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PROCEEDINGS

Part I

Earth Rotation Parameters
Earth Tides

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P r e f a c e

These volumes comprise the invited and contributed papers of the 6th International Symposium "Geodesy and Physics of the Earth", held in Potsdam, GDR from August 22 - 27, 1988. The Symposium was organized jointly by the Central Institute for Physics of the Earth, Academy of Sciences of the GDR, and the National Committee of Geodesy and Geophysics of the GDR, and co-sponsored by the International Association of Geodesy (IAG), by the International Union of Geodesy and Geophysics (IUGG) and by the Commission of the Academies of Socialist Countries for the Multilateral Cooperation on Planetary Geophysics (KAPG).

The scientific programme of the Symposium was prepared by the members of the Scientific Committee: H. Kautzleben (chairman, GDR), E. Groten (FRG), Ya. Yatskiv (USSR), P. Vyskocil (CSSR) and H. Montag (GDR). The proceedings are published following the main topics of the Symposium:

Part I : Earth rotation parameters;
Earth tides
Part II : Gravity field variations;
Development of precise terrestrial and space techniques of geodetic measuring
Part III: Recent crustal movements

Within the Symposium Prof. Dr. W. Torge (FRG), 1st Vice-president of IAG, delivered the Helmert-Commemorative-Lecture for the year 1988 entitled "Absolute Gravimetry in its Operational Phase - Some Results and Problems". It is published in part II of the proceedings.

The Symposium was attended by 155 scientists from 20 countries. I should like to extend my thanks to all authors for their contributions and to my colleagues engaged in the editorial and technical achievement of this publication.

Potsdam, December 1988

H. Kautzleben

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WELCOME ADDRESS AND INTRODUCTORY PAPER
"SOME PROBLEMS IN GEODYNAMICAL INTERPRETATION OF GEODETICA DATA"

by Heinz Kautzleben, Potsdam

Distinguished guests,
dear colleagues,
ladies and gentlemen,

On behalf of the Presidium of the Academy of Sciences of the G.D.R. I have the pleasure to welcome you to the 6th International Symposium on Geodesy and Physics of the Earth. The Presidium wishes the Symposium every success.

We expect the presentation of many new important scientific results, a productive exchange of experiences and opinions, and many stimulations to all the participants for their further work. We hope that the meeting will promote the cooperation between the colleagues by deepening the existing connections and paving the way for new contacts.

Moreover, we wish all the participants and their companions that they can renew the knowledge of or get acquainted with our Central Institute for Physics of the Earth, the town Potsdam and its surroundings. We wish you a pleasant stay and many good impressions.

I wish to thank the Potsdam Pedagogical Institute "Karl Liebknecht" which had helped the organizers to arrange the Symposium at this time in Potsdam. We highly appreciate the great support given by the Rector of this Institute and its coworkers to the Organizing Committee.

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Next year during its General Meeting in Edinburgh the International Association of Geodesy plans to celebrate the 125th anniversary of the 1st Allgemeine Konferenz der Mitteleuropäischen Gradmessung held at Berlin in 1864 and initiated by General Baeyer. The IAG considers this 1st Allgemeine Konferenz as the date of its foundation.

Ladies and Gentlemen, all of you know that the Central Institute for Physics of the Earth carries on the work traditions of the Potsdam Geodetic Institute. Because the foundation and the development of the Prussian Geodetic Institute are strongly connected with the Gradmessung, the Central Institute for Physics of the Earth has celebrated already last year the anniversary of the conference organized by Baeyer in 1862 that had prepared the 1st Allgemeine Konferenz.

We also want to use this year's Symposium on Geodesy and Physics of the Earth to pay tribute to the anniversaries of this important event and some other events in the history of IAG.

We are much obliged to Professor Wolfgang Torge, 1st Vice-president of IAG, that he agreed to deliver the Helmert Commemorative Lecture during this Symposium. He will speak about modern aspects of absolute gravimetry. In this field the tradition of our Institute started with the famous work by Kühnen and Furtwängler 90 years ago.

Many papers to be presented at our Symposium are dedicated to problems of the Earth's rotation. George Wilkins will speak about the development and activities of the International Earth Rotation Service. This IERS has replaced the former activities of the BIH

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and the IPMS including the ILS. We would like to remind you that the International Latitude Service has been successful over nearly a century. Its history began with observations by Küstner at Berlin and Potsdam. A related paper about the history of the ILS is also included in the programme.

Geodesy and Geodynamics

Ladies and gentlemen, the series of the international symposia organized by the Central Institute for Physics of the Earth is dedicated to promote the interrelations between geodesy and geophysics. Their special goal is to discuss the level reached as well as the ways for a further development of geodesy with respect to its contribution to geodynamics. Here the term "geodynamics" is to be understood in its sense as it has been developed in the International Association of Geodesy and as it has been defined in the Terms of Reference of Section V of the IAG.

In the field of geosciences the term geodynamics has been used already for more than a century. About two decades ago, the term "geodynamics" gained its present high importance for the geosciences and beyond them. By formulating the hypothesis of plate tectonics it became possible to find a basis in conformity with all sciences dealing with the rigid Earth.

Nowadays, the manifold contributions of geodesy to geodynamics group around the two large complexes plate tectonics and Earth's rotation. As for the first complex, original contributions are to be found: in particular for the determination of the recent movements of the tectonic plates as a whole as well as with respect to their internal deformations, moreover for the investigation and representation of the convective processes in the upper mantle and their relation to the kinematics of the lithosphere.

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The second complex refers to the classic problems of geodesy that is treated traditionally together with astronomy and geophysics and that is introduced into the developing large field of geodynamics as a special branch. Its level reached till now requires close cooperation with geophysics with respect to the dynamics of the Earth's core, cooperation with oceanology with respect to the dynamics of the hydrosphere, and cooperation with meteorology with respect to the dynamics of the atmosphere. All this is necessary to investigate all the constituents of the dynamic Earth system and to take into account their interrelations.

Our symposium this year here will present multifarious papers to both of these complexes. In a more or less systematic manner this introductory paper aims to consider some general as well as some special problems which are in particular interesting at present when geodetic data have to be interpreted geodynamically.

Qualifications to the observations, to techniques and to teohnology

With regard to the other geosciences, geodesy is to be understood as a discipline that is measuring and working with its measurements. It is not a common practice in geodesy to have theoretical speculations on phenomena which cannot be measured directly and to use them as a form of compensation when measurements are not possible. Consequently, every progress in geodesy is decisively determined by the progress in the field of measuring techniques and observation technology.

Concerning the problems that will be discussed during our symposium on the one hand, the most important point is to improve the observation quality in order to measure actually the phenomena which are interesting from the geodynamical point of views. On the other hand, an increase if the efficiency of the observation methods has the same importance in order to present a sufficiently large quantity of observations for the respective time interval of interest and for the observation area because the capacity of

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geodetical data for statements will be obvious only by the collective properties of the observation data as a whole. Therefore, collecting geodynamically relevant data requires a permanent or regular process of geodetic measurements in a strictly comparable way at exactly the same point or at the same area being under observation. A well-coordinated international cooperation is indispensable. Using standardized equipments and methods is neccessary, at least sufficient comparisons and harmonizing have to be done. Measuring techniques and technology have to be found which can be used on a global scale and which give data which can be interpreted for the whole Earth. In this respect methods based on satellite data are most efficient.
You may understand this as an advantage or disadvantage but the situation is so that geodesy works only with three classes of measurements: These are geodetic ones in a narrow sense, astronomical and gravimetric measurements. As the most important results of geodesy there are the reference system and the values of the coordinates for the points of the Earth's surface referred to it. Especially gravimetric data have to be considered as a form of provisional result of geodetic work. They are of a relatively independent character and can be used in a direct way.
The contributions of geodesy to geodynamics concern firstly direct measurements of the time dependent variation for the geodetically relevant parameters which are caused by dynamic processes. For them geodesy has to increase permanently the measurement quality where the stability and the homogeneity of the data series must be guaranteed. Secondly, there are the results of the dynamic interpretation of geodetically relevant quantities, which are considered as constant in time during the time interval of the measurements. The dynamic interpretation of such parameters is only possible if further appropriate data and physical models of the relevant geodynamic processes are used. The most important point there relates to the problem to introduce a structural model of the Earth that fits the interesting or assumed geodynamic process.

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Investigations on the model of plate teotonios

The outstanding importance of the hypothesis on plate tectonics is to present a unifying, consistent as well as inspiring and understandable concept for all geosciences.

For geodesy till now this hypothesis means a clear model for the dynamic Earth that is able to be transformed into a concrete measurement programme.

Plate tectonics enable a unified global consideration and in particular a systematization of the observations of the recent movement of the Earth's crust that otherwise would disperse into a lot of details. The plate tectonic hypothesis facilitates the understanding for the relations of these movements with respect to the processes in the Earth's interior.

The development of geosciences on the basis of this hypothesis has shown that the original draft of plate tectonics can only be considered as a first approximation and that essential extensions and modifications are necessary.

Systematical recording of observations enabled more differentiated investigations and made the understanding of the structure and the dynamics of the lithosphere and of the asthenosphere much more precise. This allowed to find out that the originally simple unique plate tectonic process is superimposed by a lot of geodynamic processes being in interrelation. All this has important consequences also for its use by geodesy.

From my point of view, the fundamental progress which has been reached in the geosciences since the plate tectonics had been introduced consists in the fact that in general the dynamic understanding overcame the static one. At least for all investigations of the crust and of the upper mantle up to a depth of 700 km it is necessary to take consequently into regard that the Earth nearly fulfils the condition of a dynamic equlibrium, i. e.: small effects at the Earth's surface do not necessarily indicate the absence of intensive processes in the Earth's interior but they may also result as differences between processes

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of contrary course in the Earth's interior.

This is a great difficulty which had to be overcome after the finding of plate tectonics. By a lot of information one is accustomed to the idea that the continents and the oceans are the fundamental structural units of the Earth's surface. The seismic investigations of the structure of the upper layers of the Earth's body with its structuring into crust and mantle furthermore strengthened this idea. In plate tectonics, however, the vertical structuring of the upper layers of the Earth into a rigid lithosphere and an asthenosphere being able to flow as well as the horizontal structuring of the lithosphere into plates are much more important.

Nowadays, it is clear that the lithosphere means the crust and the upper parts of the mantle. All plates are about 100 km thick and it is assumed that this is independent of the fact whether the crust in its upper parts is of oceanic or continental form. Most of the plates include oceanic as well as continental parts of the crust. Their margins are not given by those between continents and oceans but by the relative movement of the plates as spreading, subduction and transform zones. It is very important to verify this structuring by further investigations.

But also from the point of view of plate tectonics there exist essential differences between those areas of lithospheric plates where the upper part of them is an oceanic crust and those with a continental crust.

Now as before in plate tectonics convection in the upper mantle has a fundamental importance. The oceanic lithosphere including the oceanic crust can be understood as part of this convection system.

The continental lithosphere which consists of the continental crust and important parts of the subcontinental mantle floats on the surface of this convection system and does not plunge again downward into the Earth's interior. The continental crust resists nearly all the processes which destroy the oceanic one. There are

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some hints that the convection in the Earth's mantle is much more complicated than would be necessary to explain the observed movement of the lithospheric plates. However unique facts for this are not available till now. Some results to solve this problem are expected to come from more detailed investigations of the gravimetric field.

The wide investigations on the oceanic crust and lithosphere decisively contributed to the present model of plate tectonics. In particular the altimetry data of SEASAT and GEOS essentially improved our ideas on the thermomechanical structure and the development of the oceanic lithosphere.
For further investigations of the oceanic lithosphere which are especially interesting for geodesy and gravimetry among others the literature lists the following problems as the current ones:

- Investigations on the detailed structure and, consequently, on the detailed run of the magma transport in the area of the middle oceanic ridges as basis for interpreting topographic differences
- Investigations on the density structure of adjoining lithospheric plates of different age and such crossing the oceanic fault zones.
- Investigations on the structure and the development of oceanic ridges with activ volcanos and on submarine plateau mountains.

Special attention is needed for the subduction zones. For their investigation a relatively low quality of observations is to be fulfilled, but the data must be given along profiles which have to cover the oceanic up to the continental area.

With respect to geodynamic problems in the continental area may find much more interest. Observations concerning the continents are essentially more complex and not so easy to explain by the concept of plate tectonics. The continental crust presents a complex and fragmentary monitoring of the evolutionary and dynamic

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processes over an interval of 85 per cent of the Earth's history. For interrelations of the plates the oontinental crust does not have a rigid behaviour. The movements of the plates can be absorbed partly or completely by deformations of the crust. The mechanical characteristics of the crust are significantly inhomogeneous; the deformations of the crust are heavily changed by the tectonic prehistory and it is very difficult to decipher them. I have to emphasize that the whole and very confusing puzzle can only be unravelled step by step by a systematical collecting. It is possible to stress some points and to treat them with priority. Among them there are:

- investigation of the depth structure of the continental lithosphere; the seismic results are contradictory; globally unified gravimetric data could give essential support for a solution
- investigations on geodynamics in young mountain belts e. g. for enlightening the rheological conditions, the isostasy
- investigations on rift-forming processes within the continents
- investigations on the dynamics of sedimentary basins and of the passive margins of the continents, in particular in order to clarify the sinking processes and their causes. These problems are of direct economic importance.

It seems necessary to emphasize that till now only in continental areas it is possible to prove the time variation of geodetically relevant parameters by measurements directly. In particular, this refers to the proof of movements of parts of the crust. Here, also in the future, the efforts of geodesy have to be concentrated.

Investigations on the Earth's rotation

The study of the general behaviour of the Earth as a rotating deformable cosmic body under the influence of mass attraction by the Moon, the Sun and the planets made decisive progress during the last two decades. The book published by H. Moritz and I. Mueller last year is a telling proof for the progress reached. In

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close connection to this the investigation of Earth tides received an impetus during that time.

In accordance with the topics of this paper here only relevant geophysical aspects will be mentioned.

At present, there are three very effective methods available to observe the rotation behaviour: VLBI, LLR and SLE. The observation quality reached in all the three methods and being in the interval

of decimeters allows to investigate the following problems beyond the topics of polar motion, precession, nutation, Earth tides which are clear from the theoretical point of view:

- interrelations of oceanic and Earth tides as well as the tide brake of the Earth's rotation
- variations in the first coefficients of the spherical harmonic series for the gravimetric field caused by postglacial uplifts and seasonal mass displacements
- frequency structure of the Chandler constituent in the polar motion, the secular part of the inner core in the polar motion, the possible influence of earthquakes on polar motion
- correction of variations of the length of day by short-period constituents.

For the present decade the observation quality is expected to be improved by one order of magnitude, i. e. in the centimeter interval, for the methods VLBI and LLR. By this, further geophysical phenomena in the Earth's rotation could be investigated successively. From our present understanding this would concern especially the coupling between the different dynamically effecting partial systems of the Earth:
inner and outer core, Earth's mantle, hydrosphere, atmosphere.
A still further improvement of the observation quality does not seem possible from our present point of view. Consequently, there

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is no necessity now to develop essentially the geophysical theories for relevant phenomena.

On extrapolating results to longer time intervals

In all investigations of geodesy on anobviously dynamic Earth attention has to be paid to the problem that the geodetic data as well asthe astronomical-geodetic ones in every case only allow to describe a very short time interval as part of a very long process that we are not justified to treat as static or as stationary. Now it is necessary to find ways how to develop ideas about the longer periods (rhythm or other forms) that allow to work and to interpret geodetic data suffiently simply without taking the interpretation of the results in contradiction to the statements of other geophysical disciplines. In other words: In every case we have to be conscious of the limited possibilities of geodetical data for a time extrapolation and we should not try such undue extrapolations.

On the other hand, it is necessary and it is a requirement of geodesy to geophysics that the results and the ideas of the geosciences about the processes in a dynamic Earth are represented by such mathematical-physical models which are applicable for geodesy. Moreover, there should be starting points for specific methods of investigation and for open questions which geodesy can work with so that it will be able to answer them.

Contribution of geodesy to the IGBP

In the last time the IAG had repeatedly been asked for contributions to the decisive problem of global changes of the geosphere and of the embedded biosphere. These are international current problems which will decide the fate of mankind in the future. At first sight such requirements seem to be irrelevant. On the other hand, geodesists are always characterized to be very critical, and to treat objectively problems in geosciences, and because of this they are able to make real contributions to these

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points and to prove speculations for their real content.
In particular, there are two complexes: the appearing variations of climate caused by astronomical processes and the proof as well as the monitoring of variations of the sea level, especially of the secular increase of the sea level with the consequence of an overflowing of large coastal areas. In both cases the relevant assumptions have to be proved scientifically, and efficient observations have to be installed which observe the supposed processes empirically. In both cases, the most interesting time scales cover the time interval of years up to a few centuries.

All complexes mentioned here are practical problems. It is possible to list a lot of geodynamic questions to geodesy of that type. In general, this always concerns the stability of the Earth's surface and of its relevant parts or points. Because of the dynamic character of the Earth as a whole and the manifold local and regional natural or technical deformations of the Earth's surface the present problem of geodesy is to prove and to monitor the permanently deforming surface where sudden as well as gradual changes are possible. Geodesy has to present reliable measurement data but it also has the aim to interpret these processes in cooperation with all the other geosciences. Doing so, geodesy has also to seek for the causes and to develop models which enable a prediction in time on the basis of possibly only a few observations being necessary permanently. Here, geodesy is able to make an important contribution to investigate the manifold natural disasters (earthquakes, volcano eruptions, slope slidings, collapse of subsurface cavities etc.) and to prepare the people to such processes in order to minimize their negative consequences.

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EARTH ROTATION PARAMETERS

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POSSIBLE CONTRIBUTIONS OF IERS TO GEODESY AND PHYSICS OF THE EARTH

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ZUSAMMENFASSUNG

Der Internationale Erderotationsdienst (IERS) hat die Aufgaben, das konventionelle terrestrische und inertiale Referenzsystem zu realisieren und aufrechtzuerhalten sowie die entsprechenden Erdrotationparameter zu uberwachen. Einige Beispiele direkter und indirekter Beifrage des IERS zur Geodasie und Physik der Erde werden beschrieben.

SUMMARY

The International Earth Rotation Service (IERS) is in charge of maintaining terrestrial and celestial conventional frames and of monitoring Earth's rotation.

The IERS work is based on observations of the Earth's orientation by Very Long Baseline radio Interferometry (VLBI), and laser ranging to the Moon and to the LAGEOS satellite (LLR, SLR). The general organisation of observations and analysis is described by Wilkins (1989). The global combination which yields the final IERS results on reference celestial and terrestrial reference frames and the corresponding Earth orientation parameters is performed by the Bureau Central. In the implementation of the algorithm initially adopted (Boucher et al. 1988), the data consist in results obtained by several analysis centres for the three participating techniques. These results include a terrestrial frame (coordinates of the stations), in the case of VLBI a celestial frame (coordinates of radio sources), and time series of the Earth Orientation Parameters (EOP: coordinates of the pole, universal time and, in some cases, celestial poleoffsets in longitude and obliquity with respect to the conventionaly adopted position).

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The IERS contributions to geodesy and physics of the Earth are therefore of two different natures. In the course of unification of systems, diagnoses on some systematic or random differences provide to the individual analysis centres a feedback that should be helpful to improve models or procedures. Besides these indirect contributions, direct contributions are through the final results of the service, such as the monitoring of a worldwide terrestrial frame and the establishment of long homogeneous series of the EOP, having the ultimate accuracy permitted by the observations available at a given epoch.

A primary condition for ensuring the accuracy of the IERS results is the homogeneization of the models and constants which are necessary for the analysis of observations. The IERS Standards (McCarthy, 1988) provide a detailed basis in this respect. They are a continuation of the MERIT Standards (Melbourne, 1983) and they are expected to be useful to space geodesy groups which are not directly participating to the IERS work.

The comparisons of time series of the EOP and reference frames, obtained independently from different observing network operation, or in parallel by different analysis centers from the same observations, make it possible to evaluate the precision and accuracy (or consistency) of the various individual systems.

The maintainance of the IERS terrestrial reference frame (Boucher and Altamimi, 1988) should provide an accurate basis for studies of tectonic motions or ocean tides. Its extension and connexion with geodetic datums should allow improved accuracy of satellite geodesy analyses (Boucher et al., 1988b).

The preparation of long homogeneous series of the Earth Orientation Parameters (Feissel and Guinot, 1988) and their revision whenever necessary would contribute both to the better understanding of the geophysical causes of the Earth rotation irregularities and to studies of the Earth potential using satellite observations since the beginning of space geodesy.

The IERS work is based on a close cooperation between analysis centres in many countries. through its Corresponding Members, IERS maintains a consultation process with the scientific community. Thus it provides a forum for scientific and technical discussion and the opportunity of extending the international cooperation in the field of Earth rotation and related reference frames.

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THE DEVELOPMENT AND ACTIVITIES OF THE INTERNATIONAL EARTH ROTATION SERVICE

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ABSTRACT. The International Earth Rotation Service (IERS) commenced its operations on 1988 January 1 and is responsible for monitoring the rotation of the Earth, for maintaining terrestrial and celestial reference systems of high-precision, and for disseminating appropriate data and results. IERS replaces both the International Polar Motion Service (IPMS) and the earth-rotation section of the Bureau International de l'Heure, Proposals for the establishment of the new service were put forward in 1985 by a Joint Working Group on Earth Rotation (MERIT) and Reference Systems (COTES), following a successful campaign of observation and analysis in which six different techniques were used. The techniques of very-long-baseline radio interferometry (VLBI) and both satellite and lunar laser ranging (SLR & LLR) are used in international networks to provide high-precision data and results on polar motion and universal time and on the positions of the observing stations. Data on the angular momentum of the atmosphere are obtained from meteorological centres, and other relevant data, such as station positions obtained by other techniques, are also collected. Predictions, rapid-service results and standard values of the earth-rotation parameters are disseminated by the Central Bureau and Rapid-Service Sub-Bureau of IERS. The results on reference systems and other information are to be published in the Annual Report of IERS. The participation of new stations able to make high-precision (centimetric) observations by VLBI, SLR and LLR would be welcomed, especially for strengthening and densifying the network of reference points that define the standard terrestrial reference system.

INTRODUCTION

The International Earth Rotation Service (IERS) replaced the International Polar Motion Service (IPMS) and the earth-rotation section of the Bureau International de l'Heure (BIH) on 1988 January 1. The change-over took place smoothly as the observational and operational procedures of the new service were the result of a gradual evolution over the preceding years of the decade. The IERS represents the latest stage in international cooperation in the monitoring of the rotation of the Earth. The International Latitude Service (ILS) commenced operations in 1899 and soon showed that the motion of the axis of rotation of the Earth within the Earth is a complex phenomenon that, unlike its motion in space, could not be predicted with reasonable accuracy. The BIH was initially concerned only with the distribution of time but it soon became involved in the determination of a standard scale of universal time for international use. The introduction of new observational techniques, such as the photographic zenith telescope, for the determination of both universal time and polar motion led to the replacement of the ILS by IPMS. The need to allow for polar motion in the determination of universal time led to the introduction of a rapid service for polar motion by BIH. The optical astrometric techniques were supplemented by the results from the Doppler tracking of the navigational Transit satellites. It was later shown that the new techniques of laser ranging and radio interferometry had high potential for the accurate determination of both universal time and polar motion.

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MERIT/COTES PROJECT

The presentations and discussions at IAU Symposium No. 82 on Time and the Earth's Rotation in 1978 led to the decision to set up an IAU Working Group to consider how best to utilise the new techniques of observation. The Group put forward proposals for Project MERIT to stimulate the development of the new techniques and to inter-compare them. In 1980 the IAU Colloquium No. 56 on Reference Coordinate Systems for Earth Dynamics drew attention to the need for more precise definitions of the terrestrial and celestial reference systems and led to the setting up of the COTES Working Group for the establishment and maintenance of a new conventional terrestrial system. Discussions between the two working groups took place at the first Merit Workshop at Grasse in May 1981 and eventually the two groups merged.

During the MERIT Short Campaign of 1980 six techniques of observation were employed and a series of operational networks and data-analysis centres were set up. Similar operational arrangements were introduced during the MERIT Main Campaign of 1983-84 and special COTES intensive campaigns were arranged to provide better data for the new terrestrial reference system. By 1985 the power of the new techniques was clearly apparent and the joint MERIT/COTES Working Group proposed the setting up of the new International Earth Rotation Service to be based on the use of only the three techniques of highest precision, namely, very-long-baseline radio interferometry (VLBI), satellite laser ranging (SLR), and lunar laser ranging (LLR).

The recommendations were endorsed by the IAU General Assembly at Delhi in 1985, and the Provisional Directing Board of IERS had the task of soliciting support for the new service. Then followed the more difficult task of deciding between alternative proposals for some of the activities; the resulting recommendations were endorsed at the IUGG General Assembly at Vancouver in 1987. These recommendations were based on the experience gained during the MERIT/COTES campaigns and the subsequent extension of the project to the end of 1987.

