner	95	96	97	98	99
ARCT	Arctowski	Poland					x
ART1	Base Artigas	Uruguay	x	x	x	x	
BEL1	Belgrano	Argentina	x				
BELG	Belgrano	Argentina				x	
CUR1	Curitiba	Brazil	x	x			

DAL1	Jubany/ Dallmann	Argentina/ Germany	x	x	x	x	
DALL	Jubany/ Dallmann	Argentina/Germany				x	x
DUM1	Dumont d'Urville	France	x	x			
ELE1	Elephant/Gibbs Islands	U.K.	x			x	
ESP1	Esperanza	Argentina	x	x		x	
FAL1	Falkland	U.K.	x			x	
FOR1	Forster	Germany	x			x	
FOR2	Forster	Germany		x			
FOS1	Fossil Bluff	U.K.	x	x		x	
GOUG	Gough Island	South Africa				x	x
GRW1	Great Wall	China	x		x	x	x
GRY1	Grytviken	U.K.				x	
HAAG	Haag Nunatak	U.K.		x			
HAR1	Hartebeesthoek	South Africa	x	x		x	
KOH1	Kliment Ohridski	Bulgaria				x	
KOTA	Kottas Berge	Germany				x	
MAR1	Marambio	Argentina	x	x		x	
MON1	Montevideo	Uruguay	x	x	x	x	x
NOT1	Notter Point		x			x	
OHG1	O'Higgins	Chile/Germany	x	x	x	x	
PAL1	Palmer	U.S.A.	x	x		x	
PALM	Palmer	U.S.A.				x	x
PET1	Peter I					x	
PRA1	Arturo Prat	Chile	x	x		x	
PUN1	Punta Arenas	Chile	x	x		x	
RIG1	Rio Grande	Argentina	x				
ROT1	Rothera	U.K.	x	x		x	
SAN1	Santiago	Chile	x				
SAN2	Santiago	Chile				x	
SIG1	Signy	U.K.	x			x	
SMR1	San Martin	Argentina	x			x	
SPR1	Punta Spring	Chile	x			x	
SYO1	Syowa	Japan	x				
SYOG	Syowa	Japan		x			x
TNB1	Terra Nova Bay	Italy		x		x	
TROL	Troll	Norway			x		
VER1	Vernadsky	Ukraine				x	
VESL	Sanae	South Africa				x	x
WASA	Wasa	Sweden			x		
ZSS4	Zhong Shang	China			x	x	x

Table 1. GPS sites occupied in SCAR Epoch campaigns 1995-1999

The current situation with the establishment of continuous GPS installations is shown below as Figure 2

Remotely operating sites
Currently the technology available to support remotely operating sites is being extended with aim of being able to utilise continuous observations at remote sites across Antarctic to better study the surface geodynamics of the Antarctic crustal blocks. Researchers asssociated with JPL have trial sites operating in the Transantarctic Mountains, Marie Bryd Land and MacRobertson land. Although continuous GPS receivers have traditionally been used only at manned stations or short (attended) epoch occupations in the summer campaigns. Remotely operating sites have not been able to be deployed during the Antarctic winter, due to problems with power and data transmissions at unattended sites.

THE GEODETIC INFRASTRUCTURE OF ANTARCTICA (GIANT) PROGRAM

Background

At the XXII SCAR meeting in 1992, a proposal for a Geodetic infrastructure of Antarctica (GIANT) program was endorsed. The objective was to establish a precise network of points on rock sites across Antarctica, connected by space geodesy techniques, which would enable existing data based on local geodetic datums to be directly related to produce a common geographical spatial database of compatible scientific information. This geodetic infrastructure will enable earth science investigators involved in individual disciplines (such as geodynamics, oceanography, geophysics, glaciology and geodesy.) to monitor temporal changes in horizontal and vertical positions, including sea level, relative to a fixed geocentric reference system which is traceable over a period of decades. The geodetic network will provide the spatial framework for use by scientists based on rock sites and as a reference platform for moving ice cap studies. This undertaking was collectively identified as the Geodetic Infrastructure for Antarctica (GIANT) program. The program has been reviewed every two years the latest being during the XXV SCAR meeting in Concepion in 1998

The GIANT program objectives are to:

- Provide a common geographic reference system for all Antarctic scientists and operators.
- Contribute to global geodesy for the study of the physical processes of the earth and the maintenance of the precise terrestrial reference frame
- Provide information for monitoring the horizontal and vertical motion of the Antarctic.

There are now seven key elements in the GIANT Program. These elements are summarised below for the current period 1998 to 2000.

1. Permanent Geodetic Observatories (Project Leaders: John Manning, Australia, Hans Werner Schenke, Germany)
Goal: To develop an infrastructure of permanent geodetic stations to bring all individual geodetic networks to a common datum, and to provide geodetic information for the global monitoring of natural earth processes.
Key activities:

- Collaborate with other SCAR scientists to identify requirements for space geodetic sites In conjunction with SCAR working groups design an extended network of continuous geodetic observatories;
- for manned stations
- for remote locations
- Support continuation of O'Higgins VLBI for scientific purposes and as an important contribution to the global reference frame
- Establish priorities for on-line satellite data retrieval from ground stations
- Deliver regular space geodesy solutions to IGS and IERS
- Post details of all permanent sites on web site
- Develop and publish GPS base station specifications
- Evaluate accurate local ties between collocated techniques
- Facilitate tide gauge data to Southern Ocean Sea Level Centre

2. GPS Epoch Campaigns (Reinhard Dietrich, Germany, Andres Zakrajsek, Argentina, Kevin Dixon, UK, Michel Le Pape, France, E Dongchen, China, Hector Rovera, Uruguay, Alessandro Capra)
Goal: To densify the geodetic infrastructure established from the permanent observatories. This will includes links to individual geodetic networks, tide gauges and the computation of surface movement vectors within a common Antarctic reference frame.
Key activities:

- Establish guidelines for ground mark monuments
- Co-ordinate annual epoch campaigns
- Arrange orderly data archive and data access from these campaigns
- Undertake GPS connections to Tide gauge benchmarks
- Deliver results to ITRF in conjunction with results from permanent observatories
- Notify results of each campaigns occupations

3. Physical Geodesy (Alessandro Capra, Italy, Lars Sjoberg, Sweden, Andres Zakrajsek Argentina, Hans Werner Schenke, Germany, John Manning, Australia)

Goal: Collection and analysis of physical geodesy data, for the development of a new high resolution Geoid for the Antarctic.
Key activities:

- The collation of extensive data holdings related to topography, bathymetry and gravity as essential inputs to Geoid computation, includes:
- Data collection and analysis of gravity related data ground/airborne/satellite data.

– Collect relevant data from satellite altimetry
– Collaboration with International Geoid Service (IGES) and International association of Geodesy (IAG)
– Collaboration with SCAR WGs Solid Earth Geophysics, Geology, Glaciology
– Collaboration with BEDMAP, ADGRAV, RAMP as data for Geoid computation
– Participate in the ADMAP meeting and Earth Science in Antarctic, NZ, in 1999
– Preparing data base of information from collated information prior to computation
– Evaluation of EGM96 improvement over OSU91 in Antarctica
– Facilitate computation of improved tidal models
– Prepare for computation of high resolution Geoid model
–

4. GLONASS Evaluation (John Manning, Australia, Larry Hothem, USA)

Goal: Evaluate the benefit of GLONASS for global geodesy, Antarctic geodesy and navigation applications in Antarctica.
Key activities:
– Participate in the International GLONASS Experiment (IGES) pilot project with dual frequency GLONASS instruments at IGS collocated sites
– Retrieve data by satellite for analysis
– Analyse GLONASS orbits, reference frame differences and ground positions for geodesy and navigation applications in Antarctica
– Participate in presentation of IGEX results 1999
– Report on use of GLONASS for Antarctic Geodesy and navigation.

4. **Differential GPS Base Stations** (Larry Hothem, USA, Hans Werner Schenke, Germany, IHO, Kevin Dixon, UK, Jan Cisak, Poland, Alessandro Capra, Italy)

Goal: To increase the utility of Geodetic GPS base stations by making DGPS corrections available for radio transmission for scientific field and operational use.
Key activities:
– Identify global standards for use in marine DGPS transmission using Geodetic base stations
– Develop options for base station sites for shipping navigation coverage of Antarctic Peninsula.
– Examine DGPS for real time kinematics and aviation applications in Antarctica and combination with geodetic accuracy base stations
– Liaison with COMNAP regarding transmission of GPS corrections at base stations.