ORGANISATION OF IERS

The operational structure of IERS reflects the fact that there are three techniques of observation that can monitor the rotation of the Earth and establish international geodetic networks with a precision of a few centimetres. There are three Coordinating Centres that are each responsible for the organisation of the observations and data-processing associated with one technique. In addition, there is a Central Bureau that is responsible for collecting, combining, distributing and archiving the results from all three techniques and from other relevant activities. All of the operations are themselves coordinated by a Directing Board which consists of nominees (a) of each of the national organisations that host the three Coordinating Centres and the Central Bureau and (b) of the two unions (IAU and IUGG) that sponsor the Service and of the Federation of Astronomical and Geophysical Data Analysis Centres (FAGS), which provides some financial support especially for the production and distribution of the results and reports of the Service.

The Directing Board is expected to meet at least once each year to review the activities and to discuss how best the Service can be made more effective through the determination of results of higher precision and accuracy and through their distribution to the different types of users in appropriate and timely ways. The Directing Board is responsible for organising such other activities as are

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necessary to achieve the objectives of the service. A major task at the present time is to establish a new set of IERS standards that will replace the MERIT standards that are now in use.

The IERS depends on the support of a very large number of organisations throughout the world; some of these organisations operate just one observing station, but others are responsible for large networks of stations and for major data-analysis centres. The members of these organisations may make their views known directly to the Board or through the coordinators for each of the techniques. In addition the Board considers that it needs to be able to call on the advice of individual scientists and so it has set up a panel of corresponding members who will receive Board papers and be invited to comment on them; in addition, the Board will arrange open meetings at Union General Assemblies and other conferences so that the activities of the Service can be presented and discussed. This informal organisational structure is also based on the experience gained during the highly successful MERIT/COTES programme, but it has been adapted to meet the needs of a regular operational service that must satisfy the aspirations of research scientists as well as the day-to-day requirements of its regular users.

ACTIVITIES OF IERS

The principal activity of IERS is to determine and publish promptly the earth-rotation parameters that specify the varying position of the pole of rotation of the Earth with respect to the terrestrial reference frame and the variations of universal time (UT) with respect to international atomic time (TAI). These parameters, together with the motion of the pole with respect to the celestial reference frame due to precession and nutation, serve to establish the varying orientation of the Earth in space. Another major activity is to establish and then improve new standard terrestrial and celestial reference frames of the highest possible precision and to determine how the reference frames used implicitly by the different techniques of observation relate to the standard reference frames. The contributions of the various components of IERS to these day-to-day activities are summarised briefly in the following paragraphs. In addition there are data-analysis centres in countries other than those mentioned; as in the MERIT/COTES programme they will analyse the cumulative data each year using different software.

The Coordinating Centre for VLBI is based at the National Geodetic Survey in Maryland USA, and the principal observing network spans the Atlantic and consists of three stations in the USA and two in Europe. Observations are made regularly every five days and the data are correlated at the US Naval Observatory in Washington. Two stations of this Atlantic network make observations for a 2-hour period each day in order to provide data on the short-period variations in UT. There are other stations that make observations on a regular or occasional basis and a new network spanning the Pacific is under development. At present there is only one station in regular operation in the southern hemisphere; it uses a radio antenna of the US Deep Space Tracking Network in Australia. The VLBI technique is providing data on earth rotation and on station and radio-source coordinates of very high precision. The catalogue of radio sources is used to define the standard celestial reference frame of IERS, but the preliminary catalogue contains only 23 primary sources and all are north of declination -45°. The extension of this catalogue and the determination of the relationships of this standard frame to the stellar (FK5), planetary (DE200) and satellite (Lageos) reference frames will be an important future activity.

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The Coordinating Centre for Satellite Laser Ranging is based at the University of Texas at Austin, USA and the Service is supported by the data centres of the Goddard Space Flight Centre, Maryland, USA and of the Delft University of Technology in the Netherlands; there are some 30 stations that observe regularly. The principal target is Lageos and so the ephemeris of this object serves to define the celestial reference frame associated with this technique. The uncertainty in the rotation of this frame with respect to the radio source frame implies that the technique is at present limited to determining the motion of the pole and the short-period variations of universal time. The technique provides results of very high precision and the regular observations obtained for IERS can also be analysed to study other phenomena such as the variations in the gravity field of the Earth.

The Coordinating Centre for Lunar Laser Ranging is at CERGA, Grasse, France, and is supported by data centres at the Jet Propulsion Laboratory, California, and the University of Texas at Austin. At present there are only three stations in regular operation and so the full potential of the technique is not yet being achieved; it is hoped that three more stations will come into operation during the next few years.

The Central Bureau of IERS is based on the Observatoire de Paris with the direct support of the Institut Geographique National and the Bureau des Longitudes for the work associated with the terrestrial and celestial reference systems. The responsibility for the preparation and distribution of the weekly bulletin giving predictions and rapid-service results on the earth-rotation parameters has been delegated to a Rapid Service Sub-Bureau at the U.S. Naval Observatory in Washington, D.C. The Paris office prepares and distributes the monthly and special bulletins and will be responsible for the annual report which will give a combined solution for the earth-rotation parameters and catalogues defining the standard reference frames. A Sub-Bureau on Atmospheric Angular Momentum will be set up at the National Meteorological Center in Washington in 1989; at the present time a basic service is being provided by the U. K. Meteorological Office and the European Centre for Medium Range Weather Forecasting. Although there is a strong correlation between AAM and the length of day (LOD) the forecasting of AAM is not yet good enough to provide a significant improvement in the prediction of UT.

The preparation of a new set of IERS standards, which will include details of models and procedures to be used in the reduction and analysis of the observational data, is in hand. The initial IERS terrestrial reference frame will be based on the BIH terrestrial system of 1987 (for epoch 1984.0) and the Minster & Jordan (1978) model AMO-2 for the motion of the tectonic plates (BIH 1988). Observations of various kinds, including the colocation of mobile SLR systems at VLBI stations, are being made to establish better links between the reference frames of the different techniques. It is expected that GPS observations will be made to relate the IERS reference frame to other national and international geodetic networks. There are still some areas of the world, such as the USSR and the Southern Hemisphere, where there are very few stations whose positions are known accurately with respect to the network of IERS stations. New offers of participation in the IERS programme would be welcome.

A more detailed review of the MERIT/COTES programme and references to earlier reports are given by Wilkins and Mueller (1986) in the joint summary report of the MERIT/COTES Working Group. The proceedings of IAU Symposium No. 128 (Babcock and Wilkins 1988) provide a rich source of further information and discussions of general relevance to this paper. Further information about the current activities of IERS can be obtained from the Central Bureau and from the coordinators of the operational networks.

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EARTH ROTATION PARAMETERS: INTERCOMPARING DATA SETS AND GENERATING A COMBINED SOLUTION

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Abstract[3]

Two different approaches are proposed for generating a combined solution of ERP series. The first of them consists in joint solution for ERP and Sets of Station Coordinates (SSC), and is realised by BIH. The ERP and SSC data are considered separatively in the second approach. In this paper we consider the problem of intercomparing and combination of ERP data.

Several different stages could be distinguished.

I. First stage. Intercomparison different data sets derived with the same observational technique and processed by different centers of analysis.

For the determination of the weights of different time series of ERP the study of power spectrum of the errors of these time series was done. We derive different weights for different frequency regions in such a way

$$W_K = 1/\mathcal{D}_K \tag{1}$$

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where

$$\mathcal{D}_K = \sum_{f_1}^{f_2} S(f) / |F(f)|^2 \qquad (2)$$

$S(f)$ is power spectral density function,

$F(f)$ frequency response of the smoothing operator.

The total weight of time series is defined as

$$w = 1 / \sum \mathcal{D}_K \qquad (3)$$

The iterative method of determination is used and combined solution is constructed. In table 1 the values of $1/w$ for different time series are given.

<u>II. Second stage.</u> Intercomparison of data sets derived with different observational techniques.

As a result of first stage we have for each technique

$$x_c = \sum_{j=1}^{M} x_j \bar{w}_j \qquad (4)$$

where $\bar{w}_j$ is total normalised weight

$$\bar{w}_j = w_j / \sum_{j=1}^{M} w_j \qquad (5)$$

and

$$\sigma_{x_c} = \left(\sum_{j=1}^{M} w_j \right)^{-1} \qquad (6)$$

The special procedure is proposed for determination of reference system of ERP and the generating of combined solution. This procedure relies upon the analysis of differences

$$(x_{ij})_c - (x_i)_{ST} \qquad (7)$$

where i is time of observations and j is a number of technique, $(x_i)_{ST}$ is a priori choosen standard solution used for determination of weights with the iterative method of maximum likelihood proposed by Morse and Bickle (Morse P.M., Bickle A., 1967)

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Table 1. Values of $\wedge / w$ for some series used. (in 0".001).

N	Code	X	Y
1	ERP(CSR)85L07	1.1	0.8
2	ERP(DGFII)85L04	1.0	0.8
3	ERP(GAOUA)85L02	1.0	0.8
4	ERP(GRGS)85L01	3.0	3.2
5	ERP(NAL)85L02	1.0	0.5
6	ERP(SHA)85L01	1.4	1.2
7	ERP(UPAD)85L01	2.5	1.8
8	ERP(ZIPE)85L01	0.9	0.7

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ON SHORT PERIODIC PHENOMENA OF POLAR MOTION

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Summary: Considering the spectral range from 5 to 100 days results of time series analyses are presented for VLBI and SLR polar motion data. Some aspects of interpretation and excitation are discussed.

1. Introduction

Only for several years (an early trial: cf. MOCZKO 1979) short periodic effects of the polar motion in a range from 5 or 10 days to 100 or 150 days are investigated. The LOD-component of the Earth rotation vector had already been analysed with great success because of its more significant amplitude structure than polar motion basing on its linear nearly undamped relationship to the equatorial atmospheric angular momentum component (MORGAN et al. 1985, HEFTY 1986). In contrary to this good correlation any outstanding polar motion amplitudes in the same frequency band could hardly be expected from gyroscopic theory due to axis stabilisation and damping. Moreover from another point of view the complex and urgent problems in studying the mean periodic Chandlerian motion were (and are still) dominating topics.
The data from modern geodetic techniques (SLR, VLBI), especially beginning with the MERIT campaign (september 1983), gave the possibility to analyse the short periodic phenomena of polar motion (cf. f. i. Prague 1986). The low noise in the measurements and thus in the calculated polar motion data (now about at the one milliarcsecond (mas) level) revealed a very smooth pole curve in contrary to classical results. The short periodic spectral structure could be recognized more and more clearly and could be better constrained on the basis of the increasing length of the data interval. Recently some time variable effects were found in the short periodic range (KOLACZEK and KOSEK 1985, SCHUH 1988,

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NASTULA 1988 pers.comm.).However, the excitation causes can be declared by means of the atmospheric effects only partially until now. Further "sources" have to be included or identified, respectively, as stated in (EUBANKS et al. 1988). The paper presented here can be considered as the direct continuation of (BALLANI 1988) having dealt with some special MERIT time series of the CIPE MERIT analysis center.

2.Data material and time series processing

The MERIT campaign was the beginning of usable high quality polar motion data series from cosmic geodetic techniques with one mas precision as a mean value for the single point. The precision has increased only a little since then (cf.f.i.SCHUH 1988 : 0.7 mas, BIH 1986,1987).Of course, these evaluations have the character of (inner) precisions.The (outer) accuracies estimated from the comparison of different data sets exceed these values by 50 to 100 per cent and thus vary between one and two mas for the polar motion components x and y.

The analyses carried out here use 4 data series.Table 1 contains some main features. Three of the data series were sent to us from IERS by tape .The polar motion data set IRIS84-87 was taken from the IRIS Bulletin and is a preliminary version of the VLBI series from NGS.

The data time series analyses which on the one hand allow to recognize time-variable geophysical-geodynamic effects and on the other hand exclude artefacts extensively at the same time have to take into account the following "strategic" points of view (only a few of them can be considered here explicitely):

- The sufficient length of the data interval (4 years) is an important precondition for the fulfillment of statistical stationarity. The usage of filters or the separate determination and subtraction of harmonic trend components is not nessecary for the frequency analysis then. Additionally, sliding analyses give the possibility to study time variable effects.
- The application of different time series procedures can compensate their weaknesses and allows to stress their specific different advantages (sensitive period range,resolution/separation of frequencies, estimation of amplitudes,analysis of nonequispaced data series).
- Using polar motion data won by different modern geodetic tech-

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niques can help in revealing artefacts being specific for the single technique.

- The analysis of pole curves which are parametrized in different forms(Cartesian (x,y)- or polar(r,φ)-coordinates:"cross track, along track") frees from the shortages of the individual coordinate decomposition (f.i. trend problem and numerical shifting effects) and thus gives a surer basis for the interpretation as remarked in (SCHUH 1988).

For the time series analysis the following three procedures were applied:

1) the Fourier based method PERO generalized for nonequispaced data (JOCHMANN 1986,BALLANI 1989)
2) Procedures of spectral analysis working with the help of the fast Fourier transform (FFT) in the form of the Blackman-Tukey estimation with Bartlett and Parzen windows and on the other hand in the form of Maximum Entropy Spectral Analysis (MESA) by Burg (AURASS et al.1987).
3) a simple method for the evaluation of the fitting of a single harmonic plus a cubic trend function to the given time series HCF (HARNISCH 1985).

Data series which are nonequispaced like ERP(CSR) can only be analysed (from a rigorous point of view taking not into account any interpolation) properly by the first method. The amplitude values were calculated above all with method 2) via Bartlett and Parzen estimation. For the study of time variable effects all three methods were included in the investigations. The most precise results came from the short period sensitive MESA method depending mainly on the well chosen length of the autocovariance function (AKF).

3. Results:Periods and Amplitudes

3.1

Time series analysis for the whole interval from 1984 up to the end of 1987 comprehends all frequencies between the Nyquist frequency (of 1/10d for the data series ERP(NGS), ERP(BIH), ERP(IRIS)) and a different lower bound depending above all on the time series procedure applied. From different reasons (stability of results, data interval, frequency resolution, stationarity) the limit will be here 80...100d. The frequency results will have in every case the character of an average in relation to the

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actually used data interval: Persistent , non-persistent and time variable waves are collected and compressed or splitted, as well. The application of different time series procedures as mentioned above for the whole data interval of four years with varied sensitivity parameters can only be presented here in a compiled manner (Fig.2.,Tab.2). However some typical properties are remarkable: The PERO method is in general more sensitive and significant for the longer periods in comparison with the MESA, while the quality of the HCF procedure is independent from the period range, but probably provides too many periods. It is typical that the Fourier method PERO shows in some cases frequency bands instead of single lines .This effect corresponds to the frequency splitting in the MESA , but not in all cases (see below).

Table 2 contains a synoptic proposal compressing all frequencies found in the whole data interval after comparing and weighting. It is interesting - in comparison with (BALLANI 1988) -that the uncertainty of the resulting frequency intervals could be further reduced. The main reasons are the length of the data interval and the diminished error of the single data point. With the 5-day and 3-day series from the MERIT material(only for the best series!) however results of similar quality at least for the shorter periods can be reached.

Table 3 contains some results of amplitudes of polar motion r-series ($r=(x^2+y^2)^{1/2}$) via BTS-Bartlett and -Parzen estimation. This parametrization provides more reliable and stable results than the single x and y series.

The estimation of a realistic amplitude error is a difficult task. The usage of noise investigations, variations of parameters and comparing the results of all three time series procedures leads in general to error values between 30 and 50 per cent of the amplitude amount.

3.2

The length of the data interval gives the possibility to investigate temporal changes of the polar motion spectral structure. This time dependence can be expected at least partially due to the atmospheric excitation portions(EUBANKS et al. 1988) correlated with the polar motion. The investigation of these temporal changes were performed by sliding analyses, above all with the procedure MESA best suited. The other procedures were

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included too.
Resulting from comprehensive tests it follows that the step by step shifted interval should have the length of about one year in order to guarantee the significant separation of periods . This depends on the intended range of periods and the data point distance as well. The choice of 6-month intervals (after theoretical criteria sufficient in most cases) however leads to strongerly scattered frequency results which can be hardly interpreted.The figures 3.1....3.15 contain some of the results for several period ranges for the components x and r of the data series ERP(NGS) and ERP(BIH) to demonstrate different cases. Each of these (frequency) points represents the center of a one-year data interval which is shifted in steps of 30 days (6 data points).It must be noted that the frequency results for MESA up to longer periods will be coarser because of the screening of MESA frequencies depending on the length of the FFT. Moreover it is a problem to find the optimum for the length of the autocovariance function (LAKF) for the one-year interval in order to separate the different origins for the MESA frequency splitting from each other: the temporal variability within one year or/and an oversized autocovariance function length (cf.figs.3.1 ... 3.15). In any case the visible , more or less scattered, frequency point sequences belonging to different frequencies are separated significantly from each other, if the period length of the frequency difference is contained at least once in the whole data interval as a fundamental criterion (KURTHS 1982).In the cases of the more or less clear point sequences represented in the figures 3.1...3.15 this condition is always fulfilled. The results for x- and r-parametrization show some differences reflecting probably numerical stability.

4. Remarks to theory,interpretation and excitation

After some years with intensive activities in exploring the spectral structure of the short periodic polar motion the question for its causes ("excitation") became a more and more burning topic (like a century ago and until now for the Chandlerian motion).Comprehensive attention had been already devoted to mass geometric and relative angular momentum changes of the dynamic atmosphere. Atmospheric excitation functions are regularly calculated in intervals of 12 hours by different centers

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on the basis of worldwide data material.
Recent very well founded investigations have demonstrated by means of correlation analyses that the atmospheric effects cannot be the unique excitation source for the short periodic polar motion. The atmosphere can at most contribute to about 60 per cent (EUBANKS et al. 1988). However, an important part of the time variability (which has to be further investigated !) -that means non-persistent waves, variable amplitudes, phases and frequencies -should have immediately or indirectly meteorological (and oceanic) reasons. From the Earth rotation theory and the magnitudes of possible globally geodynamic effects it must be supposed that the discussed excitation sources are effects of second order which are possibly interacting and thus resulting in a certain nonlinear (or perhaps chaotic ?) behaviour. Of course this is connected with the type of the modelling integro-differential equation system.
In detail the following excitation mechanisms (and artefacts from time series analysis) for the short periodic polar motion have to be taken into account:

- An exponentially damped harmonic motion (f.i. Chandlerian motion in our interval) provides a set of discrete spectral lines in the short periodic range if a normal time series procedure is applied. The simple modelling of a harmonic one-year term superimposed with an exponentially damped harmonic Chandlerian term (in relation to realistic dissipation Q values) leads to amplitudes , above all in the medium range, which are comparable to observable ones in the frame of the general error intervals given in the tables 2 and 3. However, synthetic sliding analyses do not show any remarkable time variable frequency effect. But only some splitting and no shifting influence to additional waves could be found as observed with real data in figures 3.1 ... 3.15.

- Inhomogeneities in the rheology can shift the energy to other frequency bands. This is a well known fact in seismology. The theoretically founded supposition on the existence of an half-Chandlerian wave(valid or not) belongs to this type of possible excitation mechanisms (JOCHMANN 1981).

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- The appearance of frequencies in the polar motion possibly identical with zonal tidal frequencies (cf. table 2 ,fig.2) in principle could have two different causes:

  1) The nonlinear coupled differential equation system of gyroscopic motion contains the Earth rotation vector components ω_1, ω_2, ω_3 in nonlinear mixed form, so that periodic fluctuations of ω_3 (LOD influence from zonal tides) possibly can be transferred to the polar motion (ω_1, ω_2)
  2) The inhomogeneous continent-ocean distribution can transform zonal into tesseral tides via mass geometry. Tesseral tides can influence polar motion (JOCHMANN, pers. comm. 1987).

- The "normal" half and one-day tesseral tides influence the polar motion in direct way and can appear in the polar motion data (5 day distance f.i.) by the aliasing effect(HÖPFNER 1974).

- The (nonlinear) coupling of the media, which can have possibly in their motion behaviour some eigenfrequencies strengthening the amplitudes can play an important role . The problem of the degree of validity of the inverted barometer hypothesis is related to this coupling effects. It depends on the rheological properties of the ocean surface in the period range considered here.

- Torques on the Earth generated by atmospheric wind and pressure changes and the angular momentum exchange are transferred to polar motion in a very "inefficient" relation: Typical values of the corresponding transfer coefficients k only in the case of mass geometrical pressure changes are the following ones:

$$k(50d) \approx 1/10 \qquad k(9d) \approx 1/50$$

- Hydromagnetic waves in the Earth's fluid outer core can perhaps lead to polar motion excitation effects (GREINER-MAI, pers. comm. 1988, HIDE 1966). But the evidence for this possibility probably cannot be secured by additional geomagnetic indications on the surface of the Earth. Moreover, the Earth mantle rheology which is only very poorly known in the considered spectral range must be taken into account.

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5. Conclusions

Methodically refined time series analysis of polar motion in the short periodic range (10d...100d) reveal time variable structures with high significance. For the excitation of this part of polar motion some proposals on the basis of geodynamic interdependences and numerical artefacts are given. Most of the problems are still open. A better understanding of the correlation and the time dependent behaviour between polar motion series and the related effective angular momentum functions will be reached by spectral cross correlation procedures(cf .f.i. KOSEK 1986) and above all by further detailed physical modelling. The theoretical study of the possible effects of excitation mentioned above and their interactions require the developement of an Earth rotation theory of second order in which the dominant effects from Chandlerian and annual motion had been reduced to a certain degree. Moreover, the nonlinear behaviour of the ocean and its coupling have to be investigated in detail.

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Table 1:
Polar motions data series in the interval (1984.0,1988.0)

Data series	data point interval [days]	number of points	mean accuracy [mas]	equidistance
ERP(NGS)88R01	5	302	0.8	possible by interpolation
IRIS84-87	5	235	<1.0	possible by interpolation
ERP(CSR)86L01	3.55	411	<1.0	no
ERP(BIH)82C02	5	292	<1.0	yes

Table 2:
Compressed time series analyses results:
mean periods [days] from 3 methods and 4 data series
for the polar motion x component

10.6	22.0 ... 22.4
11.0	26.0 ... 28.0
11.4 .... 11.6 (?)	29.8 ... 31.8
12.25 ... 12.5	34.4 ... 36.0
13.5 .... 13.6	46.5 ... 49.1
14.05 ... 14.20	59.5 ... 61.5
15.1 ... .15.2	64 66
16.95 ... 17.10	69 71
18.10 ... 18.35	77
20.7 .... 21.2	80 82

Amplitudes: 0.7mas... 4.0 mas ±30%...50%

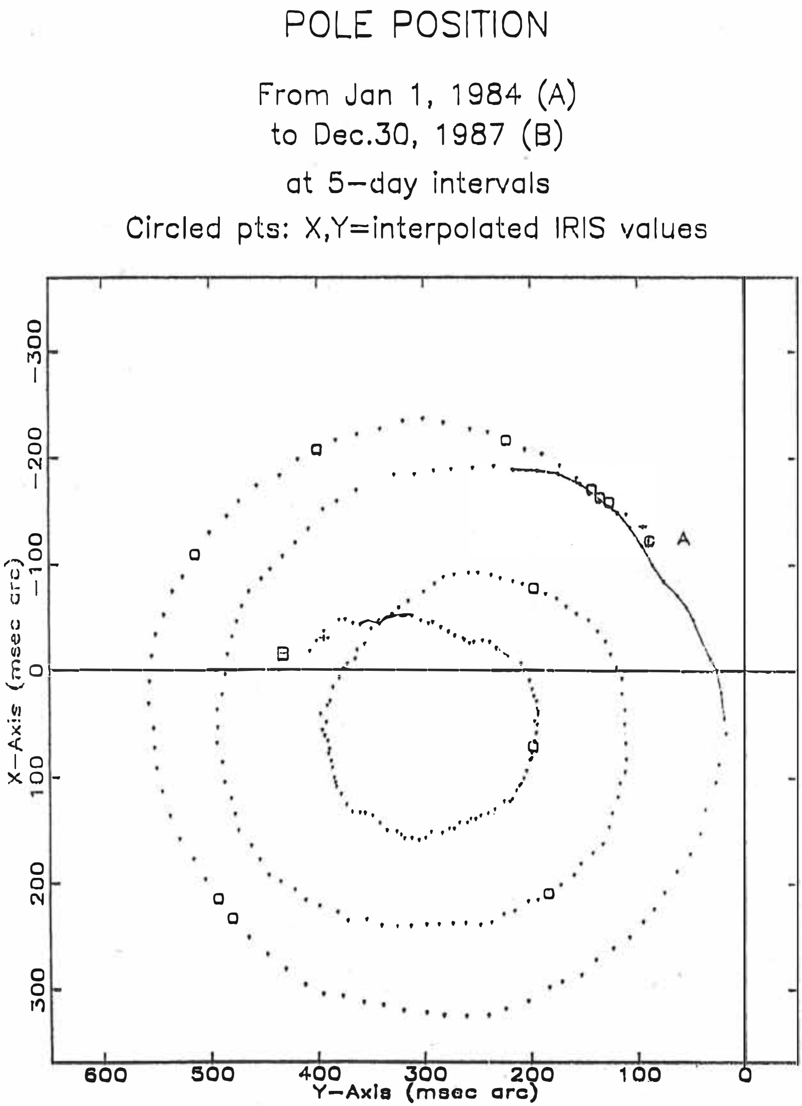
DOI: https://doi.org/10.2312/zipe.1989.102.01

Table 3:
Amplitudes estimated from the Blackman-Tukey procedure (Bartlett- and Parzen window) for the polar motion r-component from ERP(NGS) (relative error ±30%...50%).

Period [days]	Amplitude [mas]
10.6	1.0
11.1	1.2
11.8	1.2
12.5	0.8
13.3	1.0
14.2	1.2
15.3	1.1
16.3	1.1
18.2	1.5
20.4	1.4
22.1	1.5
28.4	1.9
33.0	2.0
40.5	2.3
66.0	3.7

DOI: https://doi.org/10.2312/zipe.1989.102.01

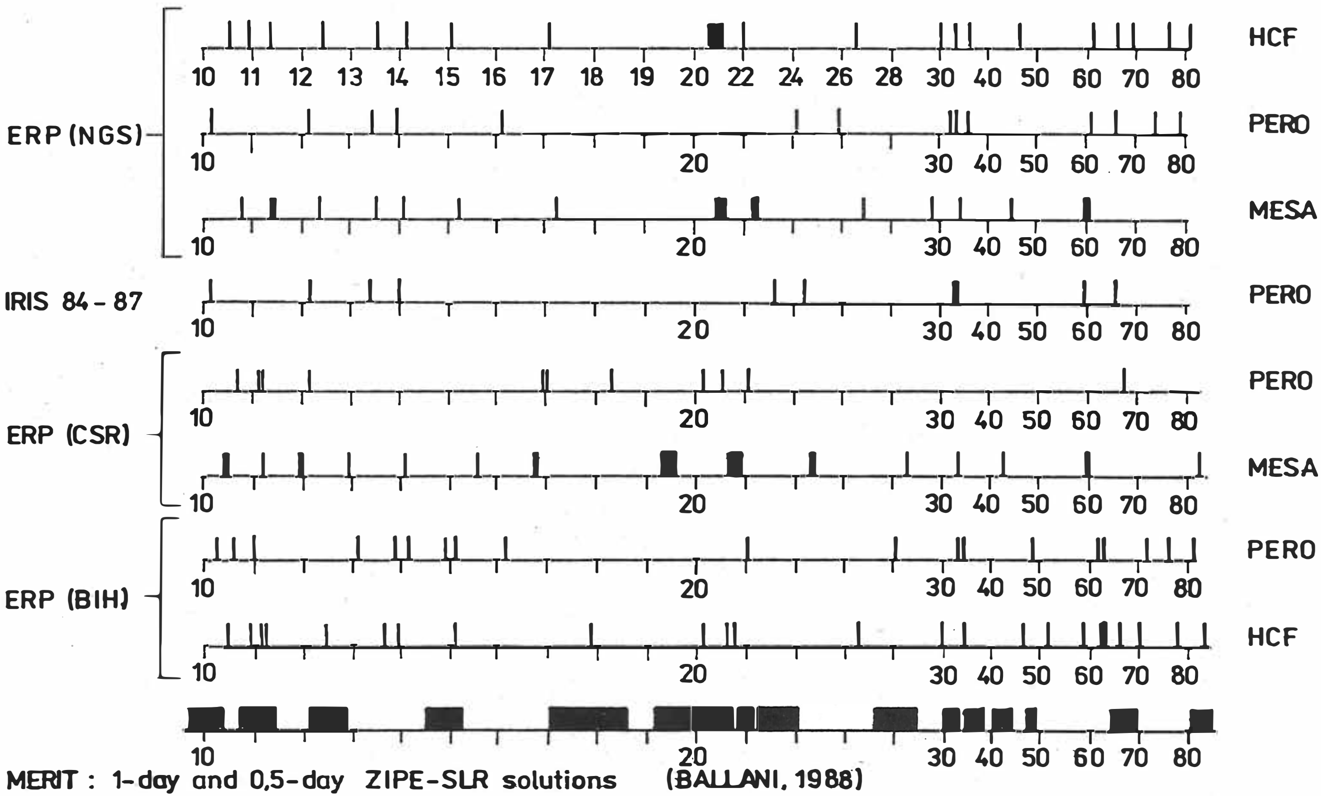
Figure 1:
Polar motion from VLBI : ERP(NGS)
(from IRIS Bulletin)



DOI: https://doi.org/10.2312/zipe.1989.102.01

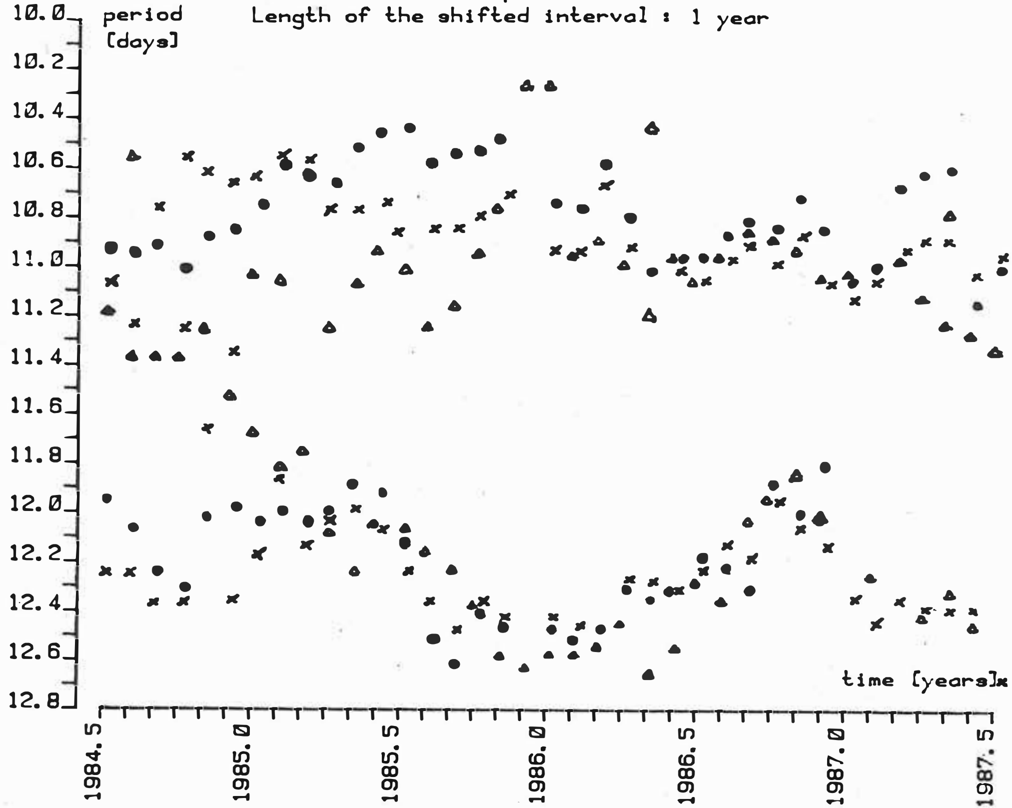
Figure 2 :

Comparison of time series analyses results (periods[d]) for the polar motion x-component: different data series and procedures



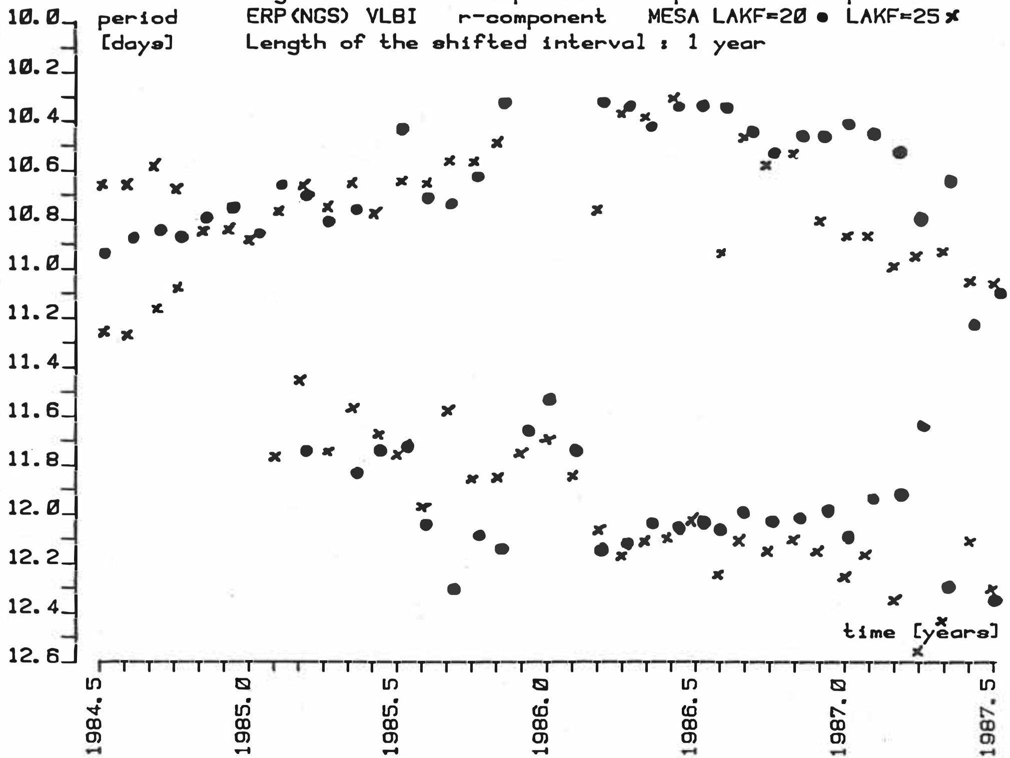
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.1 : Time dependence of polar motion periods
ERP(NGS) VLBI x-component MESA LAKF=20 ● LAKF=25 ×
ERP(BIH) x-component MESA LAKF=25 △
Length of the shifted interval : 1 year



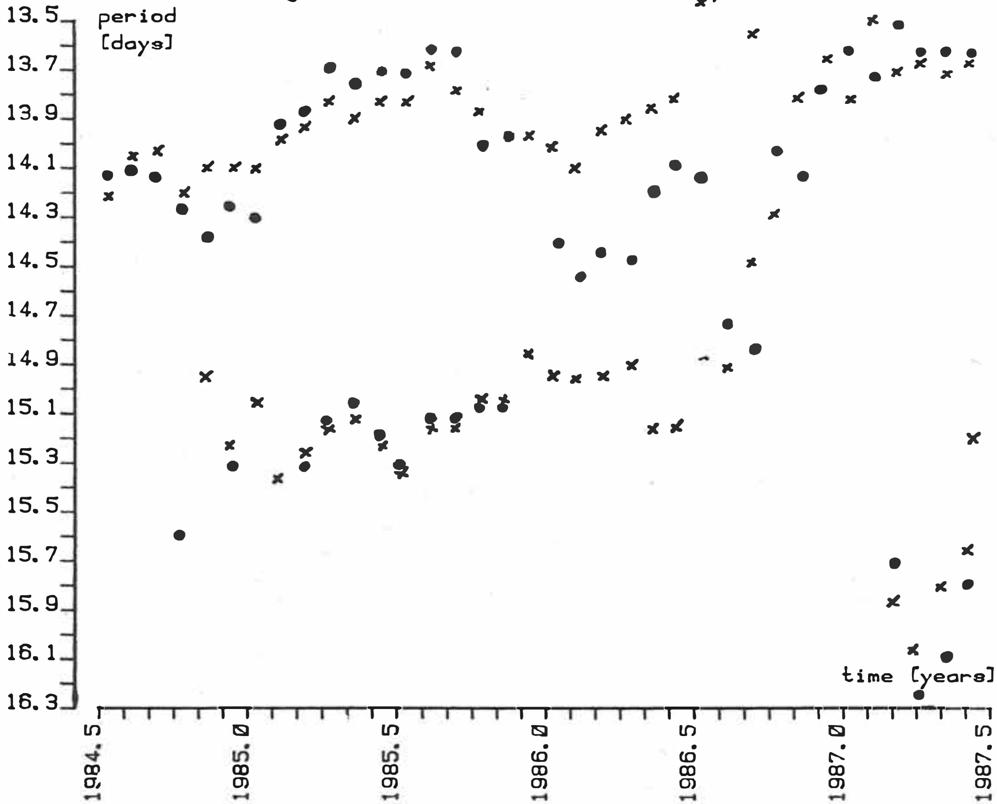
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.2 : Time dependence of polar motion periods
ERP(NGS) VLBI r-component MESA LAKF=20 ● LAKF=25 ×
Length of the shifted interval : 1 year



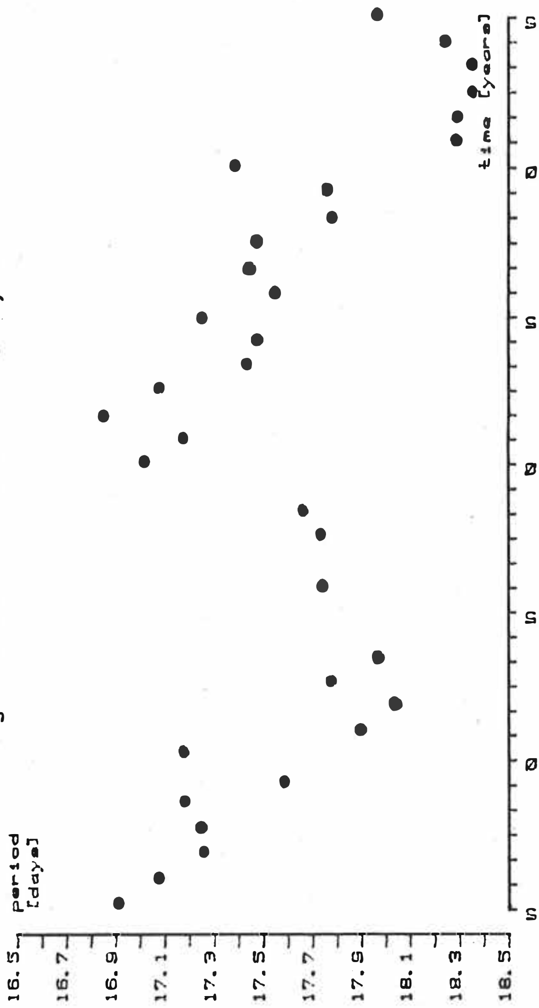
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.3 : Time dependence of polar motion periods
ERP (NGS) VLBI x-component MESA LAKF=25 ● LAKF=30 ×
Length of the shifted interval : 1 year

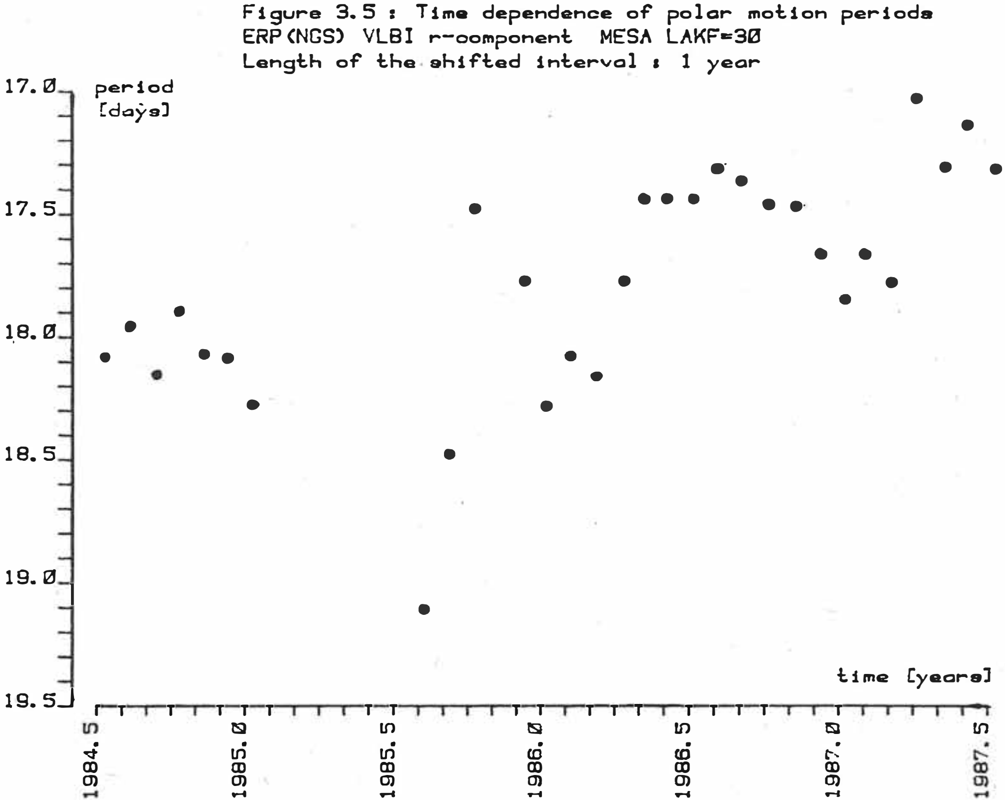


DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.4 : Time dependence of polar motion periods
ERP(NGS) VLBI x-component MESA LAKF=25
Length of the shifted interval : 1 year



DOI: https://doi.org/10.2312/zipe.1989.102.01



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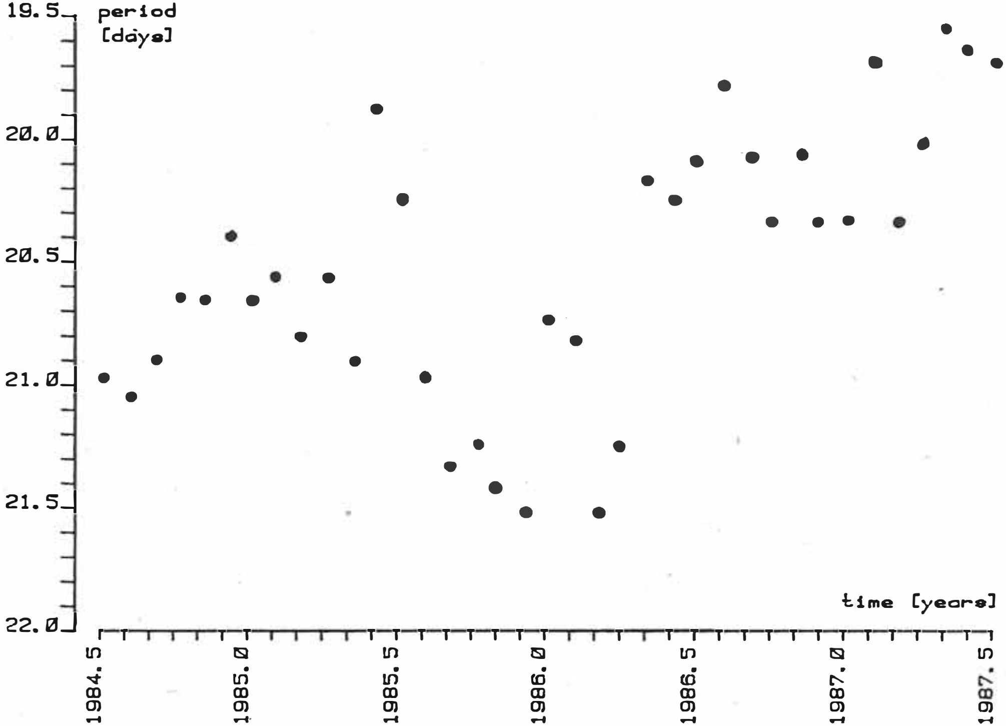
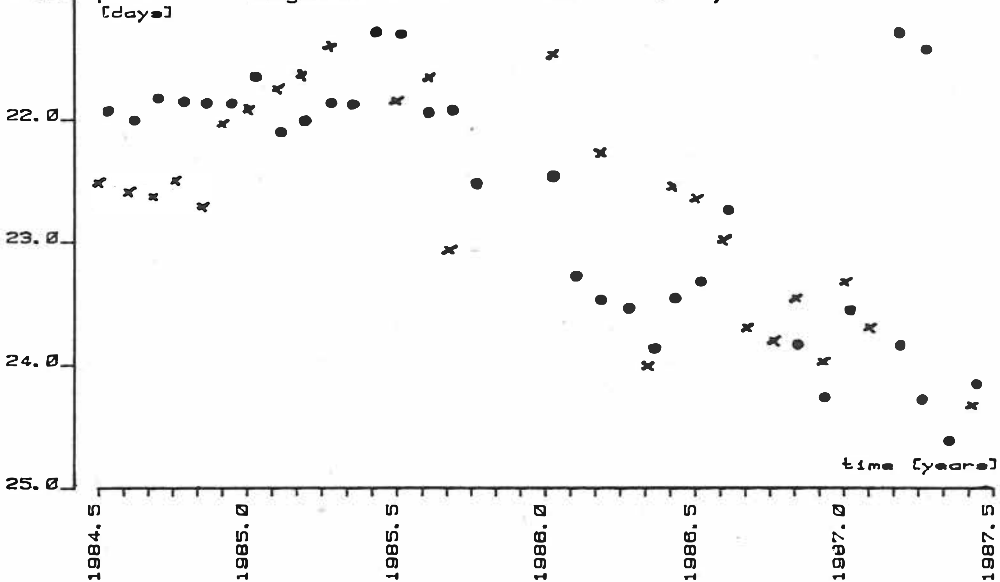
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.6 : Time dependence of polar motion periods
ERP(NGS) VLBI r-component MESA LAKF=30
Length of the shifted interval : 1 year



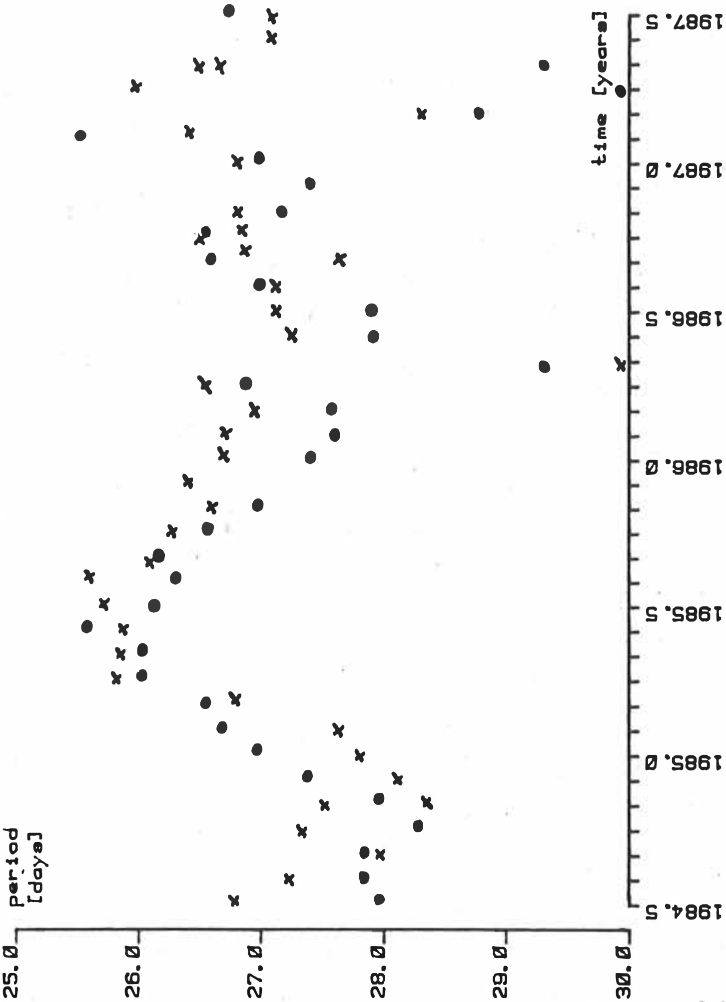
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.7 : Time dependence of polar motion periods
ERP (NGS) VLBI x-component MESA LAKF=30 ●
ERP (BIH) x-component MESA LAKF=30 ×
Length of the shifted interval : 1 year