5. **Remote Geodetic Observatories** (Larry Hothem, USA, Alessandro Capra, Italy, John Manning, Australia)

Goal: To deploy GPS equipment at unattended remote Antarctic localities for regional densification of geodetic infrastructure, and for scientific studies of surface geodynamics. This requires remote power input and data retrieval. This technology is not quite available at present and needs further development.
Key activities:
– Monitor and report on use of solar, wind and other methods of power generation for data logging information at remote GPS sites
– Monitor developments for remote retrieval of GPS data from remote sites by satellite communication techniques
– Collaboration with non-SCAR researchers

6. **Information Access** (John Manning, Australia, All members of GIANT program)

Goal: To publicise and distribute results of GIANT activities to the general Antarctic community.

Key activities:
– Prepare general papers on GIANT activities for publication.
– Ensure ready access to data from permanent observatories from host databases
– Establish cross links from WG-GGI web site to individual geodetic sites
– Develop DIFs for geodetic data in conjunction with JCADM
– Establish newsletter/newsgroup communication for information distribution on Web
– Monitor web posting of photo identifications on web sites
– Continue interaction with representatives on SCAR working Groups
– Develop IAG Commission X sub Commission on Antarctic Geodetic networks

– Publish WGS84-ITRF information paper and circulate within SCAR (SCAR Bulletin)
– Arrange an Antarctic Geodesy Symposium (AGS99) in Europe at the time of IUGG 1999.

CURRENT ACTIVITIES OF THE GIANT PROGRAM

The WG-GGI normally meets every two years during the SCAR meetings. An inter-period Geodesy symposium or GIANT business meeting is usually held to report on progress. In the period 1995-99 work has continued in all program. The WG-GGI website (www.scar-ggi.org.au/geodesy/giant.htm) has been populated with details of the current status of Antarctic Geodetic observatories for :

- Continuous GPS installations
- Permanent Tide Gauge installations
- Absolute gravity fundamental sites
- DORIS sites
- VLBI sites

These activity summaries are shown below as extracts from the WG-GGI web site:

Figure 2 Continuous GPS tracking sites

Figure 3: Tide Gauges

Figure 4: Absolute gravity sites

Figure 5: VLBI sites

Figure 6: DORIS sites

The current activities of GIANT can be summarised as:

Permanent sites
Antarctica is important in a global geodesy sense. Global Geodesy models have heavily relied on observations from Northern Hemisphere sites and the results do not always fit in the Southern Hemisphere or represent the best global picture. Antarctic geodetic observatories provide data to rectify this imbalance with some continuous GPS sites using satellite data retrieval systems to make their data available to the IGS database. Data is available from other sites only by annual manual downloads. The status of the permanent observatories is shown in figure 2.

Epoch campaigns

Germany coordinated the GPS Epoch campaigns for the past five years of summer epoch campaigns 1995 to 1999. The objective has been to densify the ITRF beyond the fiducial network of permanent GPS stations. Details of the 1995 campaign are given in Dietrich et al (1996) and the sites occupied that time are shown in Figure1 above**.** The complete list to sites occupied during the five-year period is summarised in Table 1. Data is available through University of Dresden (Dietrich@ipg.geo.tu-dresden.de)

Geoids
An accurate definition of the geoid is severely constrained in Antarctica by the lack of gravity information, especially across the inland of the continent. Australia produced early versions of the Antarctic Geoid based on GEM and OSU gravity data sets, which are available on the AUSLIG web site http://www.auslig.gov.au/geodesy/antarc/antgeoid.htm. The current situation with the geoid in Antarctica remains hampered by the continuing lack of ground gravity data.
A grid of geoid separation values initially from the OSU91A geopotential model and subsequently from the recent EGM96 are available on the AUSLIG webs site for individual interpolation for any location south of 60 degrees latitude This enables GPS users to refer their observed elevations (ellipsoidal values) to a nominal sea level surface, although the N values are limited by the amount of data in the Antarctic region
The gathering of geophysical data to improve the Antarctic Geoid is a major undertaking and data collection is being undertaken cooperatively with other groups through the newly formed SCAR Neo Antarctic Group of Specialists (ANTEC) and the BEDMAP, ADGRAV and RAMP projects.

GLONASS
GLONASS observations were undertaken in collocation with GPS at McMurdo in January /February 1999. A results seminar will be held as part of ION 99 conference in Nashville in September. A report on Antarctic applications will be prepared following this seminar.

DGPS applications
The current DGPS de facto standard for base stations is that used by the United States Coastguard for its base stations. These base stations specifications are recommended for use in the GIANT Program. Details are available on the web site (www.navcen.uscg.mil/dgps/dgeninfo/dgpsant.htm). The WG-GGI has investigated the establishment of DGPS transmission base stations along the Antarctic Peninsula. With three well distributed sites DGPS accuracies of better than two metre would be available to all shipping along the Eastern side of the Peninsula a significant safety measure.
The recommended sites are:
- King George Island
- Palmer
- San Martin or Rothera

This would also produce a significant benefit for aviation in the region and could also be used by scientists for fieldwork with hand held receivers. Eventually this DGPS transmission network would be extended through liaison with COMNAP to other manned stations around the continent during shipping or aviation activities.

Remotely operating GPS sites
At present there is a technological limitation on operating and maintaining remote placed continuous GPS equipment which need to be to be self powered and able to transmit data back to manned bases or directly by satellite to global data centres. Technological developments are continuing and ANTEC has arranged a special seminar at Pasadena USA in August 1999 to discuss the state of the technology for remote power and data transmissions for remote GPS sites.

Antarctic research symposia
There have been a number of recent Antarctic Geodesy events held including:
- IAG Scientific Assembly Rio 1997
- Antarctic Geodesy Symposium98 Santiago July 1998
- AGU San Francisco December 1998
- EUG10 Strasbourg March 1999

– EGS 99 The Hague April 1999

There will be an Antarctic Symposium arranged in conjunction with ANTEC during the European Geophysical Symposium in Italy in April2000 and a splinter GIANT meeting may be held at that time to incorporate Scandinavian and Russian geodesists.

GROUP OF SPECIALISTS ON ANTARCTIC NEOTECTONICS (ANTEC)

At the SCAR XXV meeting in Concepcion, Chile, Prof. Dalziel, IUGS Delegate, presented to Delegates a joint recommendation from the Working Groups on Geology, on Solid-Earth Geophysics, and on Geodesy and Geographic Information, that SCAR should establish a new Group of Specialists on Antarctic Neotectonics (ANTEC). The presentation highlighted some unique aspects of the Antarctic continent such as:

- It lies at the centre of a lithospheric plate that, unlike any other, is almost entirely surrounded by spreading ridges and, furthermore, has been essentially in a polar position for the last 100 million years;
- It appears to lack the intra-plate seismicity that characterises all other continents;
- It includes at least one intra-plate rift system, stretching from the Ross Sea to the Weddell Sea, that has unique characteristics including possible implications for the stability of the West Antarctic Ice Sheet.; and
- It is covered by the only extant continent-scale ice sheet, which applies unusual stresses to the crust.

The presentation emphasised the current development of new technologies that are making possible new studies in geodynamics and neotectonics. These provide an opportunity for earth scientists and allow Antarctica to be placed more precisely in the global framework. (SCAR Bulletin 133, April 1999). Geodesy representation on the ANTEC group of specialists is shown in table2 below.

Member	Country	Field of Expertise	E-mail Address
Dr Terry J Wilson (Convenor)	USA	Tectonics	wilson.43@osu.edu
Dr Robin E Bell	USA	Gravity, Geology	robinb@ldeo.columbia.edu
Dr Alessandro Capra	Italy	Geodesy, Gravity	alessandro.capra@mail.ing.unibo.it
Dr Reinhard Dietrich	Germany	Geodesy	dietrich@ipg.geo.tu-dresden.de
Dr Jesus M Ibañez	Spain	Seismology	ibanez@iag.ugr.es
Dr Tom S James	Canada	Glacial rebound	james@pgc.nrcan.gc.ca
Mr John Manning	Australia	Geodesy, Remote sensing	johnmanning@auslig.gov.au
Dr Andrea Morelli	Italy	Seismology	morelli@ingrm.it

Table 2 ANTEC Membership

COLLOCATION WITH OTHER GEODETIC TECHNIQUES

GPS is a major geodetic technique in use in Antarctica but for global observations collocation with other techniques is also important such as DORIS, Absolute Gravity, Tide Gauges, and VLBI.

The first Antarctic VLBI experiment was observed at Syowa in 1991 using a temporary configuration. A permanent installation was established by Germany at the Chilean base of O'Higgins in 1993 and has participated in a number of Southern Hemisphere campaigns. Japan refurbished the antenna at Syowa as a permanent installation in 1998 and experiments between other sites in Australia and South Africa are continuing, whilst O'Higgins continues to be operated during the summer months.

Additionally the USA have established a precise epoch based observation network as part of a geophysical research to study the deformation in the McMurdo region in the TAMDEF project. This network has been observed on a campaign basis for three years.