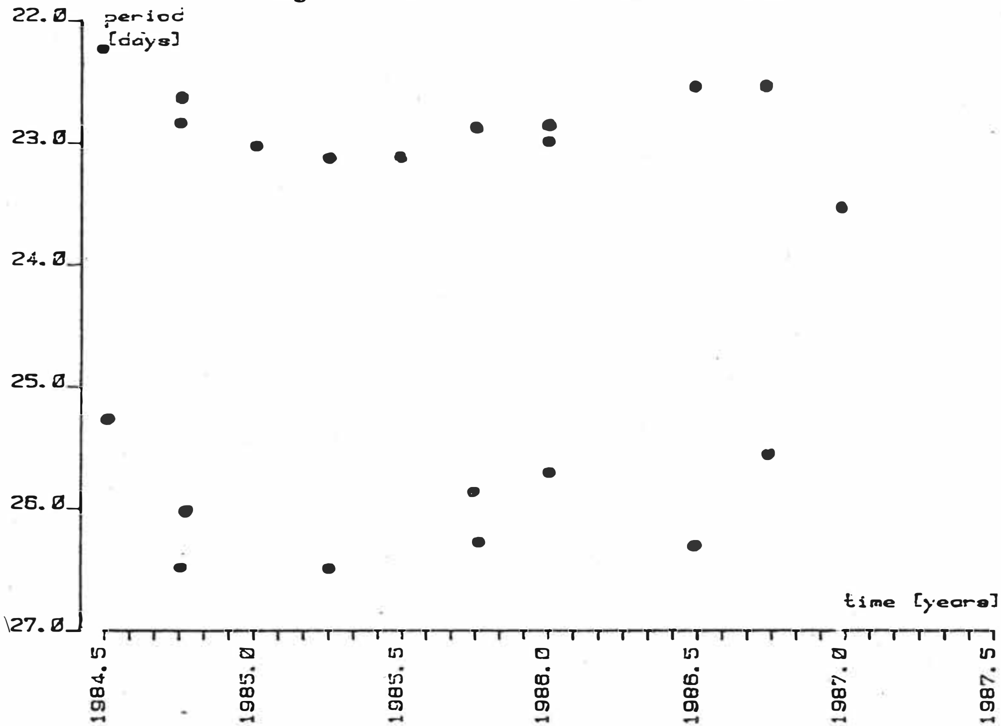
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.8 : Time dependence of polar motion periods
ERP(NGS) VLBI x-component MESA LAKF=30 ●
ERP(BIH) x-component MESA LAKF=30 x



DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.9 : Time dependence of polar motion periods
ERP (CSR) SLR x-component PERO
Length of the shifted interval : 6 months



DOI: https://doi.org/10.2312/zipe.1989.102.01

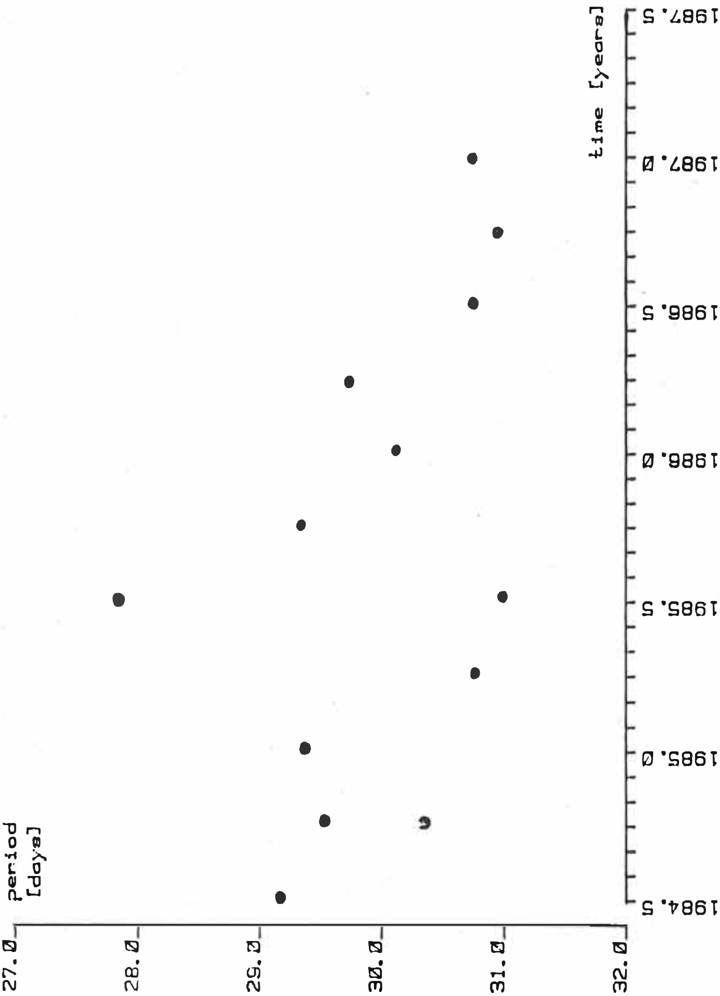


Figure 3.10 : Time dependence of polar motion periods
ERP(CSR) SLR x-component PERD
Length of the shifted interval : 6 months

DOI: https://doi.org/10.2312/zipe.1989.102.01

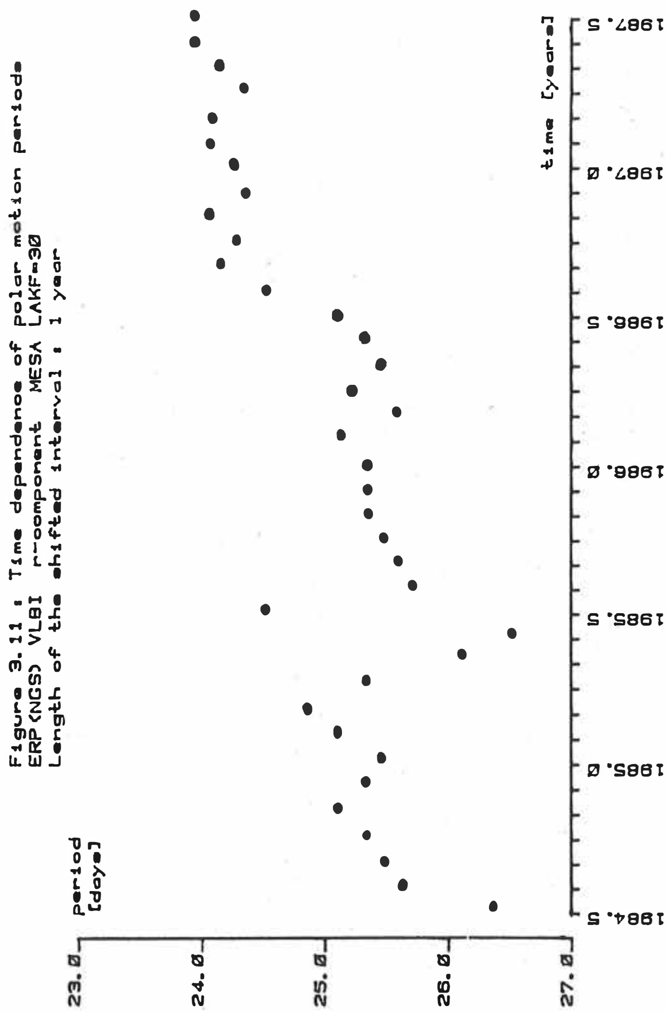
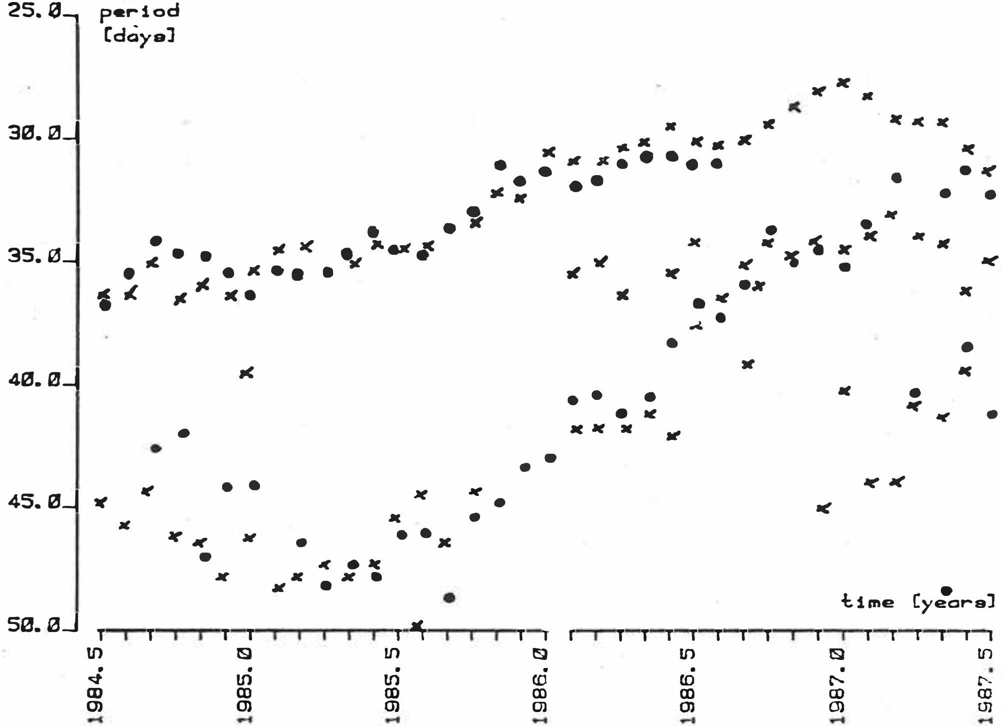


Figure 3.11 : Time dependence of polar motion periods
ERP(NGS) VLBI r~component MESA LAKF=30
Length of the shifted interval : 1 year

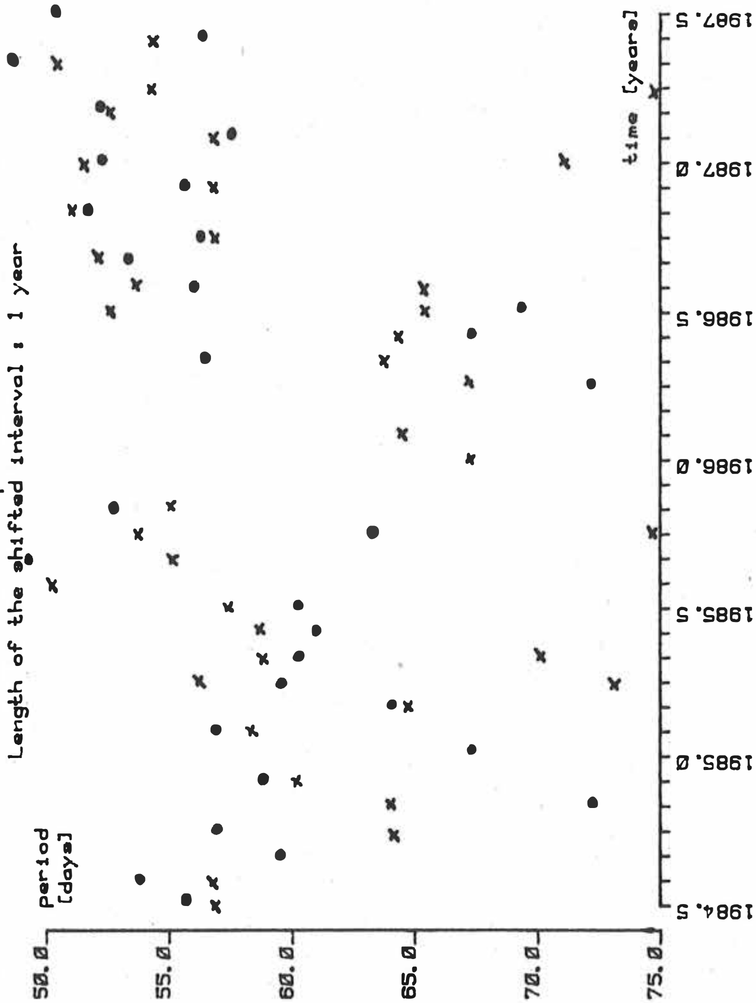
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.12 : Time dependence of polar motion periods
ERP(NGS) VLBI x-component MESA LAKF=35 ● LAKF=45 ×
Length of the shifted interval : 1 year



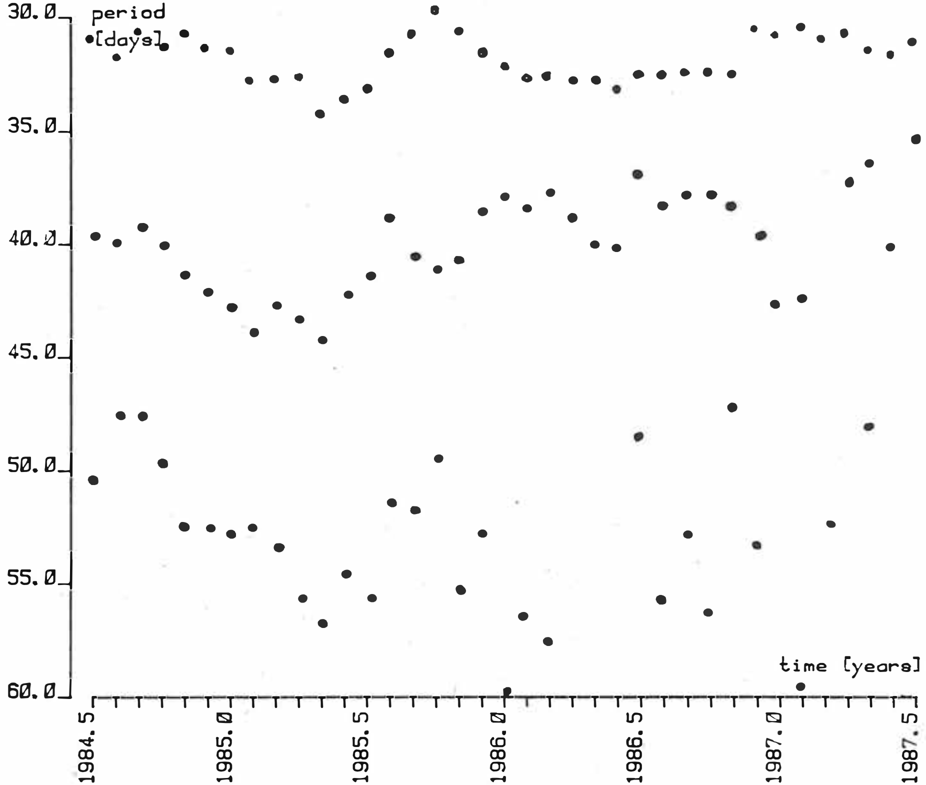
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.13 : Time dependence of polar motion periods
ERP(NGS) VLBI x-component MESA LAKF=35● LAKF=45 x
Length of the shifted interval : 1 year



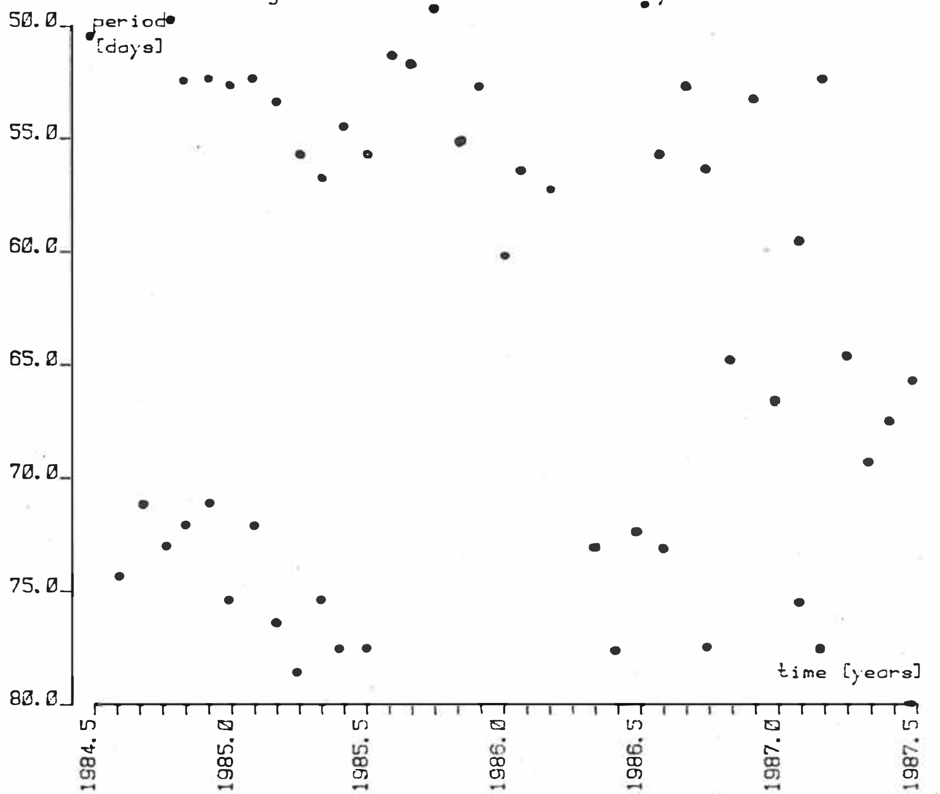
DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.14 : Time dependence of polar motion periods
ERP(NGS) VLBI r-component MESA LAKF=35
Length of the shifted interval : 1 year



DOI: https://doi.org/10.2312/zipe.1989.102.01

Figure 3.15 : Time dependence of polar motion periods
ERP(NGS) VLBI r-component MESA LAKF=35
Length of the shifted interval : 1 year



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AUTOMATED STAR IDENTIFICATION

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Abstract. An algoritm for automated star identification by computer is described. Long-time experience in plate reduction at Riga satellite tracking station has shown the algorithm to be well suited for its purpose.

Let P be the set of reference stars from the plate and C - some set of the catalogue stars from the photographed region of the sky. The rectangular coordinates (x,y) of reference stars from plate have been measured and the spherical coordinates from the catalogue are converted into the standard coordinates (ξ,η) at the scale of optical system. Let us assume the following items as elements of both the frame and the catalogue:

(i) the stars represented with their numbers,

(ii) the vectors connecting all the couples of stars as well as the directions and the modules.

Let i,j denote the numbers of stars from set C, i.e. from the catalogue, and s,t -the numbers of stars from set P, i.e. from the plate. Let the module of vector (i,j) be denoted by $d(i,j)$ and the direction by $\alpha(i,j)$ and the same for vector (s,t) correspondingly. The relations between the coordinates of the plate stars and the standard coordinates of the catalogue stars in general form is described by

$$C=\varphi(P),$$

or with the following basic formulas of linear transformation

$$\left.\begin{aligned}\xi_i &= M\cos\mu\, x_s + M\sin\mu\, y_s + e\\ \eta_i &= M\cos\mu\, y_s - M\sin\mu\, x_s + f\end{aligned}\right\}\qquad (1)$$

$$i=\varphi(s),\ i\in C,\ s\in P.$$

The case is discussed, when both the coefficients of transformation and the correspondence of the indexes, i.e. the numbers of the plate star images in the catalogue are unknown.

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Before discussing the algorithm of star identification let us look at some relations which apply to already identified stars. In such a case every plate star has an image in the catalogue

$$\forall s \quad \exists i \qquad i = \varphi(s)$$

and the coefficient M equals the quotient of the modules

$$\frac{d(\varphi(s), \varphi(t))}{d(s,t)} = M,$$

but the difference of the directions in one system of coordinates and the other one correspondingly gives the angle

$$\alpha(\varphi(s), \varphi(t)) - \alpha(s,t) = \mu .$$

Consequently a star i from the catalogue has a prototype from the plate belonging to the intersection of sets of pairs of stars with the mentioned properties

$$\varphi^{-1}(i) \in \bigcap(\{s,t\} : \exists j\, (\frac{d(i,j)}{d(s,t)} = M \;\&\; \alpha(i,j) - \alpha(s,t) = \mu)) =$$

$$= \{ s : \exists t \; \exists j\, (\frac{d(i,j)}{d(s,t)} = M \;\&\; \alpha(i,j) - \alpha(s,t) = \mu) \}$$

and this intersection generally does not give an empty set in practice. These formulas form the basis for the star identification algorithm, while the purpose is to avoid all the noises which occur in practice when some plate stars could have no images in the catalogue at all and there is a large amount of catalogue stars mistakenly selected for identification among the actual pretendents of plate star images. The aim is to have a fast and reliable algorithm.

Let us start the discussion of the algorithm now. The first step of identification is to compute all the modules of the vectors for all the pairs of stars from the plate. These data are stored according to the values of the modules in certain "boxes"

$$N_l := \{\langle s, t, d(s,t)\rangle ; \; E(\frac{d(s,t)}{\Delta d}) = l \},$$

where $E(x)$ means the integer part of a real number, Δd - the step by which the value range is partitioned. The set N represents all the pairs of stars from the plate with $s<t$

$$N := \bigcup (N_l : \; E(\frac{\min d}{\Delta d}) \leq l \leq E(\frac{\max d}{\Delta d})) .$$

Let some random star i from the catalogue be taken as the pole of diverging vector's set. The set W_i''' is obtained

$$W_i''' := \{\langle j, s, t, \Delta M\rangle : j \in C \;\; s,t \in N_q \;, q = E(\frac{d(i,j)}{\Delta d}), \Delta M = (\frac{d(i,j)}{d(s,t)} - M) \leq \varepsilon_1 \}. \quad (2)$$

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The index q is calculated in order to determine the "box" number, which is used to find quickly the likely vector modules from the plate. The identification parameter $\mathcal{E}_1$ is a rough estimate of the coefficient's M inaccuracy for a definite optical system with a certain accuracy of the optical center prediction. It should be determined by the routine's user beforehand.

Let w denote the cortège from a set W_i''' and $w[1],\dots,w[4]$ be four of its components. The determination of prototype $\varphi^{-1}(i)$ for the star pole i could be achieved by intersection [1]

$$\bigcap(\{w[2],w[3]\} : w \in W_i''') = \{s \in P : \exists w \in W_i''' \quad s \in \{w[2],w[3]\}\},$$

but the noise can result in an empty set and this way is doubtful.

Let us introduce identification parameter $\mathcal{E}_1'$ as a more accurate estimate of the coefficient's M deviation caused by the errors of star coordinates. For convenience, in further calculations let us substitute the values

$$w[4] := E\left(\frac{\Delta M}{\mathcal{E}_1'}\right).$$

Now let us select a set of those cortèges, which has the values of $w[4]$ repeated among all of those components the maximum number of times and not less than the preset threshold r_1

$$W_i'' := \{w \in W_i''' : \sigma_{iw} = \max\{\sigma_{iw'} : w' \in W_i'''\} \geq r_1\},$$

where

$$\sigma_{iw'} := |\{w'' \in W_i''' : w''[4] = w'[4]\}|.$$

The new value of the pole index is fixed and the new set of W''' is obtained if the set W_i'' turns out to be empty. Otherwise it is assumed that a star s_i from plate has been found as a prototype of the pole star i from the catalogue

$$s_i := \varphi^{-1}(i) \in \{z \in P : \sigma_{iz}' = \max\{\sigma_{is}' : s \in P\}\},$$

where

$$\sigma_{is}' := |\{w \in W_i'' : s \in \{w[2],w[3]\}\}|.$$

Let us have a new set W_i' by leaving only those cortèges from the set W_i'' in which the star s_i is involved

$$W_i' := \{w \in W_i'' : s_i \in \{w[2],w[3]\}\}.$$

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The set W is not empty and contains cortèges holding information on two sets of diverging vectors from the plate and the catalogue respectively. Let us obtain the differences of the directions of vectors $(i,w[1]) \in \Gamma$ and $(s_i,t) \in P$ divided by parameter ε_2' and converted to integers

$$\beta_{iw} := E\left(\frac{\alpha(i,w[1]) - \alpha(s,t)}{\varepsilon_2'}\right),$$

where

$$t = \begin{cases} w[2], & s_i = w[3], \\ w[3], & s_i = w[2]. \end{cases}$$

It is easy to exclude all the cortèges w where β is outside $\pi \pm \varepsilon_2$, which is the orientation in some way approximately fixed beforehand. Most frequently the angle π is unknown and the parameter ε_2' is used as the accuracy estimate of this value. Parameter ε_2' is determined by user taking into account both the parameters of the optical system and the features of the field of the reference stars. Let us select the set of those cortèges now which have equal values of β repeated among them the maximum number of times and not less than a preset threshold r_2

$$W_i := \{ w \in W_i' : \rho_{iw} = \max\{ \rho_{iw'} : w' \in W_i' \} \geq r_2 \},$$

where

$$\rho_{iw'} := |\{ w'' \in W_i' : \beta_{iw''} = \beta_{iw'} \}|.$$

The identification continues according to formula (2) with another catalogue star as a pole if $W_i = \emptyset$. Otherwise the result of identification is given in the set W_i. The number of identified stars is $|W_i| + 1$, the cortèges $w \in W_i$ contain the "names" of the identified stars

$$i = \varphi(s_i),$$

$$w[1] = \varphi(t).$$

Additional control is provided by solving the system (1) with identified stars and checking the mean square error. This procedure also provides an easy way to calculate the spherical coordinates of all the reference stars, not only those, which were found at the first attempt to determine W_i. After that it is possible to improve the coordinates of the optical

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center,too.The case of the data containing only rectangular coordinates of the plate stars has been discussed in this paper.The same mathematical apparatus,which has been devised for modules and directions here,can be applied in the case when additional information on the magnitudes of stars is available.The routine of automated star identification has been included into the astrometric software of the Astronomical Observatory of the P.Stuchka Latvian State University and is used together with a special routine of star selection from the catalogue.However the algorithm of that routine is rather complicated (heavily branched) and has not been discussed here in order to keep the volume of this report within reasonable limits.A long-time application of the automated star identification routine to plate reduction at Riga satellite tracking station [2] has demonstrated its high reliability and produced excellent results in saving both time and effort.

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Проект лазерного гироскопа для определения скорости вращения Земли

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Власов Б.И., Русаков В.К. (ВНИИФТРИ)

Служба времени Государственного астрономического института им. П.К.Штернберга (ГАИШ) совместно со специалистами ВНИИФТРИ начала разрабатывать проект лазерного гироскопа для непрерывного определения угловой скорости вращения Земли. Предполагается измерение как высокочастотных вариаций скорости вращения с периодами 100-1000 сек, так и низкочастотных - с периодами несколько суток, что позволит объединить эти данные с результатами, полученными на радиоинтерферометрах со сверхдлинными базами.

The Time Service of the Shternberg State Astronomical Institute together with specialists of VNIIFTRI began to work at the project of laser gyroscope to determine continiously the Earth's rotation. It is assumed the measurements both the high-frequency variations with periods 100-1000 sec and the low-frequency variations with periods a few days. It gives opportunity to combine these data with the VLBI data.

Возможность измерения скорости вращения Земли гироскопом, работающим на эффекте Саньяка (Sagnac, 1913), была продемонстрирована еще в 1925 г. А.Майкельсоном и Х.Гейлем (Michelson and Gale, 1925).

Наша цель - измерение скорости вращения Земли с относитель-

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ной погрешностью 10^{-9}, что по уровню точности соответствует современным достижениям.

Обзор современных методов и средств оптической гироскопии приводит к тому, что из известных методов построения оптических гироскопов для измерения параметров вращения Земли наиболее пригоден лазерный гироскоп с пассивным кольцевым резонатором (Ezekiel and Balsamo, 1977).

Суть эффекта Саньяка состоит в том, что при вращении замкнутого контура возникает оптическая разность хода $\Delta \ell$ световых пучков, распространяющихся навстречу друг другу:

$$\Delta \ell = \frac{4S\Omega}{c} \sin \varphi ,$$

где Ω – угловая скорость вращения контура относительно инерциальной системы координат, S – площадь контура, φ – угол между вектором $\vec{\Omega}$ и плоскостью контура. В гироскопе с пассивным резонатором (Ezekiel and Balsamo,1977) разность хода $\Delta \ell$ преобразуется в разность частот Δf :

$$\Delta f = f_0 \frac{\Delta \ell}{L} = K\Omega , \quad K = \frac{4S}{\lambda L} \sin \varphi ,$$

где f_0 – рабочая частота лазера, K – масштабный коэффициент гироскопа. Оценка предельно достижимой точности гироскопа показывает (Ezekiel and Balsamo, 1977; Rusakov, 1986; Sazhin,Zharov,1988), что для измерения параметров вращения Земли необходим кольцевой резонатор с площадью единицы – десятки квадратных метров. Наиболее целесообразным представляется вариант с резонатором площадью 20–30 $м^2$, когда погрешность 10^{-9} достигается при уровне мощности излучения лазера единицы – десятки милливатт. Вращение Земли для гироскопа с параметрами S =25 $м^2$, L = 20 м, λ = 6328 А приводит к разностной частоте Δf = 600 Гц. Гироскоп с указанными параметрами дает возможность измерять скорость вращения Земли на уровне $\delta\Omega/\Omega \sim 10^{-7}$ за 1000 сек и на уровне 10^{-9} за время усреднения одни сутки.

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Изменения параметров гироскопа: периметра (площади) – $\delta L/L$, рабочей частоты лазера – $\delta f/f_0$, наклона оси вращения к плоскости контура – $\delta\varphi$, приводят к изменению масштабного коэффициента K. Эти изменения даже при неизменности приводят к изменению разностной частоты:

$$\delta(\Delta f) = K\Omega\left(\frac{\delta\Omega}{\Omega} + \frac{\delta L}{L} + \frac{\delta f}{f_0} + ctg\,\varphi\cdot\delta\varphi\right).$$

Поэтому необходимо обеспечить их неизменность на уровне 10^{-10}. Следовательно, требуется стабилизация температуры до 0°.01, вакуумирование кольцевого резонатора по периметру до 10^{-6}мм.рт. столба, стабильность частоты внешнего лазера 10^{-10}. При условии экваториального расположения плоскости гироскопа ($ctg\,\varphi = 0$) необходима его стабилизация на уровне нескольких угловых секунд.

Помимо решения задач службы времени гироскоп, по нашему мнению, может использоваться для изучения лунно-солнечной прецессии, нутации и движения полюсов, т.е. для исследования Земли как астрономического тела, а также для решения некоторых геофизических задач.

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A Hypothesis on Earth Rotation

Among the diverse reflections of space and time Geodesy uses mainly two: a) the structural elements of the gravity field, b) the configuration of the earth' surface.

C l a s s i c a l Geodesy joins both directly, using layers and directions of the gravity field as geometrical reference system.

M o d e r n Geodesy is based on distance measurement. The geometrical reference system is built up from marks on the earth' surface and has no metrical link to the gravity field.

I n t e g r a t e d Geodesy combines measurements of both kinds to a single outcome for the metrical reflection of the configuration of the earth' surface and/or for the structural elements of the gravity field. But such a combination is only possible since in each case o n l y o n e solution exists.

When the M E R I T - Project was initiated to intercompare techniques for the measurement of Earth Rotation Parameters (ERP), it uncontradicted was based on the same hypothesis: only one set of ERP exists.

But this hypothesis only applies to a rigid earth. The earth however is elastic and deformable. Its rotation is reflected differently by different matter. Georgiadou and Grafarend (1986) emphasize: "For a deformable body the notion of t h e rotation does not make any sense a priori: Parts of the deformable body rotate differently."

The reference system of the cosmic-geodetic methods on the one hand and the astrometric method on the other hand belong to different reflections of space and time. They are not linked metrically and will respond differently to forces, e.g. to

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gravitational forces or to influences ot the earth' atmosphere. The effect is computable for the tidal forces. But in other cases the sources are not sufficient known till now. If for instance as geophysicists teach the surface of the earth' core is structured considerably, its rotation will vary the structural elements of the gravity field considerable more than the configuration of the earth' surface.

The differences proved between the cosmic-geodetic and the astrometric sets of ERP need therefore n o t , as concluded from the MERIT results, mainly be caused by the different accuracy of the methods or techniques. Neither the one set nor the other may be regarded as "more right" or "more wrong". Each applies specifically to that matter which forms the reference system. Many other sets are imaginable if they could be observed, e.g. for the earth' core and mantle.

T h e h y p o t h e s i s r e a d s :
The differences between the today's both sets of ERP, as they result from cosmic-geodetic and astrometric measurements respectively, could essentially be caused by different reflection of the rotation of the earth by different matter. They need not mainly be a d e f e c t of methods or techniques but could be a s i g n a l which might help deeper to investigate physical processes on the earth.

For this it becomes important also in future to know b o t h sets with highest possible accuracy.

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The 50-day Variation in Wolf Numbers

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Abstract

The 50-day variation in the duration of the day was given by Feissel and Gambis (1980). Changes in the Earth's rotation are proportional to changes in the atmospheric circulation. The 50-day variations have been found out in many meteorological parameters, especiallly in the axial component of atmospheric angular momentum (AAM).

Looking for the origin of the 50-day signal we calculated Wolf number power spectra by means of the direct Fourier transformation method. A very prominent spectral peak corresponding to 50-day variation is clearly evident.

Резюме

Вариации с периодом около 50 дней /которые давно обнаружены в изменениях продолжительности суток и во многих метеорологических величинах, особенно в моменте количества движения атмосферы/ были раскрыты в солнечной активности, описанной числом Вольфа.

It is known /1/ that the atmospheric excitation can account for most of the observed length-of-day (LOD) variations at periods between 700 and 30 days. Semiannual and annual changes in the rotation of the Earth have long been attributed to meteorologi cal causes.

The existence of a high-frequency fluctuation in the duration of the day was found by Feissel and Gambis /2/ on the basis of a mutual comparison of several series of measurements of universal time, obtained independently by different observing techniques ; the recurrence time of these fluctuation was close to 55 days with an amplitude of about 0.4 milisecond. It has been shown that these ascillation are the effect of variations in the axial component of the relative atmospheric angular

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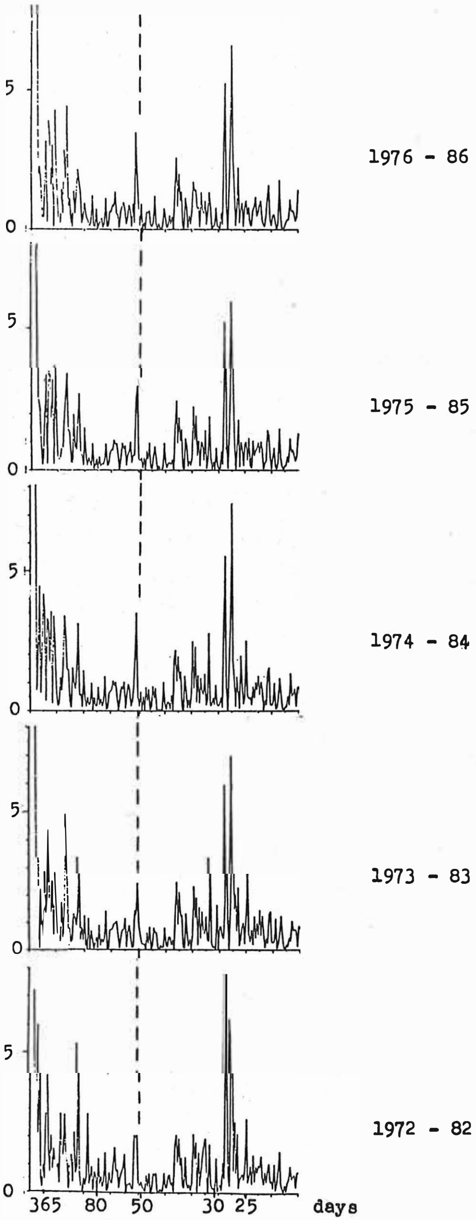

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momentum (AAM), and several years later, persistent fluctuations on a time scale of about 50 days were confirmed there /1, 3, 4, 5, 6, 7, 8/. We emphasize that the 50-day fluctuation is not a periodicity in the sense of an annual and semiannual oscillation but it is almost certainly a relatively broad-band phenomenon. An amplitude of these fluctuations amounted to 15 % of the total relative AAM, the corresponding changes in the LOD being near 0.5×10^{-3} seconds. The respective contributions to this fluctuation by the northern and southern hemispheres are comparable in magnitude and show very little systematic difference in phase. These findings strongly imply that the fluctuation is of intrinsic origin and driven by dynamical extraterrestrial processes. We tried to clarify the origin of the 50-day fluctuation of the AAM. Djurovic /9/ assumed that these variations are due to the solar radiation.

That is why we decided to search for 50-day periodicity within a time series of Wolf numbers. The data used were the daily values of the Wolf number for the period 1972-1986 as published in Meteorologische Abhandlungen /10/. The input data were arranged into five eleven-year series. Wolf number power spectra were calculated by means of the direct Fourier transform method. The results are presented in Fig. 1, where a very prominent spectral peak corresponding to a 50-day fluctuation is clearly evident in all five time series.

Pap /11/ analyzed the irradiance records provided by satellites "Nimbus 7" and "Solar Maximum Mission", and investigated the relations between the solar activity parameter (projected sunspot areas) and the solar constant variation. A good correlation was revealed between the variation of the solar constant and solar activity indicators. Both coincide so well that the solar origin of the variation on a time scale of weeks and months cannot be doubted. We could conclude that the origin of the 50-day signal in the atmospheric parameters and consequently in LOD is in the Sun processes.

Furthermore, the occurrence of quasiperiodic variation

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ranging from 30 to 60 days were indicated widely in many meteorological parameters, expecially in subtropical latitudes. Julian and Madden /12, 13/ first reported that this period is most prominent in oscillation of zonal velocity component and the surface pressure with the maximum amplitude situated along the equator. The zonal wind oscillation with a wide period range from about 30 to 60 days shows a relationship with a lot of other meteorological elements, such as temperature and surface pressure /24/, cloudiness and convective activity /14, 15, 18,22, 25/, outgoing longwave radiation /19,20,23,25/, El Nino Southern/Oscillation /21/, monsoon rainfall /27, 28, 29, 30, 31/ and with many others /16, 17/.

As already mentioned, the 50-day periodicity was verified even in outgoing longwave radiation measured by means of satellites NOAA and Tiros N since 1974. This signal seems to control the heat balance of the atmosphere thus causing variations of meteorological parameters manifesting in the axial atmospheric angular momentum component, which conditions changes in the Earth rotation. We could than admit that the physical processes in the Sun are responsible for the changes in the length-of-day.

The validity of our results is limited by the fact that only one eleven-year solar cycle is taken into consideration.

No plausible mechanism for the production of the Sun-weather correlation has been specified though a lot of apparent solar-climate relations have been advanced. We still miss a satisfactory explanation of definite physical mechanisms relating meteorological parameters to the solar activity. This problem obviously requires a collaboration of many different disciplines.

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THE CONNECTION OF THE OPTICAL AND RADIO REFERENCE SYSTEMS BY MEANS OF PHOTOGRAPHIC ASTROMETRY

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Abstract. The fundamental system of optical astrometry and the future extragalactic radio reference system can be tied together by photographic observations of optical counterparts of radio benchmark sources. In this paper we summarize the progress achieved during the last ten years and discuss the principle difficulties of these observations. Special emphasis is made on the programmes carried out with several telescopes in the USSR (since 1978) and with the Tautenburg Schmidt telescope (since 1986).

Zusammenfassung. Eine der Möglichkeiten zur Verbindung des Fundamentalsystems der optischen Astrometrie und des zukünftigen extragalaktischen Radioreferenzsystems besteht in photographischen Beobachtungen optischer Gegenstücke zu den Radioreferenzquellen. In dieser Arbeit werden die Fortschritte der letzten zehn Jahre zusammengefaßt und die prinzipiellen Probleme der Beobachtungen diskutiert. Insbesondere werden die Programme vorgestellt, welche mit mehreren Teleskopen in der UdSSR (seit 1978) und mit dem Tautenburger Schmidt-Teleskop (seit 1986) ausgeführt wurden.

1. Scientific **goal**

The introduction of new techniques with new reference frames into geodynamical investigations raises the question of their relation to the classical observations in the conventional inertial system. A special problem is the establishment of a uniform high-precision reference system for radio astrometry as well as for optical observations. This is one of the main targets of recent astrometric work.

The optical reference system is represented by the fundamental catalogue FK4/FK5 and its extensions to fainter stars (AGK3RN, AGK3, SRS, ...). Together with the constant of precession these catalogues provide a good approximation to an inertial coordinate system.

A more precise approximation to an inertial system is expected from radio observations of compact extragalactic sources by means of Very Long Baseline Interferometry. Up to now, only individual radio catalogues do exist. A uniform radio reference system is not yet established. A list of 233 candidate sources defining the system, so-called benchmark radio objects, was published by Argue et al. (1984). For the realisation of the reference frame, further observations are needed.

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VLBI observations are absolute, i.e. independent of an existing reference system, in declination and quasi-absolute in right ascension. The zero point of right ascensions is determined by observations of the compact object 3C273B, the right ascension of which is taken from the optical reference system. Nevertheless, an offset of the optical and radio right ascension systems is possible as well as of the declination systems. Observations of the optical counterparts of the radio benchmark objects in the optical reference system allow to determine this offset.

2. Progress and problems

In 1978 a working group of the IAU Commission 24 "Photographic Astrometry" was established "for the purpose of coordinating the identification of radio sources and their optical counterparts, with a view to determination of precise positions, leading to an investigation of relationships between radio and optical reference frames" (Prochazka and Tucker, 1978, p. 597). In 1984 this working group published the above mentioned catalogue of 233 benchmark radio sources with flux densities > Ø.6 Jy, displaying little or no spatial structure at the arcsecond level. All of them have optical counterparts, the distribution of which over optical magnitudes is shown in Fig. 1 for the Northern hemisphere.

Since 1978, a series of papers was published with optical positions of benchmark and other radio objects: Argue et al. (1978), Clements (1981, 1983a, 1983b), de Vegt and Gehlich (1982), de Vegt and Prochazka (1985), Geffert and Richtler (1983), Harrington et al. (1983), Kumkova (1985), Torres et al. (1984), Torres and Wroblewski (1987), Walter and West (1986), Wroblewski et al. (1981). The r.m.s. errors of these positions range between Ø.Ø5 and Ø.2 arcsec.

For the Northern hemisphere the distribution of published positions of optical counterparts over their magnitudes is shown in Fig. 2. Comparing this with Fig. 1 it can be seen, that there is a lack of optical measurements for objects beyond 18 mag. Such faint objects can not be observed by traditional instruments of photographic astrometry. Therefore, large reflectors originally developed for astrophysical investigations have to be used.

The connection of the optical counterparts with the fundamental system is possible only via its extensions to fainter stars (6 to 9 mag), e.g. the differential meridian catalogues AGK3RN and the future SRS catalogue with a density of 1 star per square degree. A further extension to stars of 7 to 12 mag is provided by the photographic catalogue AGK3, wideley used but with low accuracy at present epochs. Special observations of reference stars around radio sources are carried out in the USSR (Lazorenko, 1982) and in the US Naval Observatory (Dick and Holdenried, 1982). In many cases secondary reference stars (of about 14 mag) had to be measured on specially taken plates, since the number of primary reference stars in small fields was insufficient or they were unmeasurable on the plates with extragalactic sources.

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At present time the comparison of optical and radio positions shows an offset at the level of Ø.1 arcsec, which is unsatisfactory. Further refinements are needed to find out the reason for this offset, which may lay in the observational techniques.

3. The Programme ROAS of Soviet observatories

Photographic observations of extragalactic radio sources for astrometric purposes started in the USSR in 1978. The Programme ROAS (Radio/Optical Astrometric Sources) is based on the list of benchmark sources of the IAU Comm. 24 working group.

62 radio sources with compactness of better than 1 arcsec on frequencies > 1.4 MHz and flux densities > 1 Jy were included. The stellar magnitudes of their optical counterparts range from 12 to 18. In most cases they are quasars, some are BL Lac objects or cores of active galaxies.

7 observatories took part in this programme, essentially with astrographs (D = 4Ø cm, F = 2ØØ ... 3ØØ cm). From 1978 to 1984 2Ø5 plates were taken.

Positions of 54 objects with an accuracy of Ø.18 arcsec were determined (Kumkova, 1985). The differences of radio and optical coordinates correspond to the accuracy of the reference catalogues used.

At present time the programme is being extended to fainter objects. For this purpose several astrophysical reflectors are under astrometric investigation.

4. The Programme RORS of the Tautenburg Schmidt telescope

The Schmidt telescope of the Central Institute of Astrophysics of the GDR (Aperture 134 cm, D = 2ØØ cm, F = 4ØØ cm), originally built for astrophysical research, has been used for astrometric work for more than 15 years. In 1986 observations of faint optical counterparts of radio sources from the IAU Comm. 24 list were started. The Programme RORS (Radio/Optical Reference System) includes mainly objects fainter than 18 mag. Up to now nearly 1ØØ plates are taken, the measurements are under way.

As a preliminary result, the positions of 9 objects have been measured relative to AGK3 reference stars (Dick, 1988). The random accuracy is on the level of Ø.2 arcsec or better. Some of the determined positional values are systematicly deviated from positions published by other authors. The origin of this effect is possibly a magnitude equation on some of the Tautenburg Schmidt plates (Dick and Hirte, 1988).

This experience shows that a main problem is to avoid systematic errors over a large scale of magnitudes between reference stars and faint objects. More accurate results are expected by using fainter reference stars and automatic plate measuring facilities with elements of image processing.

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5. Future prospects

Photographic observations of radio sources are at present day the only available technique for tying together the optical and the radio reference systems. Besides extragalactic sources, stars with radio emission were measured by means of photographic astrometry (de Vegt et al., 1985), but their number is strongly limited. The main tasks for the next years are to extend the optical reference system to fainter objects, to increase the number of extragalactic benchmark sources by including objects weaker in radio frequencies and/or fainter in the optical wave band into the observational lists, and to reach better random and systematic accuracy.

Alternative methods for the connection which will be available in the near or more distant future are observations of radio stars by the HIPPARCOS Space Astrometry Mission, observations of pairs of stars and extragalactic benchmark sources by the Hubble Space Telescope, and VLBI satellite techniques.

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Fig. 1 The distribution of the number of benchmark radio sources on the Northern sky over their optical magnitudes (Total number: 141)

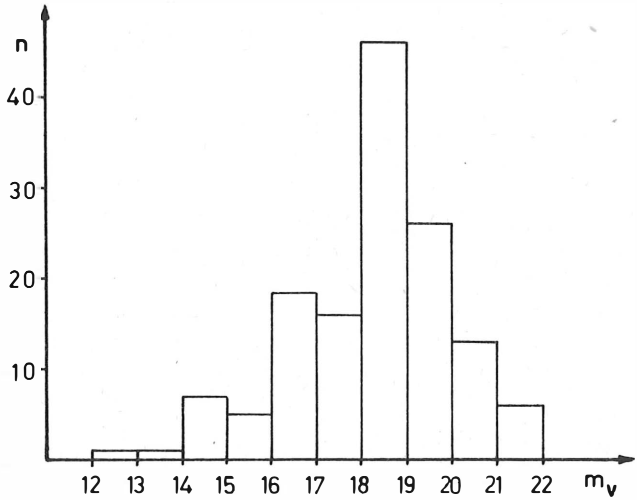
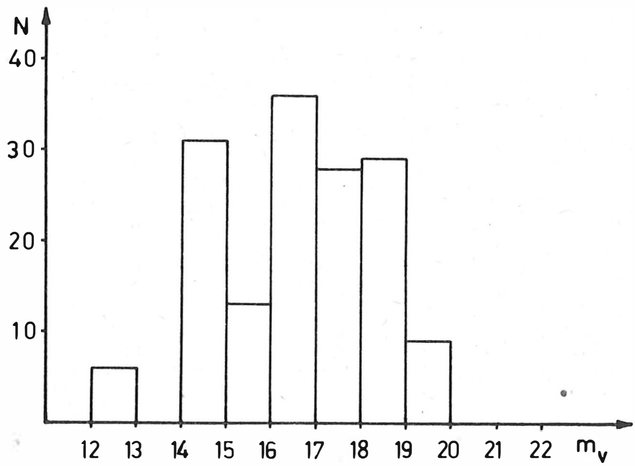


Fig. 2 The distribution of the number of published optical positions with accuracies better than 0.2 arcsec of benchmark radio sources on the Northern sky over optical magnitudes (Total number: 153)



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Ein Jahrhundert geodätische Literaturerfassung im Zentralinstitut für Physik der Erde Potsdam - 25 Jahre "bibliographia geodaetica"

H. Finger, Technische Universität Dresden

Bei allem verständlichen und notwendigen Drang, in fachliches Neuland vorzustoßen, naturwissenschaftliche und sonstige Phänomene ergründen, begreifen und beherrschen zu wollen, sollte nicht vergessen werden, was unsere "Fachvorfahren", die unverzagten Gelehrten, Forscher und Pioniere einschließlich der "Hülfsarbeiter" uns überliefert haben. Die Bibliotheken bewahren wertvolle Zeitdokumente auf, die Fundgruben für das Verstehen des eigenen Fachgebietes, aber auch der Natur und ihrer Gesetze darstellen.

Das 20. Jahrhundert neigt sich dem Ende zu. Die Bedeutung von Dokumentation und Information hat enorm zugenommen. Sie haben die gewichtige Aufgabe, für alle Gebiete der Wissenschaft und Technik abrufbare Informationen über den neuesten Stand der Entwicklung bereitzuhalten und sie den Bereichen der Gesellschaft zu vermitteln. Die elektronische Datenverarbeitung und die Möglichkeiten des Einsatzes superschneller Rechner mit großem Speichervermögen erlauben immer besser und zielgerichteter, die Bewältigung wissenschaftlich-technischer Forschung, Entwicklung und Produktion durch aussagefähige Literaturrecherchen zu unterstützen.Was vor 100, ja 200 Jahren noch in mühevoller Kleinarbeit und mit großem Zeitaufwand ermittelt, gesammelt, systematisiert und bekannt gemacht werden mußte, übernehmen heute Computer mit all ihren peripheren Geräten. Trotzdem haben natürlich weder die Bibliotheken mit ihrem Fundus an Büchern, Zeitschriften und Sammlungen an Bedeutung verloren, noch sind die geistig-produktiven Prozesse bei der Durcharbeitung des Inhalts einer Veröffentlichung und ihrer Umsetzung in die praktische Tätigkeit ohne menschliches Zutun denkbar. Allerdings sind in Dokumentation und Information vor relativ kurzer Zeit einschneidende Änderungen eingetreten.

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Es wurde die Notwendigkeit erkannt, daß in der jetzigen Zeit eine vorbereitende, recherchierende Etappe für Forschungs- und Entwicklungsaufgaben erforderlich ist, um exakte Ausgangskenntnisse zu bestimmten fachlichen Fragestellungen zu besitzen. Es fand scheinbar eine Abspaltung vom bekannten Bibliotheksgeschehen statt,und es entstand die Arbeitsteilung zwischen Bibliothek und Information/Dokumentation.