A super conducting Gravimeter has been in operation for four years at Syowa. To date Satellite Laser Ranging has not been undertaken in Antarctica but is being considered.

SUMMARY

Internationally coordinated Geodesy activities continue in Antarctic despite the problem with logistic associated with such a remote region. The lack of gravity remains a pressing concern requiring extensive aerogravity work and integration with forthcoming satellite gravity missions. The SCAR WG-GGI is an active ongoing group and geodetic activities are promoted and coordinated through the SCAR GIANT program. A new SCAR Group of Specialists on Neotectonics has been established to integrate the work of Geologists, Geophysicists and Geodesists in Antarctica

John Manning
Reinhard Dietrich
Co Chairs
Antarctic Sub Commission of Commission X
7 July1999

REPORT ON FUNDAMENTAL ASTRONOMICAL SYSTEMS

by Erwin Groten, President of SC 3 of IAG

At the General Assembly at Kyoto in 1997 the IAU Working Group on Astronomical Systems (WGAS) has created two new subgroups, the SOFA Subgroup chaired by P. Wallace and the Fundamental Constants Subgroup chaired by D. McCarthy.

Besides this, the working group on Celestial Reference Frames (chairman: L. Morrison) has concentrated on the implementation and definition of extraterrestrial frameworks and systems which became more or less pure space systems without fundamental relations to terrestrial parameters. The working group on nutation and other terrestrial parameters (such as precession etc.) under the guidance of V. Dehant and others as well as the working group on relativistic (chairman: G. Petit), mainly post-Newtonian, systems, their exact definition, implementation and realization have been active but a new complete and relativistic high-precision reference system is not expected to be available prior to the next General Assembly of the IAU. The IERS Editorial Board under the guidance of the IERS Directing Board is editing at three years intervals the IERS-Conventions in close relationship with IAU working groups and Special Commission 3 (Fundamental Constants) of IAG. IERS Conventions gained wide interest recently in view of its extended impact, besides other and related systems of global fundamental interest such as ITRS, IGS, ETRF(S), ICET.

In spite of the progress made since the last General Assembly of IUGG at Boulder (1995) and the General Assembly of IAU at Kyoto (1997) in various fields there is no official change of fundamental formulas (nutation etc.), fundamental systems or fundamental constants. Special Commission 3 has updated its „current best estimates“ of fundamental parameters, also by including improved gradients (changes of „constants“ with time). Most other groups proceeded in a similar way, without changing the official values even though there is general agreement on the need for such changes. For the year 2001 at the next IAG General Assembly official systems are expected to change significantly, IERS-Conventions 2000 are under consideration.

In view of greater impact of improved global reference systems on high-precision terrestrial and space applications there is increasing activity at related institutes of interest such as BIPM, Bureau de Longitude, GFZ, with the aim to play more substantial roles in related fields. Moreover, there are clear tendencies to interrelate the principal organizations and working groups. IAG and IUGG should pay more attention to these tendencies in order to make sure that IAG and IUGG remain in the focus of new developments. Also within IAG there should be an improved transfer structure in order to guarantee that the „know-how“ and competence is used, and the interest of IAG and IUGG is well represented in the related organizations. Recently, the traditional interrelation of IAU and IAG were mainly limited to IERS; it would be to the benefit of both organizations and the two unions to maintain the earlier broader connections between IAU and IAG. The intensive exchange of updated versions of official catalogues, the interchange and discussion of forthcoming results, such as „current best estimates“, besides official parameters and the reconciliation of interests (by electronic mail and other means) would be very valuable.

ISO TECHNICAL COMMITTEE 211 GEOGRAPHIC INFORMATION / GEOMATICS STATUS REPORT

from J. Ihde

The work within the scope of the ISO/TC 211 *Geographic Information/Geomatics* was started in 1995. The standard family 15046 of ISO/TC 211 comprises altogether 19 partial standards, 7 to 8 standards of which can be looked up as being the core. The other standards deal mostly with rules and guidelines for creating the standards, their use and the continuation of the activities especially by so-called profile standards. The part 15046-11 - *Spatial referencing by coordinates* - which was developed within the scope of the Work Item 11 under the leadership of H. Seeger belongs to the core standards and was accompanied by the IAG. This standard contains rules and guidelines for information and for the description of geodetic reference systems (datums and coordinate systems) and of the relations between geodetic reference systems (datum transformation and coordinate conversions). About 15 people from all over the world took part in this group. The group worked from the beginning of 1997 until October 1998. With the outline of the Committee Draft the work of the project group is completed. Out of the project group an „Editing Committee" is formed which continues the works on the Committee Draft (CD) up to the final version of the International Standard (IS). In November 1998 the Committee Draft 15046-11 was sent to the member countries for comments. During the 8th Plenary Meeting of ISO/TC 211 in Vienna in March 1999 the comments were processed by the Editing Committee on a meeting so that in the middle of 1999 on the standard 15046-11 will be distributed as 2nd CD.

On the 7th Plenary Meeting of ISO/TC 211 in Beijing in September 1998 it became clear that the ISO/TC 211 will not finish the work with the conclusion of the present Work Items. Three geodesy relevant standards (Profiles) were proposed: *Geodetic codes and parameters*, *Coordinate transformation services*, *Catalogue services*.

The Working Group 3 - *Geospatial data administration* - of ISO/TC 211 was instructed to present a proposal for the task of the new standard *„Geodetic codes and coordinates"* to the Secretary of the TC until November 1998. The content of the new standard *„Geodetic codes and coordinates"* continues directly the standard from WI 11. On the basis of the guidelines given in WI 11 tables for identificators and descriptions of geodetic reference systems and of parameters which express the relations between reference systems have to be developed.

At the Plenary Meeting of ISO/TC 211 in Vienna in March two new work items with geodetic scopes were discussed:

(1) Geographic information – coordinate transformation with the scope:
Specification of abstract service interfaces to be used for coordinate transformation. This service is based on the data models defined in 15046-11 – Spatial Referencing by coordinates. The intention of the coordinate transformation service is to support the functionality associated with transformation of coordinates from one coordinate system to another, including relevant support functions around this.

(2) Geographic information – geodetic codes and parameters with the scope:
To develop a Technical Specification on Geodetic Codes and Parameters in compliance with ISO 15046-11, which defines rules for the population of tables that meet the needs of 15046 users, identifies the data elements required within these tables, and makes recommendations for use of the tables. These recommendations should address the legal aspects, the applicability to historic data, the completeness of the tables and a mechanism for maintenance.

The proposed new work items will be prepared until the 9th ISO/TC 211 Plenary Meeting in September 1999.

Within the scope of IAG Subcommission for Europe (EUREF) activities are planned which correspond with the content of the planned standard „*Geodetic codes and coordinates*". On the meeting of a Working Group „*Terminology*" under the IAG Subcommission EUREF on 25 October 1998 in Paris three tasks were formulated:

1. Standardization of the terminology for the description of geodetic reference systems.

2. Description of geodetic reference systems which are used in Europe according to the guidelines of the standards ISO/TC 211, 15046-11 *Spatial referencing by coordinates*.

3. Description of transformation procedures with algorithms and parameters for datum transformation and coordinate conversion between the geodetic reference systems and map projections which are used in Europe.

Because of the fact that ISO has a leading role in the field of standardization of geodetic information for geographic information systems the main field of IAG's activities in standardization should also in future be this subject. Therefore the influence of IAG on possibly new initiated Work Items in the field of geodetic reference systems has to be ensured. In December 1998 J. Ihde was appointed as IAG representative to ISO/TC211.

THE COMMITTEE ON MATHEMATICAL GEOPHYSICS

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The Committee on Mathematical Geophysics is an Inter-Association Committee of the IUGG. It aims to encourage exchange of ideas and information in all areas of geophysics, with emphasis on the application of mathematics, statistics and computer science to geophysical problems. The Committee organizes bi-yearly conferences.

During the report period I participated in the 22nd International Conference on Mathematical Geophysics, held in Cambridge UK on July 12-17, 1998 at the Isaac Newton Institute. The conference, titled "The Dynamic Earth", was well organized by the LOC under Herbert Huppert. Forty people attended the five day conference, comprising eight symposia and two poster sessions.

The scientific level of the conference and the quality of the presentations was high to very high, offering the tintillating experience of being among "real scientists". The symposia were titled:

- Geophysical Inverse Theory and Image Reconstruction
- Atmospheric Dynamics and Secular Variation
- Small Scale Processes in the Mantle
- Large Scale Mantle Convection
- Ocean Circulation, Global Climate, Heat Transfer and Turbulence
- Modern Numerical Investigations
- Magnetic Field Generation and Core Dynamics
- Crustal Processes: Deformation, Friction and Rupture

As seen from the symposium titles, the work reported focuses on understanding the behaviour of all the concentric "onion shells" that make up our dynamic Earth, and we are starting to see a lot of detail already. I feel this complex of issues to be relevant for geodesy in four ways:

- The mass distribution inside the Earth, affected by convection and plate tectonics, imprints itself on gravity field and geoid as studied by physical geodesy.

- Crustal motions, due to plate tectonics and other processes inside the Earth, are relevant to GPS geodesy.

- The atmosphere, especially "wet" troposphere and ionosphere, are well observable with the geodetic GPS infrastructures now existing in many countries. To fully use this, an understanding of atmospheric processes is essential.

The complex: gravity field - geoid - ocean surface - sea surface topography - ocean circulation, highly relevant to the study of global climate change, possesses some physical geodetic "handles". I believe that young physical geodesists doing leading edge research in fields related to any of these could really benefit from attending CMG conferences.

THE INTERNATIONAL UNION FOR SURVEYS AND MAPPING

ACTIVITIES 1995-1999: AN OBJECT LESSON

By
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USA

Introduction

The past four years of IUSM activities, just like those of the previous four years, could be summarized as "search for identity, functions and modus operandi". First, the structure of IUSM as set up originally, consisting of a Council (representing the Member Organizations or MOs), Executive Board, Secretariat, and Working Groups, proved to be too top heavy, inflexible and cumbersome to be effective. Second, IUSM has been torn between those who wanted to use the Union to impose a particular technological culture on the MO-s and those who simply wanted the Union try to coordinate action by the MO-s to over-come perceived problems. Third, the difficulty has been identifying those common problems that need coordination of action, and in which the parties involved have been interested in collaboration. To resolve these issues and to decide on the future of the Union and its structure the Executive Board organized a 2-day strategic-planning workshop, followed by meetings of the Board and the Council in Boulder, Colorado, in 1995. At this time the membership consisted of the three 1984 founding members; ISPRS, FIG, ICA, and those who joined later; IAG (1989), IHO, and SORSA. IUSM officers were President Earl B.W. James (FIG) of Australia, Vice President Ivan I. Mueller (IAG) of the USA, and Executive Secretary J.Hugh O'Donnell of Canada. It is at this juncture of IUSM history when this report begins; highlighting the most important IUSM related events in chronological order.

June 30-July 2, 1995 Boulder, Colorado, XXI IUGG General Assembly
Probably the most important consensus among the MO-s at this, the 12th, meeting of the Executive Board was that, despite its problems, IUSM should continue. In addition,
- a new Vision Statement was drafted: "The IUSM is to be an alliance of international organizations dedicated to ensuring that science and technology related to geospatial information meet the needs of society".
- A new set of Goals were developed:
1. Cooperatively develop interdisciplinary strategies for the profession to serve societal needs.
2. Facilitate cooperation between members organizations in areas of common interest,
3. Represent the common interests of the MO-s, as a union, to international governmental and non-governmental organizations.
4. Develop opportunities for, and facilitate the promotion of scientific and technical developments in areas of common interest.
5. Foster communications and encourage the flow of information within both the profession and the user community.
6. Promote the availability and appropriate use of high quality geospatial information and related technologies.
- Two Task Forces (TF-s) were appointed:
No.1. To make recommendations for the future role and structure of the Union at the next meeting of the Board in Vienna at the XVIII ISPRS Congress, July 1996 (chaired by Christian Andreasen, IHO President).
No.2. To develop a Vision Statement for the geospatial information professions (chaired by Peter Dale, FIG President).
- The earlier appointed Working Groups on Education and on GPS were terminated.
- The Working Groups on LIS/GIS (Chair: Gottfried Konecny) and on Automated Control Measurements - ACM (Chair: Heribert Kahmen) were continued.

The meeting ended on a high note, assuming that the Executive Board and the Secretariat will start making the Goals a reality, and that the continuing Task Forces will be successful.

September 29, 1995
Hugh O'Donnell resigns as Executive Secretary, due to the elimination of his position within National Resources Canada. Hugh being a driving force of IUSM, this is considered a great blow to the organization. Cyril Penton, and later Doug Selley, both of NRC, were appointed in acting capacities until a new Executive Secretary is found.

July 16, 1996, Vienna, Austria, ISPRS XVIII Congress
The 13th meeting of Executive Board was occupied mainly with the Task Force reports:
- TF1 noted that the focus for realistic actions is Goal 2 above; that actions on Goals 1, 4, and 5 are encompassed within Goal 2; Goal 3 was viewed as a future item for IUSM to address; and actions within Goal 6 were viewed as "dead". The TF suggested that the IUSM statutes be left unchanged. In addition, recommendations were made to set up an IUSM data base (Andreasen agreed to do so), to sponsor "special sessions" at Congresses, to sponsor "short courses" where needs are of interest to multiple MO-s, to develop a web page, to add a sub-name to the name of the Union (see the above title of this report), and to modify the IUSM Vision Statement adopted in Boulder to read:
"IUSM is an alliance of international organizations which facilitates scientific and technological developments in the field of geospatiial information", i.e., no more "societal needs"! The Executive Board accepted the recommendations and disbanded TF 1.
- Tom Kennie, FIG Vice President (substituting for Peter Dale) reported for TF2 without specific recommendations. The discussion focused on issues that impact on the visions of MO-s, including common areas, standards, the marketplace and the changing nature of the discipline. This Task Force was also disbanded.
- TF3 was formed to develop a strategy on restructuring the IUSM, including the orderly rotation of officers. Michael Wood ICA President undertook the task of leading the group and to report back at the next Board meeting.

It was also noted that the Working Groups are having difficulties meeting their goals. The Working Group on ACM was disbanded due to lack of interest.

April 21, 1997, Monaco, XV IHO Conference
The four-year terms of the Officers expired at this 14th meeting of the Board, and a new executive was elected. There were two candidates for the presidency, Gottfried Konecny (ISPRS), Germany and Ivan I.Mueller (IAG), USA. Mueller was elected to the position. The other offices went to Vice President Christian Andreasen (IHO), USA, and Executive Secretary Pascal Willis (IAG), France, without opposing candidates. The TF3 report generated a lengthy discussion, including a number of alternate proposals for reorganization and a number of straw votes were taken to get a sense of the group. Much time was spent on the controversial issue of the Council, its role, its responsiveness to MO's needs for the Union, it's post-activeness, etc. Based on this input Michael Wood agreed to extend the charter of TF3, which from now on becomes TF4, amend the TF3 report as per the discussion and circulate it. The last Working Group on LIS/GIS, after completing its task, was disbanded.

October 7, 1997
ISPRS withdraws from IUSM. The following are quotes from the letter: "Unfortunately, the Union has not addressed the expectations or scientific and techno-logic needs of its Members, but rather has devoted its efforts to structural bureaucracy. Although, ISPRS has strived to make the Union successful for the common good of all our disciplines, we find that the Union has ceased most activities envisioned originally and also as re-visioned at the Boulder Strategic Workshop. To demonstrate its commitment to the future of IUSM, ISPRS sent three officers to the three day Boulder Strategic Workshop in July 1995. Our expectations and message at the meeting was for a strong unified body to be established which would be able to represent all professionals in the fields of surveying and mapping. However, despite the agreement of all parties to the goals that were set at the Boulder meeting, they were watered down to such an extent by July 1996 in Vienna, that they were largely discarded. That is, the goals that took the many leaders of our professions to establish over three days were simply discarded as too difficult to achieve. In Monaco the last of the four IUSM Working Groups were terminated and several members of the Executive Board proposed that the IUSM Council should also be abolished. These are grave disappointments considering the high ideals that were espoused in Boulder, and particularly in light of the considerable efforts that were made by former and present ISPRS Council members to ensure that IUSM function effectively."

It was difficult not to agree with the above sentiments (except for the perceived need for the Council and the Working Groups).

December 10, 1997, San Francisco
The President called a special Executive Board Meeting (No.16th) to facilitate the final recommendations of TF3/4 and to try to move IUSM from the existing impasse. After lengthy discussion on whether or not IUSM should continue to function with both an Executive Board and a Council, there was general consensus that the current IUSM structure must be streamlined and reflect more closely the Goals established at the Boulder strategic meeting in 1995. A number of proposed revisions to the Statutes, from now on called the "IUSM Terms of Reference", have been accepted and forwarded for a Council vote by mail-balloting. Specifically, the new Terms of Reference:

dissolved the Council, replaced the Objectives of the organization with the Goals developed in Boulder, reduced the terms of office for the Officers and changed the mode of their election, and removed unneeded restrictive aspects of the original Statutes.

It was also noted that the IUSM web site has been initiated by the Secretariat at IGN, France.