Im Fachgebiet Geodäsie haben wir in den letzten Jahrzehnten in instrumenteller, meß- und auswertetechnischer Hinsicht eine einschneidende Technik-und Technologie-Revolution erlebt. Wenn im 19. Jahrhundert den Fachkollegen wissenschaftlich-theoretische Fragen der sphärischen Berechnung sphäroidischer Dreiecke, der Landestriangulation , der Höhennullpunkte, der Europäischen Gradmessung, Fragen über Größe und Figur der Erde und viele weitere Probleme interessierten, so konstatieren wir nach 100 Jahren ein weltweites Forschen an ähnlichen Fragenkomplexen, aber mit völlig veränderten Meßmitteln, Beobachtungsverfahren und Auswertetechnologien.

Von den Mitarbeitern des damaligen Königlich Preußischen Geodätischen Instituts, einem traditionsreichen Zentrum für die Geodäsie in Europa und Vorgänger des heutigen Zentralinstituts für Physik der Erde in Potsdam, sind im 19. Jahrhundert zu exakt abgegrenzten Aufgabengebieten Literaturzusammenstellungen veröffentlicht worden. Bereits 1876 von Baeyer /1/, 1881 von Sadebeck /2/ und 1884 von Börsch /3/ Zusammenstellungen zu den Gradmessungen und in Bibliographien herausgegeben. Im Jahre 1889 hat Börsch /4/ sämtliche Literatur über die Internationale Erdmessung veröffentlicht. Obgleich bei den zitierten Arbeiten meist nur ein Fachthema dominierte, soll die zuletzt genannte Bibliographie mit Überblickscharakter von Börsch benutzt werden, um dem Veranstalter des 1988 durchgeführten "6th International Symposium - Geodesy and Geophysics of the Earth" in Potsdam eine Reverenz zu erweisen. Vor 100 Jahren erblickte hier in Potsdam der Dokumentationsdienst "Höhere Geodäsie" das Licht der Welt. Wir befinden uns also auf fachlich historisch bedeutsamen Boden in mehrfacher Hinsicht. Es gingen von diesem Geodätischen Institut wichtige fachliche Impulse

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aus, und namhafte Wissenschaftler bestimmten maßgebend die geodätischen Aufgaben, Untersuchungen und Prozesse. Erinnert sei an die Gedanken zu einer europäischen bzw. mitteleuropäischen Gradmessung von J. J. Baeyer /10/, die Berichte über die Tätigkeiten des Internationalen Centralbureaus /11/, /12/, um nur einige herauszugreifen.

Die von O. Börsch /4/ auf Wunsch der Internationalen Erdmessung erarbeitete Literaturzusammenstellung stellt die erste Internationale Fachbibliographie zur "Höheren Geodäsie" dar. Die Bearbeitungsform ist, verglichen mit unseren heutigen Anforderungen, als recht modern zu bezeichnen. Sie enthält Hinweise auf Veröffentlichungen, Referate über Bücher und wissenschaftliche Arbeiten. Für den Zeitabschnitt von 25 Jahren (1863 - 1888) sind aus 17 Ländern Literaturbeiträge zusammengestellt worden. Es ist sicher nicht vermessen, wenn wir sie als "Bibliographie Geodesique" bezeichnen, da kontinuierlich in den Veröffentlichungen des "Centralbureau der Internationalen Erdmessung, Verhandlungen und Berichte" Raum für einen bibliographischen Teil vorgesehen wurde.

An dieser Stelle sollte aber unbedingt Erwähnung finden : ... "Am 16. Dezember 1871 wurde zu Coburg durch Delegirte geodätischer Techniker aus verschiedenen deutschen Staaten ein deutscher Geometer-Verein gegründet, dessen Zweck die Hebung und Förderung des gesammten Vermessungswesens, namentlich durch Verbreitung wissenschaftlicher Kenntnisse und praktischer Erfahrungen ist. Dieses Ziel wird in erster Linie durch Herausgabe einer Zeitschrift als Organ des Vereins zu erreichen versucht "/5/. Der 1. Jahrgang der "Zeitschrift für Vermessungswesen" wird im Auftrage und als Organ des deutschen Geometervereins 1872 herausgegeben. Neben der oben erwähnten Zielstellung erfolgen von Anbeginn an Informationen über Aktivitäten der Geodäten in deutschen Ländern. Im Bericht über die "Coburger Delegirten-Konferenz" wird ausgeführt, daß ... "bei der bayrischen Bezirks-Geometer-Conferenz im Juni 1859 ... die Herausgabe einer Zeitschrift für Geometer" beschlossen wurde /6/. Die Länder Württemberg (1867) und Baden (1871) haben ebenfalls Zeitschriften bzw. Monatsblätter herausgegeben.

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Bereits vom 1. Band an der "Zeitschrift für Vermessungswesen" (ZfV) wurde unter der Rubrik "Literaturzeitung" über Fachliteratur informiert. Eine "Uebersicht der Literatur für Vermessungswesen auf 1875" erfolgte erstmalig im Band 5 (1876) als Ergänzungsheft /7/, verfaßt von Helmert, Franke und Jordan. Die Übersicht ist in 22 Abteilungen untergliedert und informiert über mehr als 400 Quellen und außerdem noch über rund 150 Kartenwerke. Zusätzlich werden die erworbenen Bücher, die die Bibliothek des Deutschen Geometervereins darstellen, aufgezählt und in 17 Gruppen eingeteilt. Für 1875 sind mehr als 70 Monographien und Beiträge aufgezählt. Während für 1876 nur für 22 Zeitschriften "Abkürzungen für häufig citirte Schriften" genannt sind, werden ab 1877 Unterscheidungen zwischen "Allgemeine Literaturberichte für 1877" (13 Titel), "Zeitschriften" (37 Titel), "Lehrbücher etc." (5 Titel) aufgeführt. Die Zeitschrift für Vermessungswesen - ZfV - wird immer mehr im deutschsprachigen Raum zum geodätischen Sprachrohr. Der Jahrgang 1879 muß bereits zwei Ergänzungshefte bringen, einmal "Beiträge zu einem Literaturverzeichnisse der physikalischen Höhenmessung" von Kunze mit 115 Seiten und dann noch die Literaturübersicht fürs Vermessungswesen /8/. Diese Übersichten haben sich bis in unsere Zeit erhalten und werden von der ZfV als ein in sich abgeschlossenes Heft in jedem Jahrgang ausgeliefert. Die Sachgebiete haben sich selbstverständlich verändert. Das letzte Heft /9/ weist 27 Untergruppen aus, die ausgewerteten Publikationen bzw. Zeitschriften, Serien usw. liegen bei 222, auf 40 Seiten werden mehr als 2500 Quellen nachgewiesen.

Nach dieser kurzen Abschweifung sei aber auf die von O. Börsch verfaßte Literaturzusammenstellung zurückgekommen /4/. Während 1889 das "Centralbureau der Internationalen Erdmessung" mit Sitz in Berlin (seit 1896 in Potsdam) im Königreich Preußen Auftraggeber war, wurde 40 Jahre später von der inzwischen entstandenen Vereinigung geowissenschaftlicher Disziplinen in einer Internationalen Union von deren Sektion Geodäsie 1930 beschlossen, zu jeder Generalversammlung eine jeweils 3 Jahre umfassende Bibliographie über die geodätische Fachliteratur vorzulegen. Als Name für diese permanent erscheinende Literaturzusammenstellung wählte die Sektion Geodäsie "Bibliographie Géodésique Internationale" (BGI).

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Der Band 1 sollte die Fachveröffentlichungen aus den Jahren 1928 - 1930 enthalten. 1935 erschien schließlich von der "Association de Géodésie de l'Union Géodésique et Géophysique Internationale" der von Perrier und Tardi zusammengestellte Band 1 /13/. Die Sektion Geodäsie hatte sich 1932 in "Assoziation Internationale Géodésique" (AIG) umbenannt. Außer Bearbeitungsrichtlinien und Benutzungsvermerken in Französisch und Englisch erfolgten bereits die Zuordnungen der Veröffentlichungen nach dem "Decimal System" bzw. dem "International Catalogue (Royal Society)". Die fachliche Untergliederung erfolgte für die "Geodesy" in die Gruppen :

- Generalities on Geodesy
- Work already carried out or projected (Publications of official Services, Tables of Geographical Positions, etc.)
- Mathematical Geodesy
- Geodetic and Positional Astronomy
- Physical Geodesy
- Determination of the Figure of the Earth
- Study of some Constants and Properties of the Earth as a whole
- Topography

es werden über 1430 Titel angegeben, teilweise mit Referat. Von den 40 Mitgliedsländern hatten 32 einen offiziellen Berichterstatter nominiert. Bei den durchgearbeiteten Publikationen kommt man auf die stattliche Anzahl von 392 Zeitschriften, Serien, Institutsmitteilungen usw. aus 32 Ländern /13/. Im Jahre 1959 stellte die AIG fest, daß der Beschluß, zu den Generalversammlungen die Literaturangaben der verstrichenen 3 bis 4 Jahre anzubieten, den Forderungen der Fachkollegen nach aktuellen Informationen nicht mehr gerecht werde. Bei kritischer Analyse muß man auch feststellen, daß teilweise 4 bis 6 Jahre zwischen der Veröffentlichung und der Dokumentation in der "Bibliographie Géodésique Internationale" lagen. Diese verspätete Informationsbekanntgabe war die eine Prämisse, die finanzielle Situation der AIG die andere, die zu der Entscheidung führten, das Erscheinen der "Bibliographie Géodésique Internationale" mit Jahrgang 10 einzustellen.

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Das Vorwort des 10. Bandes führt die Bearbeiter seit 1924 auf. Es wird darüber berichtet, daß im vorliegenden Band die Veröffentlichungen der Jahre 1958 - 1960 erfaßt werden und auf der Generalversammlung der AIG 1960 in Helsinki eine Resolution verabschiedet worden ist, die die weitere Veröffentlichungsform beinhaltet. Ab 1961 soll eine monatliche Zeitschrift herausgegeben werden, in der über relevante geodätische Literaturquellen inhaltlich referiert und dokumentiert werden soll. Jede Quelle wird in den Sprachen Deutsch, Englisch, Französisch und Russisch angeboten, außerdem werden zusätzlich zu der Zeitschrift noch in den vier Sprachen Dokumentationskarten im Format A 6 für den Aufbau von Karteien geliefert. Die Gruppe I behandelt das Gebiet der "Höheren Geodäsie". Weiterhin wird mitgeteilt, daß sich an der Erarbeitung 8 wissenschaftliche Institute aus Argentinien, der Bundesrepublik Deutschland, der Deutschen Demokratischen Republik, Finnland, Frankreich, Großbritannien, der UdSSR und den USA beteiligen werden. Das Geodätische Institut an der Technischen Universität Dresden erklärte seine Bereitschaft, die Übersetzungen, die Endredaktion und den Druck zu übernehmen. Zeitschrift und Dokumentationskarten wurden auf obige Weise seit 1962 herausgebracht, und die Literatur des Jahres 1961 stand als Sonderdruck 1966 zur Verfügung. Abschließend wurde sowohl dem Geodätischen Institut Dresden als auch den anderen Regional-Institutionen für ihre Bereitschaft der Unterstützung der neuen Bibliographie gedankt /14/.

Einige Reminiszenzen über die Vorgeschichte der vom Geodätischen Institut Dresden weitergeführten "Bibliographie Géodésique Internationale" : 1956 war am Geodätischen Institut der Technischen Universität Dresden unter dem Direktorat von Prof. H. Peschel eine Dokumentationsstelle Geodäsie eingerichtet worden. Die Aufgabe bestand darin, Fachliteratur für die laufenden Lehr- und Forschungsarbeiten, aber auch für Praxisaufgaben zu ermitteln und aufzubereiten. Das Dokumentieren und Auswerten von Fachartikeln und Fachbüchern erfolgte in enger Zusammenarbeit mit fast allen geodätisch-kartographisch arbeitenden Institutionen, Hoch- und Fachschulen, Diensten und Betrieben der Deutschen Demokratischen Republik.

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1957 erschienen die ersten Arbeitsergebnisse als "Dokumentationsdienst Geodäsie", einer Referatekartei, und in Heftform gemeinsam mit Referaten der Geophysik und Geologie in den "Montanwissenschaftlichen Literaturberichten, Reihe C, Geowissenschaften" /15/, /16/ und /17/.

In den 60er und 70er Jahren wurde staatlicherseits die Bedeutung von Dokumentation und Information verstärkt betont, und viele Wirtschaftszweige bauten für ihre Fachdisziplinen ähnliche Dokumentationsdienste auf. Die Dokumentation Geodäsie, aber auch die der Kartographie, Polygraphie, Geographie und anderer Wissenschaftszweige wurden zum Aufbau eines Informationsspeichers benutzt, der aus einer nach der internationalen Dezimalklassifikation (IDC) geordneten Sach- und Verfasserkartei besteht.

Wie bereits angedeutet, erfüllte die von der AIG herausgegebene Bibliographie nicht mehr die Anforderungen der zweiten Hälfte des 20. Jahrhunderts. Um Informations- und Dokumentationsarbeit entsprechend den praktischen Erfordernissen leisten zu können, machte sich auch eine rationellere Organisation der ablaufenden Prozesse erforderlich. Durch eine Expertenkommission der AIG wurde deshalb über eine Modernisierung der bisherigen Dokumentationsformen beraten. Es wurde der Vorschlag unterbreitet, der jungen, aber gut funktionierenden Dokumentationsstelle Geodäsie in Dresden internationalen Charakter zu verleihen. Mit Beginn des Jahres 1962 wurde ihr die Nachfolgeschaft der "Bibliographie Géodésique Internationale" übertragen. Von diesem Jahre an übernahm die aus den "Montanwissenschaftlichen Literaturberichten" /17/ hervorgegangene "bibliographia geodaetica" mit dem Untertitel "Bibliographie Géodésique Internationale, Nouvelle Série" die Fortführung der geodätisch relevanten Literatur in der AIG. In der Deutschen Demokratischen Republik liegt die Bearbeitung bei der "Zentralstelle für Internationale Dokumentation der Geodäsie" an der Technischen Universität Dresden. Herausgeber dieses Referateorgans ist das Nationalkomitee für Geodäsie und Geophysik der Akademie der Wissenschaften der DDR.

Nach personeller Erweiterung der Arbeitsgruppe am Geodätischen Institut in Dresden erschien die "bibliographia geodaetica"

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monatlich in den obigen vier Sprachen. Jedes Heft umfaßte ungefähr 120 Nachweise aus den Fachgebieten "Höhere Geodäsie", "Angewandte Geodäsie" und "Photogrammetrie", letztere nur in deutscher Sprache. Von 1963 bis 1973 erschienen noch als Heft Nr. 13 je ein "Supplementband" mit weiteren 1200 bis 1500 bibliographischen Titelangaben.

Obgleich bei der Konzipierung der internationalen Zusammenarbeit die AIG-Mitgliedsländer Unterstützung geben wollten,lastete die Hauptarbeit auf den Mitarbeitern der Zentralstelle in Dresden. Die zu den Generalversammlungen vorgelegten Berichte und statistischen Angaben besagen, daß der Anteil Dresdens 50 - 60 o/o der erfaßten Titel betrug. Überlegungen zur Rationalisierung ohne Qualitätseinbuße wurden notwendig.

In den vergangenen 25 Jahren der Bearbeitung und Herausgabe der "bibliographia geodaetica" machte diese verschiedene Wandlungen durch. Aus sachlichen und fachlichen Gründen wurde von der Permanenten Kommission VI der AIG (Bibliography of Geodesy) die Herausgabe in englischer Sprache vorgeschlagen. Ab 1980 erschien dann die "bibliographia geodaetica" nur noch englisch, auch wurde Kritik daran geübt, daß das fachliche Profil der Zeitschrift nicht den Aufgaben der AIG voll entspräche. Bei den Überlegungen für die Nutzung der Rechentechnik für unsere internationalen Aufgaben wurde die gemeinsame Anwendung des "Automatisierten Informations- und Dokumentationssystems für Geodäsie, Fotogrammetrie und Kartografie" (AIDOS) vom VEB Kombinat Geodäsie und Kartographie, vom Zentralinstitut für Physik der Erde der AdW der DDR und von der Technischen Universität beschlossen. Für die "bibliographia geodaetica" veränderten sich ab 1985 die Gliederung und die äußere Form des Schriftbildes. Es wurde zur rechnergestützen Ausgabe übergegangen und nur noch über die Fachbereiche "Höhere Geodäsie" und "Allgemeine Fragen der Geodäsie" referiert. Die Nutzer wurden bereits seit 1983 auf eine bevorstehende Umstellung aufmerksam gemacht. Mehrmals wurden den Heften Benutzungsanleitungen beigelegt. Mit Heft 1/1987 wurde das Ausgabeprogramm AIDOS modifiziert und ein gesonderter Rechnerausdruck realisiert. Bis 1987 erschienen 6 Hefte pro Jahrgang in der rechnergestützen Form, ab 1988 sind es 10, um die Aktualität zu verbessern und den Zeitraum zwischen Originaleingang der Literatur und der Dokumen-

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tation in der "bibliographia geodaetica" zu verkürzen. Der Inhalt ist strenger den Aufgabengebieten der AIG angepaßt worden, so daß die "bg" eindeutiger das Dokumentations- und Informationsmittel der Internationalen Assoziation der Geodäsie geworden ist.

Von 1963 bis einschließlich 1987 sind in der "bibliographia geodaetica" insgesamt 48 667 Quellen ausgewiesen worden, davon 19 309 in der "Höheren Geodäsie", 8 119 in der "Angewandten Geodäsie", 6 248 in der "Photogrammetrie" und in den Supplementbänden nochmals 14 991 Titel. Von den rund 48 000 Nachweisen beinhalten mehr als 33 000 auch Referate.

Die gute Zusammenarbeit der Zentralstelle für Internationale Dokumentation der Geodäsie mit den Nationalkorrespondenten der AIG als Übermittler der fachlich relevanten Arbeiten ihrer Länder sowie die Kooperation mit dem Informationszentrum für Wissenschaft und Technik des VEB Kombinat Geodäsie und Kartographie und dem Zentralinstitut für Physik der Erde der Akademie der Wissenschaften der Deutschen Demokratischen Republik werden weiterhin die Grundlage bilden, um die im In- und Ausland tätigen Geodäten schnell und umfassend über relevante Literatur informieren zu können.

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SYNTHETIC COMPUTATIONS OF EARTH ROTATION PARAMETERS (ERP) FROM DIFFERENT EXCITATION MECHANISMS

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ABSTRACT

The inverse problem how to identify the origin of the observed polar motion and length-of-day variations is defined and exemplified by synthetic computations of different geophysical effects, which cause ERP variations. The analysis is based on on a deformable earth whose heterogeneous equilibrium figure is perturbed by various forces, namely those of volume and surface. Examples for core-mantle coupling, atmospheric and oceanic excitation as well as the tidal force are given.

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An interpretation of the periodic variations of the magnetic core-mantle coupling torques and the core drift rate

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Abstract

The influence of recently computed axial magnetic core-mantle coupling torques [1] on the Earth's rotation was investigated. These torques derived from poloidal geomagnetic field within the mantle and at the core-mantle boundary are retarding torques with respect to the model of a rigid relative rotation between core and mantle. The mean magnitude of the variations of these torques is $2.5 \cdot 10^{17}$ Nm. The variations of the mechanical torques necessary to excite the variations of the "length of day" (l.o.d.) are essentially the same. Because the torque balance was not valid for periodic variations the existence of additional accelerating torques was suggested. An accelerating torque due to the action of unknown parts of the core field was estimated by the inverse solution of the equation of the mantle rotation for two periodic variations of the magnetic field and the l.o.d.. For the nearly 30 years period of the variations the magnitude of the accelerating torque was $4 \cdot 10^{17}$ Nm, for the 66.7 years period of the mantle rotation it was about $7.1 \cdot 10^{17}$ Nm. The first value regards to the model of the rigid rotation of core surface layer, whereas the second value is a rough estimate for the 66.7 years period of the l.o.d. for which an equivalent model of a core motion has not yet been found. This period, shurely estimated within the time series of the mantle rotation rate ω_m was not found in the time series of ω, that is the core rotation rate (core drift rate) derived from geomagnetic secular variation field [2], and in those of the torques. In spite of this, it was shown that a close connection exists between the time variations of ω and ω_m by core-mantle coupling at this period.

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The variations of ω were compared with those of ω_m for a force-free Earth by conservation of the angular momentum and the model of a rigid rotation. The time constants of the coupling process were estimated and discussed in connection with the magnetic coupling of the mantle with an upper core layer of the thickness d. The values estimated for the time constant τ and d for the 30 years periods are τ = 4.2 years and d = 275 km. The main conclusion was that the model of a rigid core rotation is valid by the resulting values of ω and ω_m, if the core drift rate is ordered to the rotation of an upper core shell.

The 66.7 years period should be investigated in future too. Two ways of investigation were proposed: to order the 66.7 years period to a more complex motion of the fluid core material or to order the 66.7 years period to a transient phenomena of the core-mantle interaction caused by a single event near the core surface. With respect to the strong 22 years period of ω the same investigations should be made.

(Be published in the "Astronomische Nachrichten" Vol. 309/6 or 310/1 (1988)).

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The Optical Astrometry Determination of Earth Rotation Parameters after 1984.0

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ABSTRACT

The determination of polar motion and universal time by means of optical astrometry after the introduction the IAU 1976 system of astronomical constants, the IAU 1980 theory of nutation and the new computational alghoritms in 1984.0 is investigated. The comparison with space techniques shows that the Earth rotation parameters from optical astrometry in 1984--1987 are not homogeneous with the period before 1984. The inhomogeneity manifests itself as a drift in the y pole coordinate and as a change of the behaviour of annual terms. Possible reasons for these phenomena are outlined.

INTRODUCTION

The optical astrometry determination of latitude and universal time analysed and combined by Bureau International de l'Heure (BIH) for more than 25 years, underwent several changes during this time. The BIH algorithm took account of the known changes in order to keep the consistency of the derived Earth rotation parameters (ERP). The last important change was in 1984.0 when all the participating observatories had to change their reduction procedures in accordance with the IAU 1976 system of astronomical constants and the IAU 1980 theory of nutation. Simultaneously the new reference epoch J2000.0 was introduced, the abberation E-terms were no more included in the mean places, the correction to the deflection of light in the Sun's gravitational field is considered, and the reductions are performed rigorously using the matrix formulation directly from the mean places at fundamental epoch.

For securing the continuous transition from the previous system to the new one BIH requested in end of 1983 all the participating stations to grant the results from one month of observations reduced in both systems of constants. Their correctness was checked individually on each latitude and/or time series according the modelled corrections (Capitaine and Feissel, 1983). In the reduction procedures for ERP determina-

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tions after 1984.0 only the stations with no discrepancies in the controlled period were included. The algorithm for preservation of reference system (Feissel, 1971) was applied without changes. The time and latitude determination at individual stations before 1984.0 had been brought to the new system of constants by the modelled corrections back to 1978.0. In spite of the precautions mentioned above the comparison with ERP from space techniques showed that the long term stability of pure optical astrometry solution was deteriorated after 1984.0 Therefore, the assumption can be made that the transition at some observatories apart from the checks at BIH was not continuous. It is worthwile mentioning also that after 1984 the observational activity of optical astrometry was changed. This can be documented particularly by latitude observations where the total weight is decreased about 15%

THE OPTICAL ASTROMETRY SOLUTION AFTER 1984.0

To find the possible reasons of inhomogeneity in optical astrometry ERP the attempt was made to check statistically the continuity of latitude and time series at individual stations. On the basis of normal values at 0.05y intervals the station corrections are computed yearly over 1980-1986 under the form

/1/ $R = -a - b \sin 2\pi t - c \cos 2\pi t - d \sin 4\pi t - e \cos 4\pi t$

for latitude and

/2/ $S = -a' - b' \sin 2\pi t - c' \cos 2\pi t - d' \sin 4\pi t - e' \cos 4\pi t$

for universal time, where t is the date in Besselian years. The reference series is the original optical astrometry ERP. If there are no inhomogeneities in time series of φ or UTO-UTC at an individual station, each coefficient a,b,... e' should have random fluctuations about a constant value over the whole observational period . If the transfer from the old to the new system in 1984.0 is not continuous, a jump occurs in some of the a,b,... e' coefficients. If the value is statistically significant the jump can be detected using an appropriate statistical test. On the basis of the Fisher tests performed on each series of coefficients for all the participating stations the hypothesis of homogeneous transition was rejected for nine latitude and four time stations For these stations the systematic corrections to prediction coefficients were estimated Together with the original normal values at 0.05y intervals and with unchanged prediction coefficients and normal values for the rest of stations they were used for recomputation of ERP after 1984.0. This new time series represents the homogenised optical astrometry solution at 0.05y intervals. It is the direct continuation the pre-1984.0 period considering the statistically detectable systematic jumps after 1984.0 in individual latitude and time series. The RMS difference between the original and recomputed ERP are of order 0.005" , the maximum difference do not exceed 0.020". The optical astrometry ERP at 0.05y intervals consistent with the IAU 1980 theory of nutation are available as ERP(BIH) 83 A 01 from 1978.00 through 1987.95

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The behaviour of the optical astrometry ERP is further investigated using comparisons with the ERP determinated by space techniques. The differences dx, dy and dUT1 of x, y and UT1 at 0.05y intervals are defined as ERP(BIH) 83 A 01 - - ERP(BIH) 87 C 01 , where ERP(BIH) 87 C 01 is a combination series of ERP derived in the computation of the BIH Terrestrial System for 1986. It is based mainly on VLBI and SLR For the years 1980-1986 the differences are plotted on Figure 1 together with the z-term from optical astrometry. The graphs show that the character of oscillations in dx,dy,dUT1 and z is remarkably changed in the second half of the investigated period.