March 1, 1998
The Terms of Reference was adopted by the Council which, in effect, voted itself out of existence, and gave the Executive Board greater flexibility to act faster without the need for Council's approval on many issues. The "restructuring" was followed on by the distribution of a Questionnaire addressed to the MO-s, and requesting guidance as to what they expect from the "new" IUSM. The Executive Board was looking for "action items"!

July 17, 1998, Brighton, UK, XIX FIG Congress
The 16th meeting of the Board was mainly concerned with looking for the "action items" resulting from the Questionnaires. The questions asked were as follows:
1. Do you want IUSM to provide a unified voice on behalf of the
profession(s)? If so, can this be by consensus or is unanimity considered essential for
IUSM to act?
2. IUSM abolished its Working Groups but might play a useful role in the inter disciplinary exchange of information. Should IUSM act to facilitate inter disciplinary exchange of information? If so, by organization of meetings or symposia?
3. Should IUSM focus on the identification of common fields of Member Organization activities? Where common fields are identified, should IUSM seek organizational efficiencies and foster coordination between the various MO commissions, working groups, etc?
4. Face to face meetings are generally an effective means for accomplishment of activities. Should IUSM maintain (annual or other) face to face meetings? If so, should these meetings be held alongside Member Organization meetings as has been done and should this continue on a rotational basis?
5. Do you feel that IUSM should expand its membership? If so, what organizations would you suggest as candidate organizations to be approached?
6. What role should IUSM play in fostering higher education in the
geospatial sciences/engineering? How should such a role be accomplished?

The responses indicated a definite "no" to Questions 1 and 2, a definite "yes" to 3, 4, and 5, and a "maybe in the future" on 6. Based on these it was decided
- to continue with the development of the data base,
- the MO Presidents will supply the IUSM President, for synthesis, a list of topics/working groups/commissions where collaboration with other IUSM MO-s could be beneficial,
- the MO Presidents will continue to have face to face meetings with each other at regular intervals, preferably, not during the MO Congresses,
- the IUSM President will contact other potential MO-s (e.g., IMS, URISA).

February 11, 1999
FIG withdraws from IUSM. In an e-mail message they congratulated the IUSM President for his "patient leadership these past few months" and "argue that the failure of the IUSM members to respond is not a failure of leadership - it has been merely a symptom of the weakness of the whole concept of IUSM. In coming months and years FIG will all satisfy the more important purpose of IUSM, a cooperative communication among our individual members, through more efficient and effective bi-lateral liaison agreements."

February 12, 1999
The IUSM President offers his resignation, and in view of the small number of MO-s remaining (IAG, IHO, ICA and SORSA) suggests to disband IUSM via a mail ballot. After lengthy correspondence, neither of these was accepted and another meeting of the Board was recommended to take place on August 14, 1999 in Ottawa at ICA1999. The main purpose of the meeting is to draw to its conclusion the future of IUSM as per the IUSM President's letter in which he stated the following:

"After volumes (bytes) of correspondence finally here is the (faint) light at the end of the tunnel: Most colleagues agree that we, either should sustain IUSM as an adjunct to the Member Organizations with limited roles that offset future expenditures, or scrap it and ignore the residual potential from all the effort and goodwill (at least by several of us) that has been expended. Most colleagues also agree that in the first case we should meet and discuss what is tenable (from the old sister-society concept, through web building, to higher order tasks (?)), and confirm the specific and limited tasks for the future IUSM. In the second case, disbanding be made in a constitutionally correct fashion."

By the time this report is published the reader should know what has transpired in Ottawa.

The End

Epilogue.

The IUSM was abolished in Ottawa on August 14, 1999.

REPORT ON THE SOUTH AMERICAN GEOCENTRIC REFERENCE SYSTEM (SIRGAS)

by
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IAG Representative in the SIRGAS project

Introduction

The project for the establishment of a South American Geocentric Reference System (**Si**stema de **R**eferencia **G**eocéntrico para **A**mérica del **S**ur, SIRGAS) was initiated in October 1993 during an international conference held in Asunción, Paraguay, and organized by the International Association of Geodesy (IAG), the Panamerican Institute of Geodesy and History (PAIGH), and the U.S. Defence Mapping Agency (DMA). The objectives of the project defined at this meeting were

to define a reference system for South America,

to establish and maintain a reference frame,

to define and establish the geocentric datum for all South American countries.

The first objective was achieved already during the constitutive meeting in Asunción. It was decided that

the SIRGAS reference system shall coincide with the IERS standards and refer to the IERS Terrestrial Reference Frame (ITRF),

the geocentric datum shall be based on the SIRGAS reference system and the ellipsoid parameters of the Geodetic Reference System 1980 (GRS 80).

To realize the other objectives, two Working Groups were initially installed:

Working Group I: Reference System

Working Group II: Geocentric Datum.

The Working Groups started their activities in 1993 and held some meetings to define the project plan in Bogotá, Colombia, April 1994 (WG II) and La Plata, Argentina, October 1994 (WG I and WG II). Later, in September 1997, a third Working Group was created:

Working Group III: Vertical Datum.

Realization of the SIRGAS Reference Frame

A total of 58 sites on the South American mainland and the surrounding areas were selected to form the SIRGAS reference frame. All these sites were observed simultaneously during a continuous GPS campaign from May 26, 1995, 0:00 UT to June 4, 1995, 24:00 UT. The observation data files were collected and are available at two data centers at Deutsches Geodaetisches Forschungsinstitut (DGFI), Munich, Germany and Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, Brazil.

The data processing was done by two processing centers at DGFI and the National Imagery and Mapping Agency (NIMA, formerly DMA), St. Louis, MO/USA using different softwares (Bernese at DGFI and GIPSY at NIMA). The two independent results were combined and transformed to the ITRF 94 by means of nine identical stations of the International GPS Service (IGS). The precision of station coordinates is in the sub-centimeter level.

All the processing procedure was discussed during project meetings at Santiago, Chile, August 1996 and Isla Margarita, Venezuela, April 1997. At the latter meeting the final station coordinate solution was adopted as the official SIRGAS reference frame and recommended to be used by all South American countries as the basis for the national reference frames.

Realization of the Geocentric Datum

The South American countries started to refer their national reference networks to the SIRGAS frame immediately after its realization. In most cases completely new GPS networks were installed including some identical stations with the existing classical triangulation networks. By this means, a transformation from the old datums (e.g. the Provisional South American Datum 1956, PSAD 56, or the South American Datum 1969, SAD 69) to the new SIRGAS datum is feasible.

At present, in nearly all South American countries a national GPS network within the SIRGAS frame has been installed. Thereby a dense station distribution covering the total continent with a unique datum for its coordinates is established. The typical spacing between stations is 100 km. A further densification (second order networks) has started in several countries.

Vertical Reference System

During the IAG Scientific Assembly in Rio de Janeiro 1997, the SIRGAS Working Group III "Vertical Datum" was created. The objective of this WG is to define and to establish a unique vertical datum for the existing and future height systems in all South American countries.

The WG III met for a Workshop in Santiago, Chile, in August 1998 and released the main resolutions

> to adopt a unique vertical reference system for all South America with two types of heights: ellipsoidal heights and another type based on geopotential numbers,
>
> to realize the vertical reference system by a set of stations which have levelled heights, gravimetric measurements, and coordinates in the SIRGAS system, including those tide gauges that define the classical vertical datum.

With respect to the first resolution it was recommended to introduce normal heights as the second type besides the ellipsoidal heights. A network of stations realizing the vertical reference frame and being observed by GPS is in preparation.

Future Acitivities

The activities of the SIRGAS Working Groups will continue during the next years. In order to monitor the coordinate changes of the SIRGAS reference frame (station velocities) it's striven for permanent GPS observations in most of the stations. Presently, about 20 sites are included in the IGS regional network weekly processed by the Regional Network Associate Analysis Center for SIRGAS (RNAAC-SIR) at Deutsches Geodaetisches Forschungsinstitut (DGFI), Munich. A repetitive GPS campaign shall be planned for those stations not included in the RNAAC network.

Litterature

Costa, SMA., K.D. Pereira, D. Beattie: The integration of Brazilian geodetic network into SIRGAS. IAG Symposia, No. 118, 187-192, Springer 1998.

Drewes, H., L.P. Fortes, M.J. Hoyer, R. Barriga: Status report of the SIRGAS project. IGS 1996 Annual Report, 433-436, 1997.

Drewes, H.: Time evolution of the SIRGAS reference frame. Springer, IAG Symposia, No. 118, 174-179, Springer 1998.

Drewes, H., H. Tremel, J.N. Hernandez: Adjustment of the new Venezuelan national GPS network within the SIRGAS reference frame. Springer, IAG Symposia, No. 118, 193-198, Springer 1998.

Fortes, L.P., M.J. Hoyer, W.H. Subiza, H. Drewes: The SIRGAS project. IGS Annual Report 1994, 247-250, 1995.