In Table 1 are compared the dx,dy and dUT1 series from two separate 3-years periods 1981-83 and 1984-86. The global scatter is characterized by RMS of dx, dy, dUT1. The high frequency oscillations are characterized by residuals from a weak Gaussian smoothing. The degree of smoothing h=180 secures that the residuals contain all informations about oscillations with periods 0.05 - 0.50 year The stability of time series is estimated by pair variances for sampling time 0.05 - 0.80 year. The ratios of corresponding RMS residuals and pair variances show the general deterioration of agreement between the optical astrometry and space techniques after 1984.0 . In all the three ERP the main feature is the decreasing of the long term stability.

SOME REMARKS ON THE DETERIORATION OF OPTICAL ASTROMETRY ERP

The described recomputation and analysis show that the increasing of discrepancies in optical astrometry cannot be explained only as the consequence of inhomogeneous transition to the new conventions at some stations. To the further investigate the mentioned instability it is necessary to define more precisely the time evolution of differences dx, dy and dUT1 From the comparisons in (Feissel and Hefty, 1988) it follows that the most serious changes are in long term behaviour and in annual components.

Figure 2 shows the strongly smoothed (h=550 days) dx, dy, dUT1 and z . It is obvious that the most remarkable feature is the drift of dy in years 1985-86, while the other components do not present substantial long term changes. The stability of annual variations are checked using the method of decomposition of nonstationary time series (Andel, 1976). The amplitude diagram describes the continuous amplitude variations of a process with stable frequency but changeable amplitude. This type of diagrams for annual component in dx, dy, dUT1 and z are on Figure 3 . The increase of dx and dUT1 amplitudes in 1984 are evident . From Figures 2 and 3 and Table 1 it follows that it is possible to restrict the problem of inhomogeneity in optical astrometry ERP to the drift in the y pole coordinate and in nonstationarity in the annual components of x and UT1.

The variations of dx, dy, dUT1 and z can be projected into the latitude variations $d\varphi$ and time variations dUT0 for arbitrary point with coordinates φ_0,L_0 using following equations

/3/ $$d\varphi = dx \cos L_0 - dy \sin L_0 + z$$

$$dUT0 = (dx \sin L_0 + dy \cos L_0) \,tg\, \varphi_0 + dUT1$$

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Such a projection will enable to find out the regions where the influence of inhomogeneities is the most significant. The essential part of stations participating on optical astrometry is concentrated in four geographical regions - European (EU) West Asian (WA), North American (NA), and South American (SA). The evolution of predicted long term weights of stations used for preservation of optical astrometry reference system for the mentioned regions is on Figure 4.They represent 95% of the total weight shown in the upper part of the Figure 4 . Using the mean latitude and longitude for each region, the variations of dφ and dUT0 according to /2/ are shown on Figure 5.

Considering the regional latitude variations of Figure 5 and the distribution of long term weights of Figure 4, the drift in y is most probably due to latitude stations of West Asia. For studying the drift at individual observatories we analysed the differences of measured minus predicted a-terms - the the constant part from the yearly analyses according to /1/. However the series ERP(BIH) 87 C 01 based on space techniques are taken as the reference in this case. If there exists a drift in station's mean latitude it will be manifested as a systematic change of Δa . Let us divide the stations situated in WA into two groups. The first one consists of three most stable stations BJB, TJZ, and ZIB, regarding their observations continuity and long term stability.The second one includes the rest (14) of observatories in this region. The three stations have 1/3 of weight of WA in 1984 and 1/2 in 1985-86. As the Figure 6 shows the three stations are consistent with respect to space techniques while the mean latitude for the other stations is drifting in the sense corresponding to the Figure 5. In general the 1985-86 period is characterized by a decrease of observational activity and long term stability for the stations in the WA region. This produced the non-predictable change of the net geometry and the effect of shifting the mean latitude. We assume that introducing a posteriori determined weights would diminish the shift in y pole coordinate.

The variations of annual amplitudes in dx and dUT1 are studied using the amplitude diagrams of time series dφ and dUT0 in the four geographic regions. Figure 7 shows the increase of dφ amplitudes during 1983-84 in EU and during 1986 in NA and SA On the contrary the WA region do not present serious variations in dφ annual amplitude. Because of contributions of the longitudes according to /3/, the dx variation is connected only with dφ variation in EU. This region is characterised by a steady decreasing of total weight and in the same time the distribution of stations with important contribution is considerably modified. The scatter of annual terms at individual stations compared to the total effect do not permit to decide whether the anomaly is caused only by some observatories. In our opinion the variation of dx amplitude could be ascribed to changes in the EU part of optical astrometry net.

The situation with variation of dUT1 annual amplitude is more complicated as in dUT0 projections are mixed the effects of inhomogeneities in all the three ERP. The increase and variation of dUT0 amplitudes after 1983 is evident in all the four regions. But while the amplitude of dUT1 increases in 1983-85, the increase of dUT0 in the WA region with the essential

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contribution in time observations is only in 1985. Analysing the annual amplitudes of the four most stable UTO-UTC time series (OS, BJB, WHF, ZIG - 25% of total weight in UTO-UTC in 1983-86), we found the amplitude variations close to dUT1 variations on Figure 3. It implies that the variations of dUT1 annual amplitude is a common effect to all the time stations. This finding is also supported by further investigations with 10 selected stations (50% of total weight)

SUMMARY

Our analysis of the long term stability of ERP determined by optical astrometry shows that after 1983-84 the homogeneity of BIH solution is deteriorated. Similar discrepancies exist in the IPMS solution (Feissel and Hefty, 1988). We found discontinuities at some stations in 1984.0 , when the new system of astronomical constants and computing conventions were introduced. However this is not the main reason for enlarging the differencies between optical astrometry and space techniques ERP. The inhomogeneities in pole coordinates are connected with decreased observational activity at latitude stations. The enlarging of annual amplitudes in UTO-UTC determination by optical astrometry is an effect common to the majority of the participating stations. Since the network of time stations is not so significantly changed, the optical astrometry UT1 determination is more perspective comparing to polar motion. To avoid the influence of erroneous x and y it will be useful to solve optical astrometry UT1 utilizing the pole positions determined by space techniques.

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Table 1. Comparison of differences dx, dy and dUT1 from two periods I. - 1981-83 and II. - 1984-86. The RMS differences, RMS residuals and pair variances are in units of 0.001"

	Period	RMS difference	RMS residual to gaussian smoothing	Pair variances				
				0.05y	0.10y	0.20y	0.40y	0.80y
dx	I.	12.7	10.8	10.0	8.3	8.7	6.6	1.7
	II.	17.5	12.7	12.3	11.8	10.9	8.7	7.2
	Ratio II./I.	1.37	1.18	1.23	1.42	1.25	1.31	4.20
dy	I.	9.5	8.8	8.7	7.4	6.3	3.4	2.3
	II.	14.5	8.4	8.0	6.6	5.7	4.9	7.6
	Ratio II./I.	1.53	0.96	0.91	0.89	0.91	1.48	3.31
dUT1	I.	9.1	7.5	8.3	4.3	4.0	4.9	2.9
	II.	12.8	9.0	9.4	6.2	6.7	9.5	3.7
	Ratio II./I.	1.40	1.20	1.14	1.44	1.71	1.92	1.27

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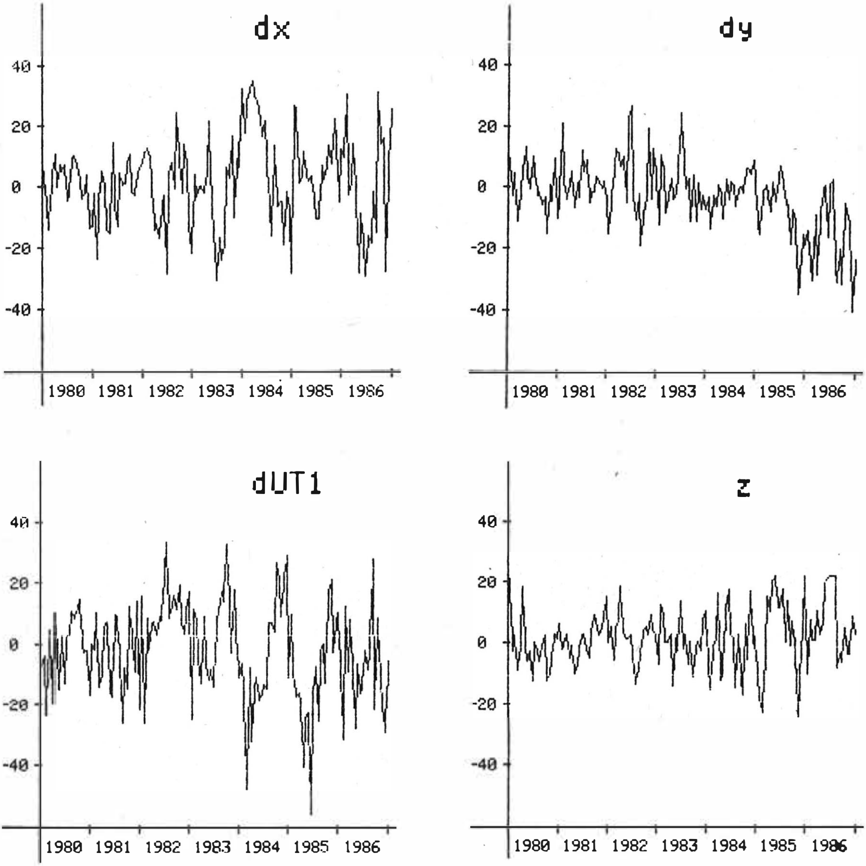

Fig. 1: Differences dx, dy, dUT1 between the optical astrometry and space techniques ERP, and the z-term (unit:0.001").

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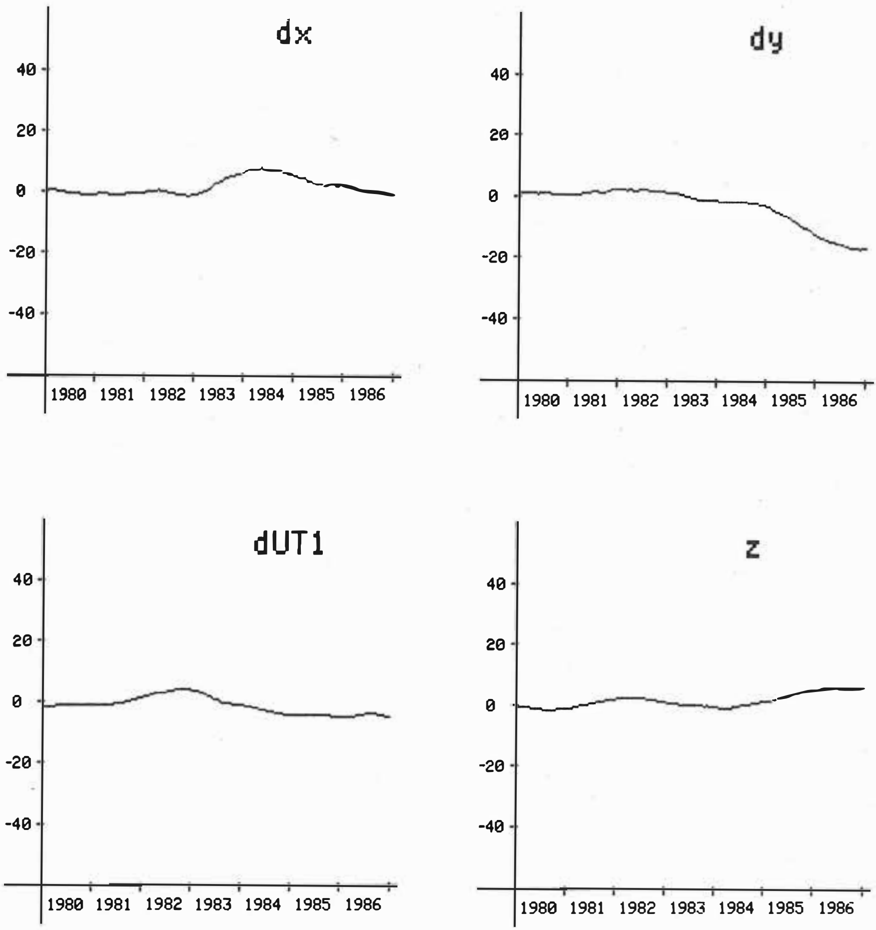

Fig. 2: Gaussian smoothed (h=550 days) dx, dy and dUT1
(unit:0.001").

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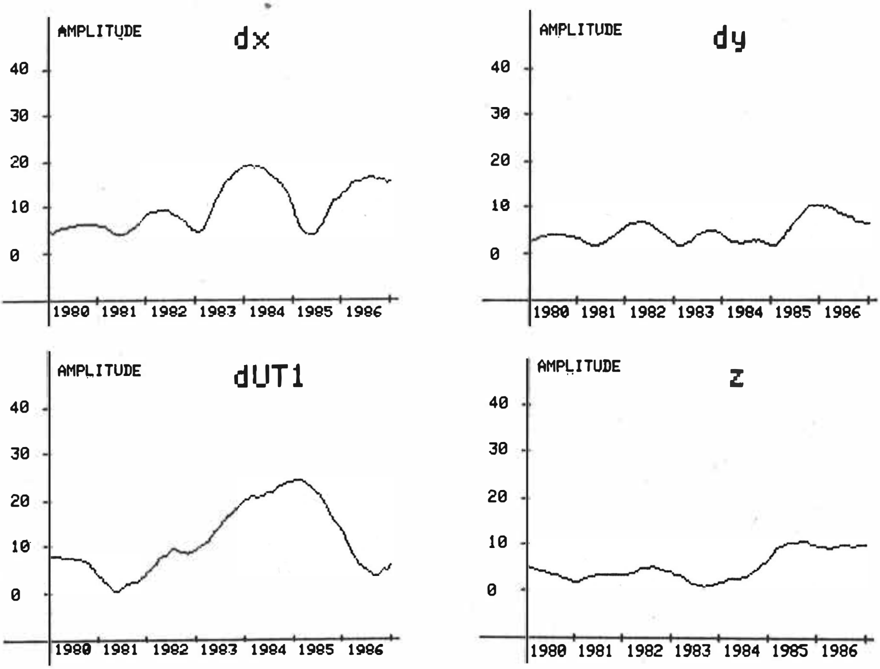

Fig. 3: Amplitude diagrams of annual terms in dx, dy, dUT1
(unit:0.001").

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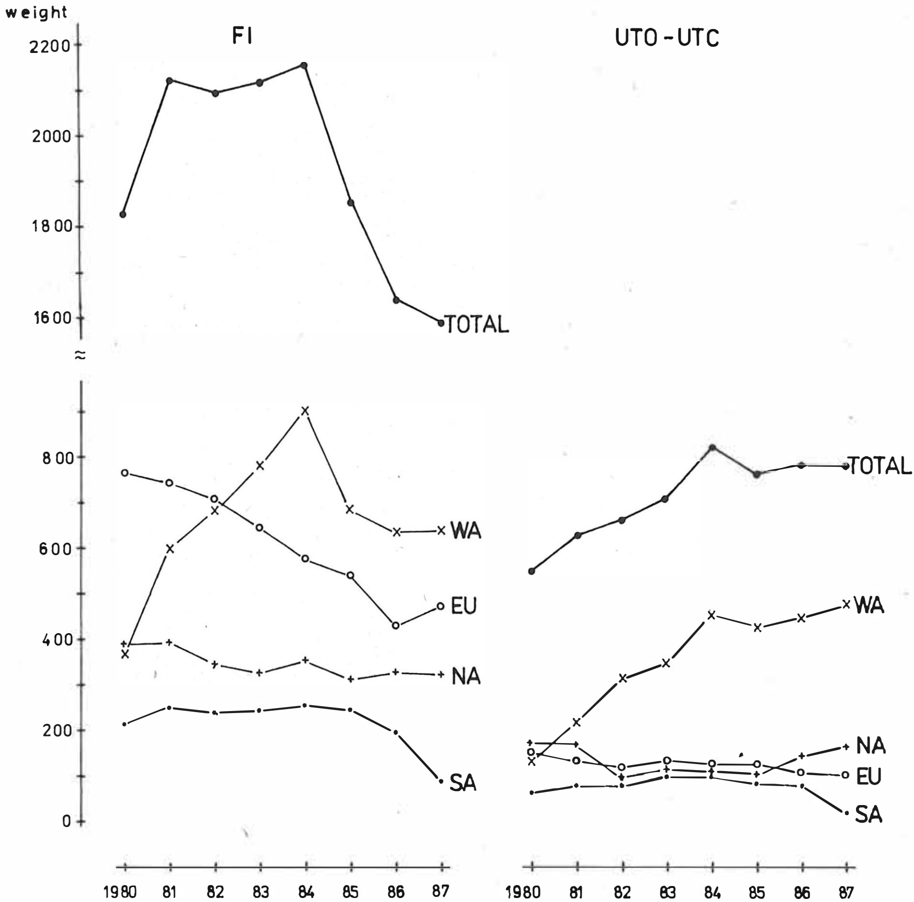

Fig. 4: Evolution of long term weights in and UTO-UTC in four geographical regions and the weights of the whole network.

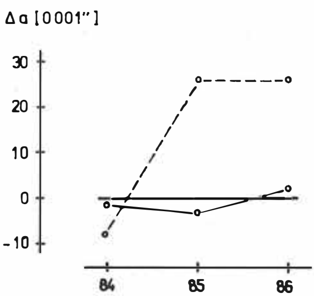

Fig. 6: Evolution of Δa terms in WA region. The horizontal line represents the space techniques reference, the full line the three most stable stations and the dashed line the rest of stations in this region.

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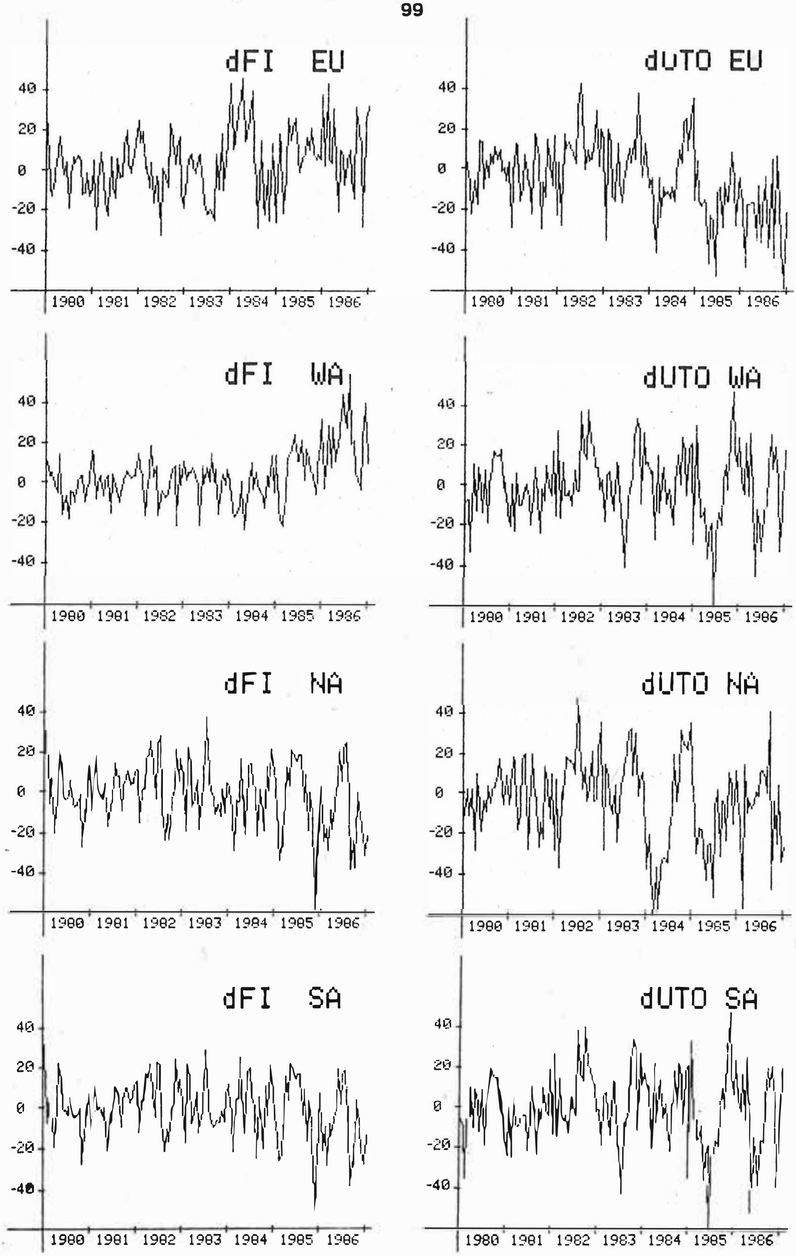

Fig. 5: Projections of dx, dy, dUT1 and z into dφ and dUTO for four geographical regions (unit : 0.001")

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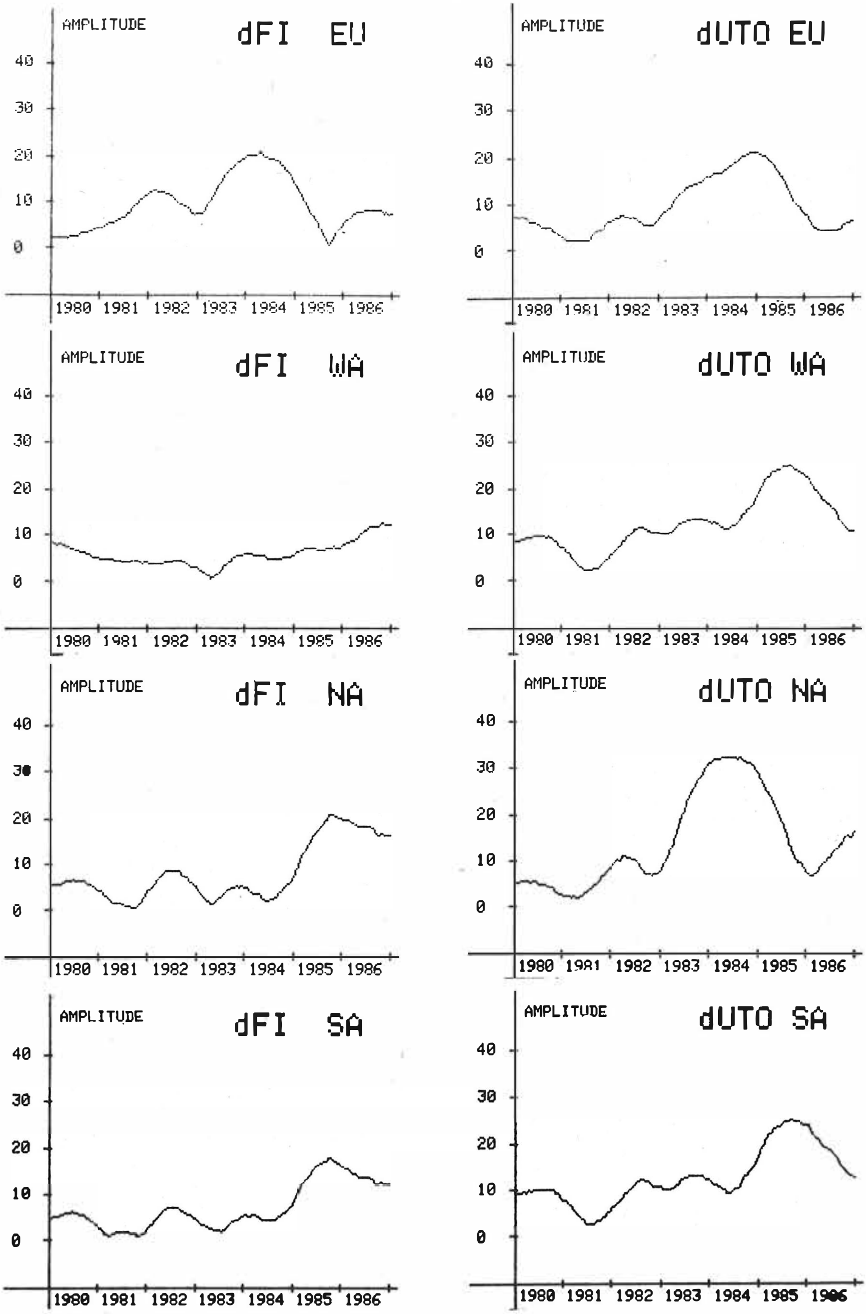

Fig. 7: Annual term amplitude diagrams of the regional projections $d\varphi$ and dUTO (unit:0.001").