Hoyer, M., S. Arciniegas, K. Pereira, H. Fagard, R. Maturana, R. Torchetti, H. Drewes, M. Kumar, G. Seeber: The definition and realization of the reference system in the SIRGAS project. Springer, IAG Symposia, No. 118, 167-173, Springer 1998.

Kaniuth, K., H. Drewes, K. Stuber, H. Tremel, J. Moirano: Results of the SIRGAS 95 GPS network processing at DGFI/I. Springer, IAG Symposia, No. 118, 180-186, 1998.

Moirano, J., C. Brunini, H. Drewes, K. Kaniuth: Realization of a geodetic reference system in Argentina in connection with SIRGAS. Springer, IAG Symposia, No. 118, 199-204, Springer 1998.

Sanchez, L., H. Tremel, H. Drewes: The Colombian national geocentric reference frame. XXII Gen. Ass. IUGG, Birmingham 1999.

Seemüller, W., H. Drewes: Annual report 1997 of the RNAAC SIRGAS. IGS 1997 Technical Reports, 173-174, IGS CB, JPL Pasadena.

Subiza, W.H., R.R. Pérez, F. Barbato, S.M.A. Costa: The redefinition of the geodetic reference system of Uruguay into SIRGAS frame. IAG Symposia, No. 118, 217-222, Springer 1998.

SIRGAS: Final Report Working Groups I and II. IBGE Rio de Janeiro, 96 pp, 1997.

REPORT ON IUGG/IAG ACTIVITIES 1995-1999

related to the

Panamerican Institute of Geography and History (PAIGH)

Wolfgang Torge, Hannover

The reporter has been appointed as IAG representative to PAIGH in 1991, and as IUGG liaison officer in 1995.

The International Association of Geodesy (IAG) continued its cooperation with PAIGH, which started through a joint agreement on cooperation signed in 1990. From the previous period, we mention two joint symposia (San Jos! 1990, IUGG Gen. Ass. Vienna 1991) and a jointly organized workshop in Asuncion 1993, together with the US Defense Mapping Agency (now US National Imagery and Mapping Agency NIMA). The latter one was the start of a subcontinent wide project of precise geodetic positioning, which was carried out in the period 1995 - 1999. Within the SIRGAS (Sistema de Referencia Geocentrico para America del Sur) project, a continental geocentric reference frame was established for South America, by cooperation of practically all South American countries, and under the sponsorship of IAG, PAIGH, and NIMA. IAG scientists are represented at the SIRGAS project committee and in the project's working groups.

The SIRGAS Working Group I organized in 1995 an extended GPS observation campaign including 58 sites all over the South American continent. The processing of the observation data was coordinated by the IAG representative and discussed in several international meetings (1996 in Santiago de Chile, 1997 in Isla Margarita, Venezuela). These meetings were financially supported by PAIGH. The results of the processing are precise three-dimensional geocentric station coordinates in the International Terrestrial Reference Frame (ITRF) which is installed and maintained by the IAG International Earth Rotation Service (IERS). The coordinate set was officially released as the final SIRGAS result during the IAG Scientific Meeting in Rio de Janeiro 1997.

An increasing number of SIRGAS sites is being equipped with permanently observing GPS receivers. These stations provide their observation data to the IAG International GPS Service (IGS). They are processed by the Regional Network Associate Analysis Center (RNAAC) which is coordinated by the IAG representative in the SIRGAS Project at Deutsches Geod!tisches Forschungsinstitut (DGFI), Munich, Germany. The continuous monitoring and processing provides thus the maintenance of the SIRGAS reference frame. The SIRGAS coordinates have been adopted as the basis for the national reference networks by several South American countries.

In SIRGAS Working Group II, the national geodetic reference networks of the individual South American countries are installed as a densification of the continental network and in connection with the existing (classical) horizontal networks. The IAG, by means of its official representative and some cooperating institutions (university and research institutes) gave considerable assistance to several countries (Argentina, Brazil, Colombia, Peru, Venezuela).

SIRGAS Working Group III was officially installed during the IAG Scientific Assembly, Rio de Janeiro 1997. Its task is to define and to realize the vertical reference system in connection with the classical levelling networks based on different tide gauges of the South American continent. The first scientific meeting of this Working Group was held in 1998 in Santiago de Chile. The vertical reference system is closely related to the Earth's gravity field (geoid determination, gravity correction of spirit levelling, mean sea level deviation from the geoid at tide gauges). Consequently there is a close cooperation between SIRGAS Working Group III and the IAG International Geoid Service (IGeS).

The IAG Geoid Commission (Subcommission for South America) is collecting gravity data from all South American countries in cooperation with PAIGH in order to improve the geoid determination. All the national geodetic agencies coordinating their activities in the meetings of the "Directores de los Institutos Geograficos de Sudamerica, DIGSA") agreed to provide these data. Several countries started to perform improved geoid computations on the basis on the IAG coordinated procedure. The data base of the precise gravimetric observations in the united Latin American gravity network (RELANG) is maintained by PAIGH and presently moved from Canada (which is no longer a PAIG member) to Colombia. There is a strong interest of IAG (Commission III and Bureau Gravim!trique International, BGI), in this PAIGH activity.

During the period 1995-1999, several scientific and organizational meetings took place, which were sponsored by PAIGH, in coordination with IAG. The outstanding event was the IAG Scientific Assembly in Rio de Janeiro 1997, the first IAG Congress in Latin America at all. An international school on geoid determination was organized by IAG in Rio de Janeiro after the IAG Scientific Assembly. PAIGH not only cooperated in the scientific program organization, but also gave support by travel grants. Financial support by PAIGH to the travel costs was also given to a number of participants (including the IAG representative) at the SIRGAS working group meetings, and to the geoid school in Rio. This is also expected for South American participants at the IAG General Assembly in Birmingham 1999, where special meetings on the SIRGAS and the South American Geoid projects are under preparation.

The intensive activities of IAG in South America and the close cooperation with PAIGH has driven a lot of initiatives in several countries. As a consequence, there has become more awareness of IAG in the continent. In Colombia, which left IUGG in the seventies, there is an actual discussion to return into the Union, driven in particular by the IAG activities.

With respect to the other Associations of IUGG, the result is less favorable. From the six geophysical Associations of IUGG only two responded to a corresponding investigation started by the reporter in 1995. Although a multitude of activities in South America was mentioned, there is obviously no cooperation with PAIGH. No suggestions were made how to eventually establish such a cooperation. Although the PAIGH Secretary General welcomed the appointment of an IUGG liaison officer to PAIGH, there was no reply from the presidents of the PAIGH commissions for Geophysics and Cartography, on the question of how to start an eventual cooperation, and in which areas of common interest.

As a result, the reporter concludes:

- a cooperation between IUGG and PAIGH can be extremly successful on the Association level as demonstrated by IAG. This is due to the personal engagement of Association scientists with a long experience in Latin America, and the organisational effort of the Association's administration,

- the attempts to trigger cooperation top-down i.e. through an IUGG liaison officer, failed, due to lacking personal contacts with scientists engaged in South America, and related to either IUGG or PAIGH.

It is proposed to abolish the post of an IUGG liaison officer to PAIGH, but to encourage the Associations to appoint Association representatives, in order to exploit the possibilities which obviously exist through a close cooperation, for promoting geodesy and geophysics in South America.

IAG SCHOOLS

Fernando Sansò

During the period 1995-1999, two IAG International Geoid Schools on the Determination and Use of the Geoid were held.

School Reports

SECOND INTERNATIONAL GEOID SCHOOL ON THE DETERMINATION AND USE OF THE GEOID

FIRST CONTACT

During the GRAGEOMAR96 meeting in Tokyo, Japan, I was contacted by Dr. Michael Sideris in order to verify the possibility of IBGE host The Second International School for the Determination and Use of the Geoid. The idea was to take advantage of the IAG meeting that would happen in Rio de Janeiro, Brazil, when the teachers and many possible students would come and the expenses of air tickets for the school would be cut. At that time, the following items were stated:

- TEACHERS:

Day	Teacher	Topic
1st	Fernando Sansó	Fundamentals of Geoid Computation
2nd	Nikos Pavlis	Geopotential Models
3rd	Christian Tscherning	Collocation
4th	René Forsberg	Terrain Effects on Geoid
5th	Michael Sideris	FFT Computation

As the teachers would be already in Rio for the IAG meeting and the only support they agreed was just receive the accomodation and living expenses.

- STUDENTS:

The school would be opened to graduate students, teachers and government employees.

- REGISTRATION FEE:

Typical US$ 500. Would be checked the possibility of including accomodation, local transportation and one or two dinners. The lecture notes and all software would be provided free only for research use by universities and government agencies.

- LECTURES:

5 days from 9 - 12 each morning for the theoretical part and 14 -18 for practical experience of using the software.

- COMPUTERS:

- At least 2 UNIX - workstations with FORTRAN and C or C^{++} compilers.
- Several PC's (5 to 8) all networked together and with the workstations- Xwindows software would be desirable.
- All computers should have ETHERNET connections for E-mail and for software transfer.
- Some graphical capabilities for displaying geoid and gravity anomaly maps.
- RAM requirements: 16MB computer minimum and 32 MB preferable (at least for each of the workstation)
- Hard disk space of 500 MB.

- ADVERTISING:

EOS (AGU), Journal of Geodesy, IGeS Bulletin, E-mail, Brazilian geophysical and geodesy societies and web page.

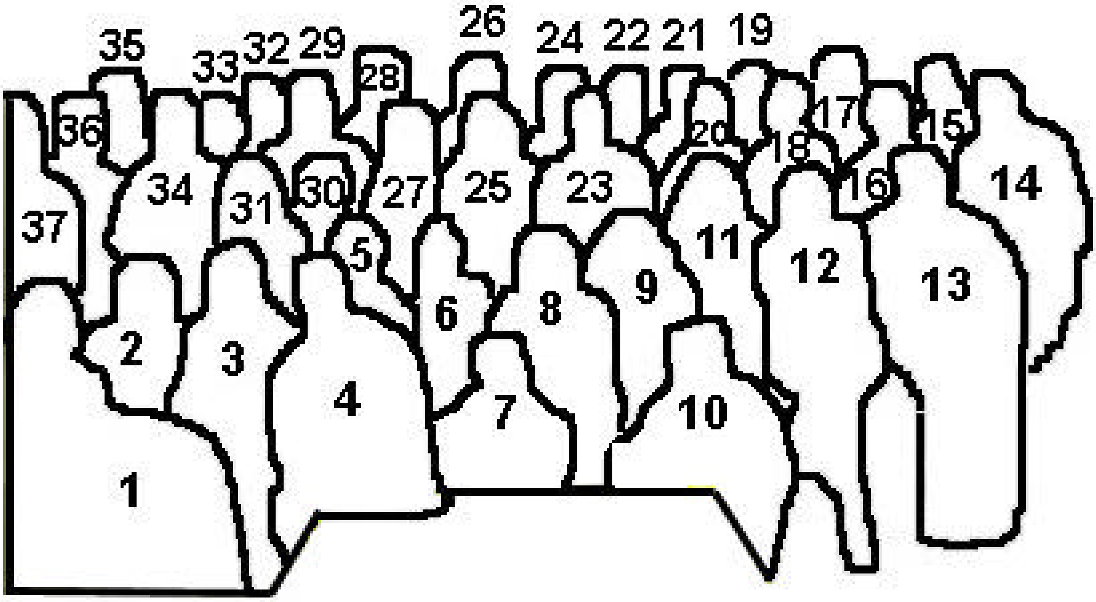
INVITATION AND PLANNING

The first circular was sent to the following groups:

- IAG web page;
- SIRGAS (South American Geocentric Reference System) representatives and many other research institutions, universities and every group that used to receive the SIRGAS bulletin;
- IAG/SBC meeting circular;
- by fax to the representatives of the South America Geoid Comission;
- by E-mail to the Brazilian Universities that have regular courses on geodesy (graduation and post-graduation);
- Brazilian Oil Company;
- Bernese GPS software students of february and march 1997.

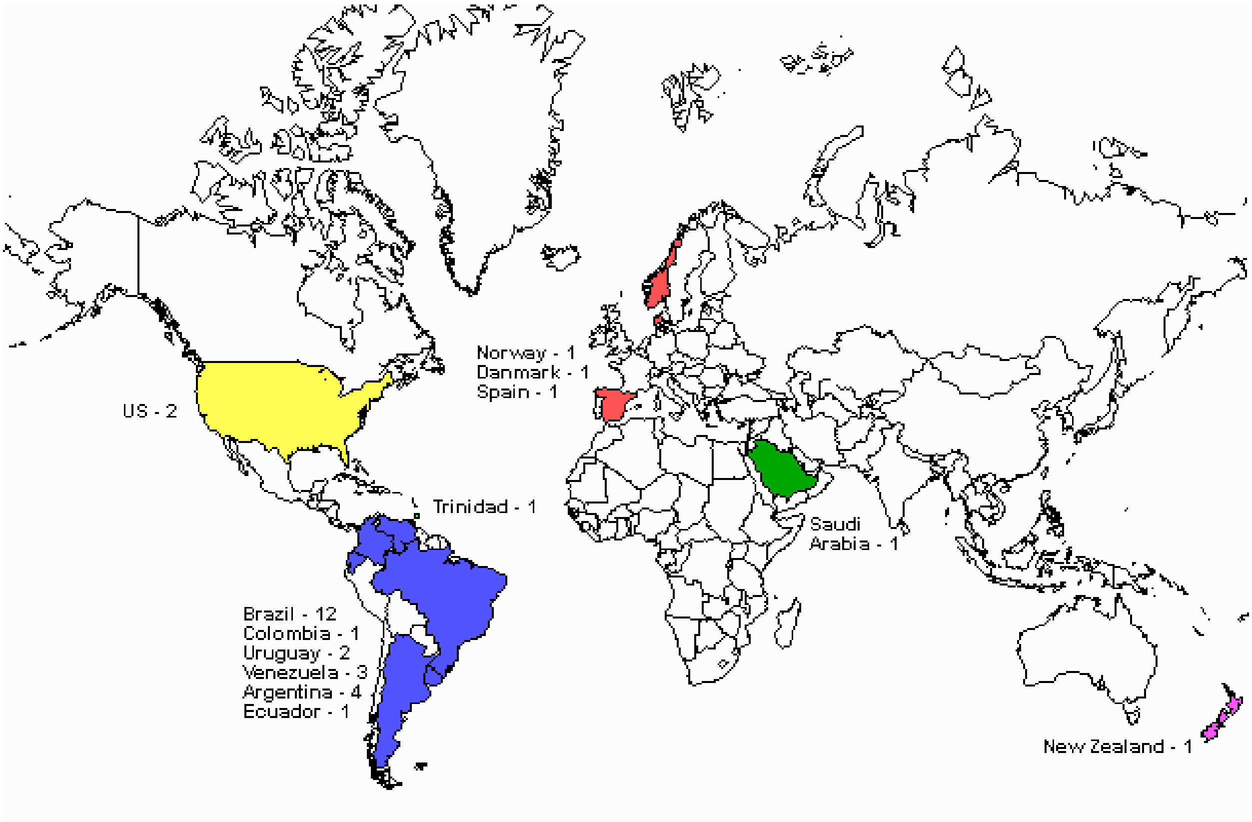
STUDENTS

We were contacted by 45 people from the first anouncement to the end. We've got a final number of 31 students.

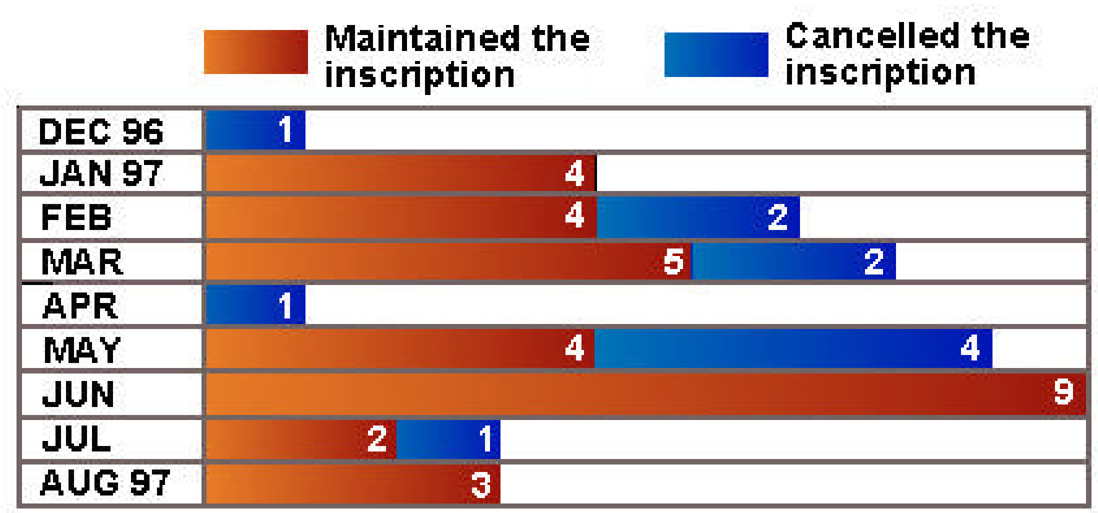


1	Sonia Costa	20	Nelsi Cogo de Sá
2	Frank Lemoine	21	Silvio R. Freitas
3	Merrin Pearse	22	Luciano Montenegro
4	Fabian Barbato	23	Alfonso Tierra
5	Karla Edwards	24	Fernando Sansó
6	Assumpcio Termens	25	Laura Sanchez
7	Denizar Blitzkow	26	Tscherning
8	Graciela Font	27	Nikos Pavlis
9	Elaine Nunes Jordan	28	Steve Kenyon
10	Michael Sideris	29	René Forsberg
11	Cláudia Tocho	30	Kátia Duarte Pereira
12	M. Cristina Pacino	31	Cristina Lobianco
13	Melvin Hoyer	32	Ove Christian Dahl
14	Freddy Fernandez	33	A. Simões Silva
15	Guilhem Moreaux	34	Walter Subiza
16	Mario E. Borgna	35	Luiz Paulo S. Fortes
17	Eugen Wildermann	36	Marco A. da Silva
18	José Milton Arana	37	Frederico Marinho
19	Mauro A. Sousa		

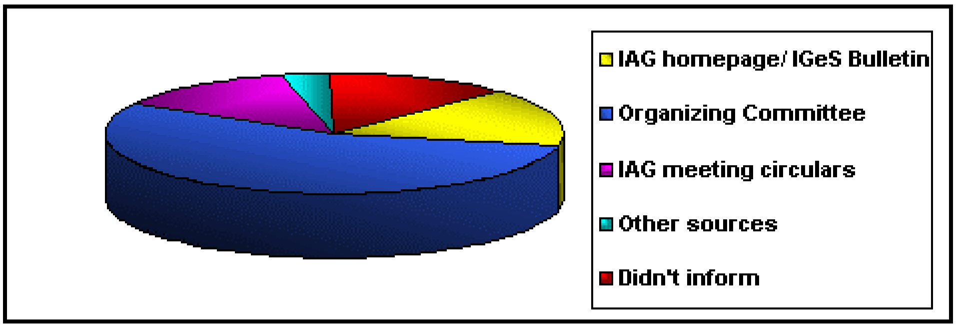
Distribution of the students by country:



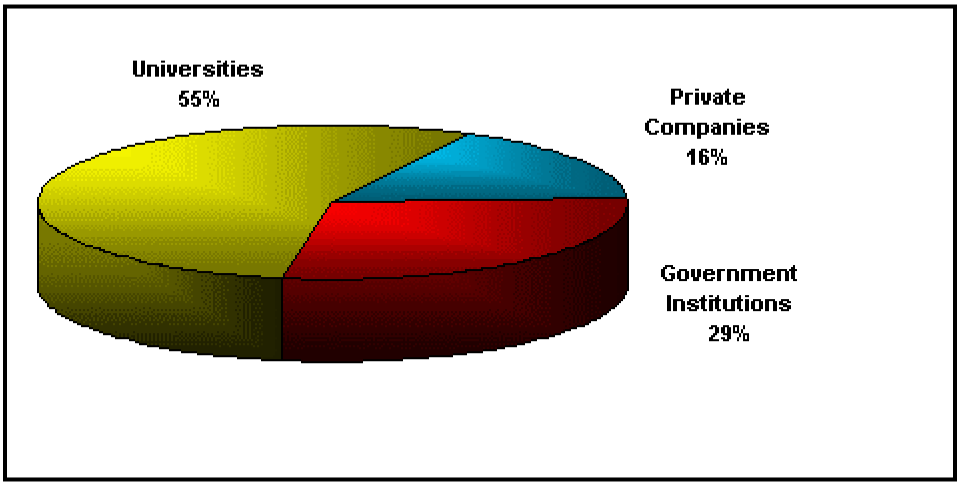
Month and number of students that made their inscription to the Geoid School:



How did they hear about the Geoid School:



Main activity of the students:



THIRD INTERNATIONAL GEOID SCHOOL ON THE DETERMINATION AND USE OF THE GEOID

MILAN, FEBRUARY 15-19, 1999

During the week of February from 15 to 19, 1999 the International Geoid School on the Determination and Use of the Geoid has been held in Milan.

The courses included:

Monday: a general introduction to physical geodesy and geoid computation, by F. Sansò

Tuesday: the computation and use of global models of high and ultra-high degree, by H.G. Wenzel

Wednesday: the collocation solution for the geoid computation, by C.C. Tscherning

Thursday: the terrain and residual terrain correction, by B. Benciolini and R. Barzaghi

Friday: fast Fourier techniques to perform the computation of the main formulas in physical geodesy, by M. Sideris

The school has been successfully attended by 23 students coming from Algeria, Bulgaria, Denmark, Egypt, Germany, Ghana, Hungary, Italy, Morocco, Mozambique, Spain, USA.

Old and new Lecture Notes have been provided and IGeS software as well as numerical exercises have been made available to the students.

International Geoid School on the Determination and Use of the Geoid
Milan, February 15-19, 1999

IAG home page on the Internet

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Internet: http.gfy.ku.dk/~iag

The IAG central bureau have set up a home page on the Internet as an open and up to date information medium. On the IAG home page it is possible to acces information for general use relevant to the IAG community.
The IAG homepage is updated at least once a week,
Below is a list of the contents of the IAG homepage as of september 1999. I currently holds several hundred documents online. You will also find the geodesists handbook and an internet version of the Travaux.

International Association of Geodesy

<table>
<tr><td rowspan="2">IAG General
Awards
IAG 1999-2003
IUGG
Meeting Calendar
Schools/Training courses
Meeting Announcements
Miscellaneous
Bibliographic serv.</td><td>International Association of Geodesy, Central Bureau,
c/o Department of Geophysics
Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark.
Phone: +45 35320600 , Fax: +45 35365357 E-mail: iag@gfy.ku.dk</td></tr>
<tr><td>The International Association of Geodesy (IAG) is one of seven associations within the International Union of Geodesy and Geophysics (IUGG) (e-mail: balmino@pontos.cst.cnes.fr).</td></tr>
</table>

IAG General

Geodesists Handbook 1996 - Manuel du geodesien Internet version.
IAG Structure & Officers elected at the XXI General Assembly, Boulder, Colorado, July 1995. Includes updated information on IAG Special Commisions - Special Study Groups, 1995-1999.
IAG Information Service provided by the Central Bureau. NOT UPDATED !
Adresses of officers, fellows and (a part of) the associates of IAG.
E-mail adresses of officers, fellows and (a part of) the associates of IAG.

XXII General assembly of IUGG99, Birmingham

IUGG Officers elected at the XXII General Assembly, Birmingham, 1999
IUGG Resolutions adopted at the XXII General Assembly, Birmingham, 1999
IAG Resolutions adopted at the XXII General Assembly, Birmingham, 1999
Minutes of IAG ececutive committee meeting
IAG Officers elected at the XXII General Assembly, Birmingham, 1999
National correspondents at IAG council meeting Birmingham, 1999
Report for 1995-99 by secretary general, Financial Report for 1995-99, Budget for 1999 - 2003

Fellows elected at 22nd IUGG general assembly
New Special study groups created at the 22nd IUGG general assembly
New International Laser Ranging Service (ILRS)
New International VLBI Service (IVS)
Young Authors Award (K.-P. Schwarz)
Some contributions to Travaux 95-99.
National Reports 95-99.

IAG awards and IAG fund

IAG Best Paper Award for young scientists..
The Guy Bomford prize..
The Levallois medal..
The IAG fund..
IAG Travel Award Application Form

IUGG

IUGG International Union of Geodesy and Geophysics. IUGG Structure 91-95.
IUGG Officers 1995-99.

Calendar

List of Future Meeting & Symposias relevant to geodesists.
IAG and related schools and training courses

Meeting Announcements:

Please look up the IAG homepage for current content.

Miscellaneous

Changes to the IAG Statutes and By-laws suggested by the Cassinis committee
European Gravimetric Geoid 1997 available on CD rom
Vacant positions within geodesy
Journal of Geodesy the journal of IAG
IAG Newsletter in Journal of Geodesy
IAG Fast bibliographic entries 1996 - 1998
Minutes of IAG exececutive committee meetings: Copenhagen, Nov, 95., Potsdam, April, 1997 Paris, March 1999 Birmingham
Proceedings of IAG Symposia published by Springer Verlag
History of Com. on Int. Coordination of Space Techniques for Geodesy and Geodynamics (By I. I. Mueller)
CDDIS Bulletin Crustal Dynamics Data Information System Bulletin, Published by NASA GSFC.
SCAR WG Geodesy & Geographic Information
DOD WGS84 Definition and relationships to local geodetic systems, NIMA TR 8350.2, 1997.

Beside these entries you will find

Bibliographic services

Geoscience WWW links