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Rotational Motions of the Inner Core and the Polar-Motion

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Summary

Correlations between geomagnetic field parameters and polar motion were explained using the hypothesis of inner core motions. For a number of periodic oonstituents of both phenomena it could be proved that this model works well.

Zusammenfassung

Korrelationen zwischen den Parametern des geomagnetischen Feldes und der Polbewegung werden unter Voraussetzung einer Innenkernbewegung erklärt. Für eine Anzahl periodischer Anteile beider Phänomene konnte die Brauchbarkeit dieses Modells nachgewiesen werden.

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Introduction

Correlations between variations of the geomagnetic field and parameters of the Earth's rotation could be physically proved only for the variations of the length of day applying the theory of electromagnetic core-mantle coupling (see e.g. Stix and Roberts (1984), Greiner-Mai (1987)). Similar variations of polar motion could not be proved by electromagnetic core-mantle coupling, because the components of coupling torques, which influence polar motion, are too small. Therefore it is obvious to assume that decade fluctuations of polar motion are caused by mass motions within the Earth's core, which correspond to variations of the geomagnetic field. Smylie et. al. (1984) supposed that the variation of the geomagnetic dipole, the west drift, indicates a precessional motion of the solid inner core.

This means that the observed geomagnetic dipole field is a result of the dipole field produced by motions in the fluid outer core and the induced dipole field of the solid inner core due to relative motions with respect to the outer core field. Several authors have proved (see e.g. Bullard (1949), Schmutzer (1978))that the axis of the resulting dipole coincides with the axis of rotation of the inner core.

Supposing this we consider subsequently the motions of the geomagnetic dipole as an indication of the motion of the inner core.

Since between the inner and the outer core there exists the largest density difference, the motion of the inner core causes mass redistributions which are the reason for excitation functions of variations of polar motion and the length of day.

1. Basic relations

Considerations of the influence of inner core motions on polar motion and the length of day must be based on an Earth's model consisting of three components, the mantle, the fluid outer core, and the rigid inner core. An investigation of

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this model leads to the conclusion that besides the Chandler-period and the nearly diurnal period, caused by the fluid core an additional nearly diurnal period must be taken into account as eigenperiod of the model.

Since the rotational motions of the inner core, detected by variations of the geomagnetic dipole field have much larger time scales as represented by the diurnal wobbles of the considered Earth's model, it is allowed to apply a simple visco-elastic model for the Earth in all further investigations.

Then polar motion is governed by the complex equation

$$(1) \quad m + \alpha m = i \sigma_{CH} \left(m - \frac{\sigma_{EU}}{\sigma_{CH}} \psi\right)$$

$$(m = m_1 + i\, m_2; \; \psi = \psi_1 + i\, \psi_2)$$

and for the variation of the relative rotational velocity holds the equation.

$$(2) \quad m_3 = \psi_3$$

In equation (1) $\sigma_{CH} = 2\pi/1.19$ 1/a is the Chandler-frequency and $\alpha = 0.05$ 1/a stands for its damping coefficient $\sigma_{EU} = 2\pi/0.842$ 1/a is the Eulerian-frequency, valid for a rigid Earth. ψ and ψ_3 are the excitation functions of polar motion and the rotational velocity.

1.1. <u>The excitation function of inner core motions</u>

The excitation function of polar motion is given by

$$(3) \quad \psi = \frac{c_{12}}{C-A} + i \frac{c_{23}}{C-A}$$

and for the excitation function of the relative variation of the rotational velocity there holds the relation

$$(4) \quad \psi_3 = - \frac{c_{33}}{C} .$$

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c_{13}, c_{23} and c_{33} are temporally varying components of the tensor of inertia, which can be written in the notation

$$(5)\quad I = \begin{pmatrix} A + c_{11} & c_{12} & c_{13} \\ c_{12} & A + c_{22} & c_{23} \\ c_{13} & c_{23} & C + c_{33} \end{pmatrix}.$$

The tensor of inertia of the Earth I consists of the tensors of inertia of the mantle I_M, the core I_C and a temporally variable amount of I_C, which depends on the tensor of inertia of the inner core I_i. Thus we obtain

$$(6)\quad I(t) = I_M + I_C + \frac{\varrho_i - \varrho_c}{\varrho_i} I_i(t)$$

where the coefficient $(\varrho_i - \varrho_c)/\varrho_i$ takes into account that by motions of the inner core matter of the outer core is replaced by matter of the inner core. If the principal axes of inertia of the inner core coincide with the axes of the mantle-fixed coordinate system the tensor of inertia of the inner core is given by the formula

$$(7)\quad I_{i0} = \begin{pmatrix} A_i & & \\ & A_i & \\ & & C_i \end{pmatrix}$$

From (7) we obtain the temporally variable term in (6) if we apply a tensor transformation using a temporally variable transformation matrix R(t)

$$(8)\quad I_i(t) = R(t)\, I_{i0}\, R^{-1}(t)$$

The transformation matrix R(t) is constructed by the geographic position of the geomagnetic dipole, which is given by the pole-distance Θ and the geographic longitude λ. With these quantities we get

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$$(9)\quad R(t) = \begin{pmatrix} \cos\lambda\ \cos\Theta & -\sin\lambda & \sin\Theta\ \cos\lambda \\ \sin\lambda\ \cos\Theta & \cos\lambda & \sin\Theta\ \sin\lambda \\ -\sin\Theta & 0 & \cos\Theta \end{pmatrix}$$

Inserting (9) into (8) and considering (5) we obtain following excitation functions

$$\psi = \frac{C_i - A_i}{C - A}\ \frac{\varrho_i - \varrho_c}{\varrho_i}\ \frac{\sin 2\Theta}{2}\ \exp(i\lambda)$$

(10)

$$\psi_3 = \frac{C_i - A_i}{C}\ \frac{\varrho_i - \varrho_c}{\varrho_i}\ \sin^2\Theta$$

where Θ and λ vary with time.

1.2. The geographic position of the geomagnetic dipole

Pole distance and geographic longitude of the dipole can be calculated according to

$$\Theta = \arctan \frac{\left({g_1^1}^2 + {h_1^1}^2\right)^{1/2}}{g_1^0}$$

(11)

$$\lambda = \arctan \frac{h_1^1}{g_1^1}$$

where g_1^0, g_1^1, and h_1^1 are coefficients of the dipole portion of a spherical harmonic expansion of the surface geomagnetic field,

$$V_{DIP} = r_o\,[\,g_1^0\ P_1^0(\cos\Theta) + (g_1^1\cos\lambda + h_1^1\sin\lambda)\ P_1^1(\cos\Theta)\,].$$

Spherical harmonic expansions of the geomagnetic field are given for different epochs which enables us to establish a time series for Θ and λ and with (10) time series of the excitation functions ψ and ψ_3.

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2. Numerical results

To evaluate formulae (10) numerical values for the quantities

$$\frac{C_i - A_i}{C - A} \quad \text{and} \quad \frac{\varrho_i - \varrho_o}{\varrho_i}$$

are required. The first quantity was calculated using $C_i - A_i$ given in Smylie et al. (1984). The second quantity was obtained from density distributions according to the Earth's models of Bullen and Jeffreys and Gilbert and Dziewonski (model 1066A). To compare time series of polar motion derived from the first formula (10) and the formula (1) with the polar motion obtained from ILS-data we applied a Fourier-transformation to these time series. For this procedure a version of a method was used given in Jochmann (1986), which was extended to the case of a two dimensional motion.

By Fourier-transformation of formula (1) following relation between polar motion and its excitation function is obtained

$$(12) \quad m(t) = \sum_{\omega - \infty}^{\infty} I(\omega)\, \psi_\omega(t)$$

where

$$I(\omega) = \frac{1 - \frac{\omega}{\sigma_0} - i\frac{\alpha}{\sigma_0}}{(1 - \frac{\omega}{\sigma_0})^2 + \alpha^2/\sigma_0^2}$$

is the transfer function.

Taking into account that each periodic constituent of polar motion represents an elliptical motion we compared in fig. 1 the semi-major axes of these ellipses.

The upper spectrum in fig. 1 has been derived from inner core motion using density distributions according to the Earth's model of Jeffreys and Bullen. The crosses in this spectrum denote the amplitudes due to the model of Gilbert and Dziewonski. Comparing these results with the spectrum from pole coordinates, it is found that short period variations correspond to the model of Gilbert and Dziewonski while long period variations are better explained by the model of Jeffreys and Bullen. The parameters of the periodic constit-

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uents obtained in the two different ways agree sufficiently, because the differences between the semi-axes are not larger than their standard deviations. A further proof of the hypothesis of inner core motion is the phase lag between the corresponding periodic constituents derived in the two different ways. Table 2 displays the phase lags in years for the different periodic constituents.

Tab. 1 Phase lag between corresponding polar motion constituents derived from inner core motion and from ILS pole-coordinates

period	50	30	26	20	years
phase lag	27,8	25,2	31,8	27,2	"
mean value			28.0 years		

These phase lags represent the propagation time of a magneto-hydrodynamic disturbance through the outer core. By the distance between the bounderies of the inner and the outer core

$$\Delta r = 2,258,500 \text{ m}$$

we obtain the velocity of propagation

$$v = 2.6 \cdot 10^{-3} \text{m/sec}$$

This value must agree with the Alfven-wave velocity

$$v = \frac{B}{\sqrt{\mu_o \varrho_c}} \qquad (13)$$

In formula (13) is B the magnetic flux density, μ_o is the permeability and ϱ_c the density of the outer core.

If we introduce in (13) the mean flux density at the core-mantle boundary

$$B = 2.21 \cdot 10^{-4} \text{ Tesla}$$

and $\mu_o = 4\pi \cdot 10^{-7}$ Vs/Am,

$$\varrho_c = 11.2 \cdot 10^3 \text{ kg/m}^2$$

we obtain from (13)

$$v = 1.9 \cdot 10^{-3} \text{ m/sec}$$

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This velocity is smaller than that derived from the phase lags. This is to be expected, because the Alfvén-wave velocity was calculated assuming the mean magnetic flux density at the core-mantle boundary as a related quantity for the fluid core. Taking into account that the magnetic flux density increases within the outer core, a larger value should be obtained for the Alfvén-wave velocity, so that really the value derived from phase lags is not in contradiction to the real Alfvén wave velocity in the outer core.

The influence of the inner core motion on variations of the rotational velocity depends on the distance Θ of the dipole from the geographic pole. Since variations of Θ are too small, the corresponding excitations of the variations of the velocity of rotation cannot be used to establish a relation to the real variations of the rotational velocity.

Besides the periodic variations of polar motion discussed above the motion of the inner core causes components of the secular variation of the pole. We obtained the following secular components

$$\Delta m_s = (6.952 \cdot 10^{-9} + i\ 4.227 \cdot 10^{-9})t\ .$$

From ILS pole coordinates

$$\Delta m_s = (3.102 \cdot 10^{-9} - i\ 1.212 \cdot 10^{-8})t$$

(t in years)
was evaluated. It is seen that both results are in the same order of magnitude, so that the inner core motion should be noticed in investigations of the secular polar motion.

3. Conclusions

Foregoing discussions have shown that a number of periodic constituents of both polar motion and variations of the dipole component of the geomagnetic field could be related to each other using the hypothesis of an inner core motion as indicated by the temporal variations of the geomagnetic dipole.

Two essential periods (66 years and 43 years) which are not implied in the spectrum of the observed polar motion and which

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are caused by the hypothesis of inner core motion must be attributed to magnetohydrodynamic processes in the fluid outer core that are not related to inner core motion. The hypothesis of inner core motion is confirmed by the phase lags between polar motion constituents derived from inner core motion and from ILS pole coordinates. For all periodic constituents the phase lags are related to the Alfvén-wave velocity in the fluid outer core.

These results show that the hypothesis of an inner-core motion is a suitable model to explain the correlations between the decade fluctuations of the geomagnetic field and of polar motion.

This hypothesis could be confirmed, if a time series of the coefficients of the spherical harmonic analysis of the gravity potential of the Earth with sufficient accuracy would be available.

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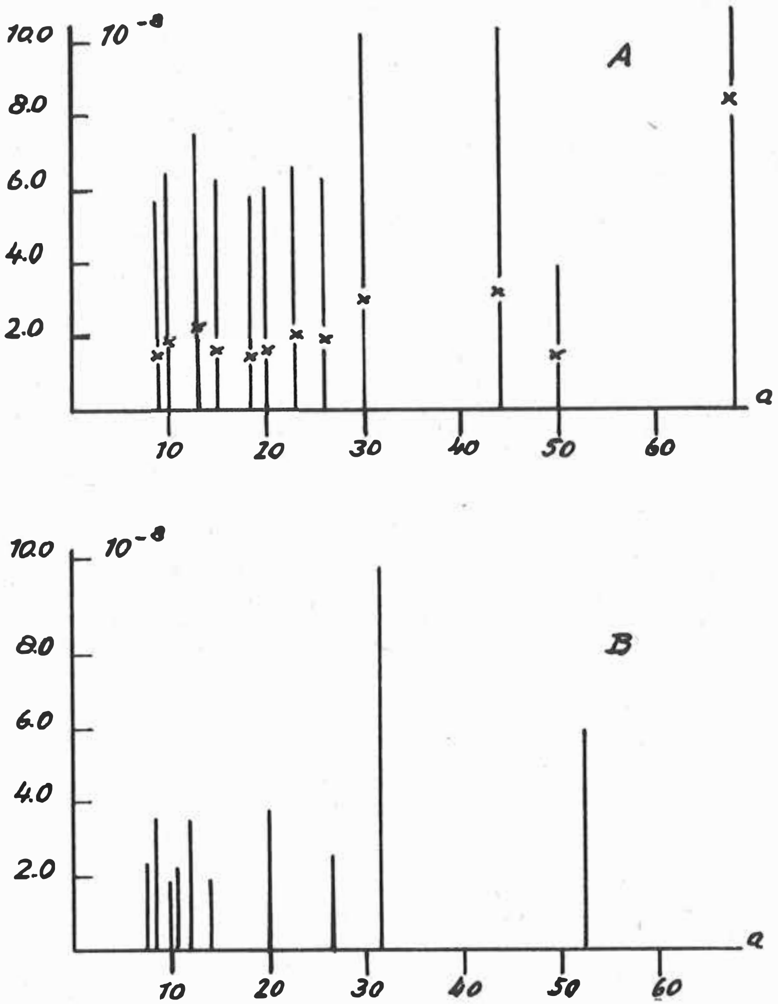

FIG.1 Amplitude spectra of decade fluctuations of polar motion

A. Derived from hypothetical inner core motion

B. Derived from ILS polecoordinates

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Investigations on the stability of the terrestrial reference frame for the determination of ERP using SLR data

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Abstract:

A terrestrial reference frame is realized by a set of station coordinates. These station coordinates are not errorfree. The deviations of the station coordinates from true values cause biases in the determination of Earth rotation parameters.
If the amount of data from the individual stations is changing with time, these biases will also be time-dependent.

Model computations for the LAGEOS laser ranging stations of the MERIT campaign with their real time-dependent contributions were performed to estimate the influence of random uncertainties of the station coordinates as well as the influence of neglected plate tectonic motions on the Earth rotation parameters.

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1. Introduction

The terrestrial reference frame is realized by a set of station coordinates (MUELLER 1980). In the ideal case these station coordinates are errorfree, and if observations and a computation model without any errors are available the resulting Earth rotation parameters would also be errorfree. In practice the station coordinates are not errorfree. This causes errors also in the Earth rotation parameters.

This relation can be expressed in the following similarity transformation:

(1) $$\underline{X}_i^2 + \underline{v}_i = \Delta\underline{X} + (1+\mu)\begin{pmatrix} 1 & \gamma & -\beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{pmatrix} \underline{X}_i^1$$

with:
$\underline{X}_i^1$ -"true" coordinates of station i
$\underline{X}_i^2$ -real coordinates of station i
$\Delta\underline{X}$ -translation parameters
μ -scale difference
α,β,γ -infinitesimal rotation around the x-, y- and z-axis
$\underline{v}_i$ -residuals after transformation

For a certain time interval, which contains the data for the determination of coordinate set 2, the transformation parameters $\Delta\underline{X}$, μ, α, β and γ can be set to zero. One can say that the condition

(2) $$\sum_{i=1}^{N} \underline{v}_i^T p_i \underline{v}_i \Rightarrow Min$$

was the basic relation for the realization of the terrestrial reference frame.

In reality the individual stations do not contribute contineously to the Earth Rotation Service (weather conditions, observability of satellites, technical problems, "weekend effect" etc.). Therefore (2) must be written correctly:

(3) $$\sum_{i=1}^{N} \underline{v}_i^T p_i(t) \underline{v}_i \Rightarrow Min$$

The station weights are consequently time-dependent. This leads to the fact that - even with constant values $\underline{v}_i$ - the transformation parameters in (1) are also time-dependent including the rotation values around the axes:

(4) $$\begin{aligned} \alpha &= \alpha(t) \\ \beta &= \beta(t) \\ \gamma &= \gamma(t) \end{aligned}$$

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Finally one can state that the realization of the terrestrial reference frame by a set of (not errorfree) station coordinates and time-dependent contributions of the individual stations will cause time-dependent biases of the ERP too, because the ERP are related to the directions of the x-, y- and z-axes.

2. Model computations

We performed model computations in the following way:

- SLR station distribution from MERIT campaign (Fig. 1)
- Observation statistics also from MERIT campaign (Fig. 2)
- Computer-simulated errors of the "true" station coordinates with $\sigma = \pm 3$cm (this value corresponds to the real accuracy of station coordinates during MERIT - see e.g DIETRICH 1988)
- station motions from AMO-2 (MINSTER and JORDAN 1978); in this case the $\underline{v}_i$ are linear functions with time (Tab. 2)
- station weights:

$$p_{ij} = \sqrt{N_{ij}}$$

with: N_{ij} -Number of observed LAGEOS passes of station i in the time interval j

This way similarity transformations between the "true" station coordinates and the erroneous station coordinates with time-interval-dependent station weights were performed. The resulting changes of α, β and γ as a function of the time interval were received. (Changes of $\Delta\underline{x}$ and μ were 1...2 orders of magnitude smaller and can be neglected.)

3. Results

The results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ are shown in the following figures:

- For neglected plate tectonic motions, if the real ones correspond to the AMO-2 model in Figures 3a, 3b, 4a and 4b, the results for variants b having been devided by the epoch difference between initial epoch and mean MJD of the time interval. This leads to stationarity of the resulting random changes of α, β and γ. Besides clear trends coming from the secular drifts of the coordinate axes (Fig. 3a, 4a) the random noise is of interest for further investigations.
- For random but fixed deviations of the station coordinates from the true values in Figures 5 and 6 (one realization of the numerical experiment).
- For the sum of both effects in Figures 7 and 8.

One can summarize the magnitudes of the effects as follows:

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Time interval of ERP solution	Simulated effect	Mean influence on ERP arc seconds	(mm)
5 days	neglected plate tectonic motions *)	0.000 18	(6)
	erroneous station coordinates	0.000 22	(7)
	sum of both effects	0.000 25	(8)
1 day	neglected plate tectonic motions *)	0.000 37	(12)
	erroneous station coordinates	0.000 50	(15)
	sum of both effects	0.000 55	(17)

Tab. 1: Mean magnitudes of the investigated effects
*) values for a time difference of one year

These values reflect possible noise contributions of inaccurate modelling of the CTS realization on the Earth rotation parameters.

A spectral analysis for the sum of both effects (Fig. 8 and 9) using a method of JOCHMANN (1986) was performed; the results are shown in Fig. 9, 10 and 11.

The following main conclusions can be drawn:

1. The discussed effects can produce amplitudes of up to $1x10^{-4}$ arc seconds at different frequencies, which have consequently no physical cause or real background in the Earth rotation itself.
2. The detection of a significant peak for the 7-day period of $7x10^{-4}$ arc seconds (Fig. 12) seem to correspond to the weekend effect of observation activities, especially in the station network of the USA (comp. Fig. 2).

The investigations presented lead to the final conclusion that for the analysis of the fine stucture of ERP possible noise contributions caused by the "nonideal" terrestrial reference frame must be taken into account.

In interpretations of the spectrum of polar motion, especially for periods below 100 days, amplitudes up to $1x10^{-4}$ arc seconds and more can be expected, which are only noise caused by erroneous station coordinates. An increasing number of observing stations, increasing measurement and model accuracies will help to reduce the magnitude of this noise contribution.

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DIETRICH, R. (1988): Untersuchungen zur Nutzung künstlicher Erdsatelliten für die geodätische Koordinatenbestimmung. Veröff. Zentralinst. Physik der Erde No. 96, Potsdam 1988.
JOCHMANN, H. (1986): Eine Methode zur Ermittlung periodischer Anteile eines Prozesses. Vermessungstechnik 34(1986)1, S. 18-20 VEB Verlag für Bauwesen, Berlin.
MINSTER, J.B. and JORDAN, T.H. (1978): Present-day plate motions. J. Geophys. Res. 83, 5331-5354.

Plate name	Rotation around the x-axis	y-axis	z-axis
	arc seconds per year		
Pazific	-0.000 441 94	0.001 121 87	-0.002 359 33
Cocos	-0.002 294 14	-0.004 793 11	0.002 612 02
Nazca	-0.000 327 10	-0.001 918 12	0.002 270 20
Caribbean	-0.000 100 33	-0.000 203 80	0.000 388 08
South America	-0.000 201 74	-0.000 384 19	-0.000 311 11
Antarctica	-0.000 190 30	-0.000 341 71	0.000 776 52
India/Australia	0.001 741 39	0.000 900 40	0.001 552 75
Africa	0.000 203 76	-0.000 692 96	0.000 864 58
Arabia	0.001 003 86	-0.000 602 78	0.001 344 92
Eurasia	-0.000 110 56	-0.000 571 14	0.000 705 78
North America	0.000 118 76	-0.000 821 81	-0.000 051 37

Tab. 2: Cartesian rotation vector for each plate using kinematic plate model AMO-2 (no net rotation). MINSTER and JORDAN (1978)

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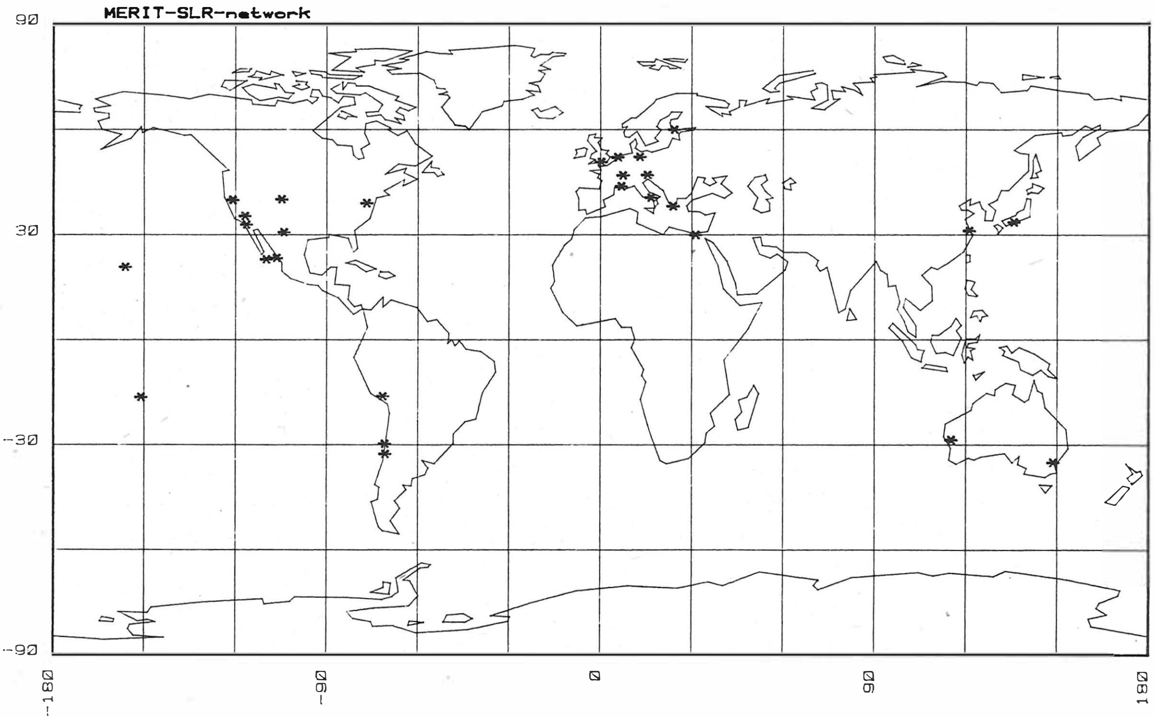

Fig. 1: Used SLR station distribution (MERIT campaign).

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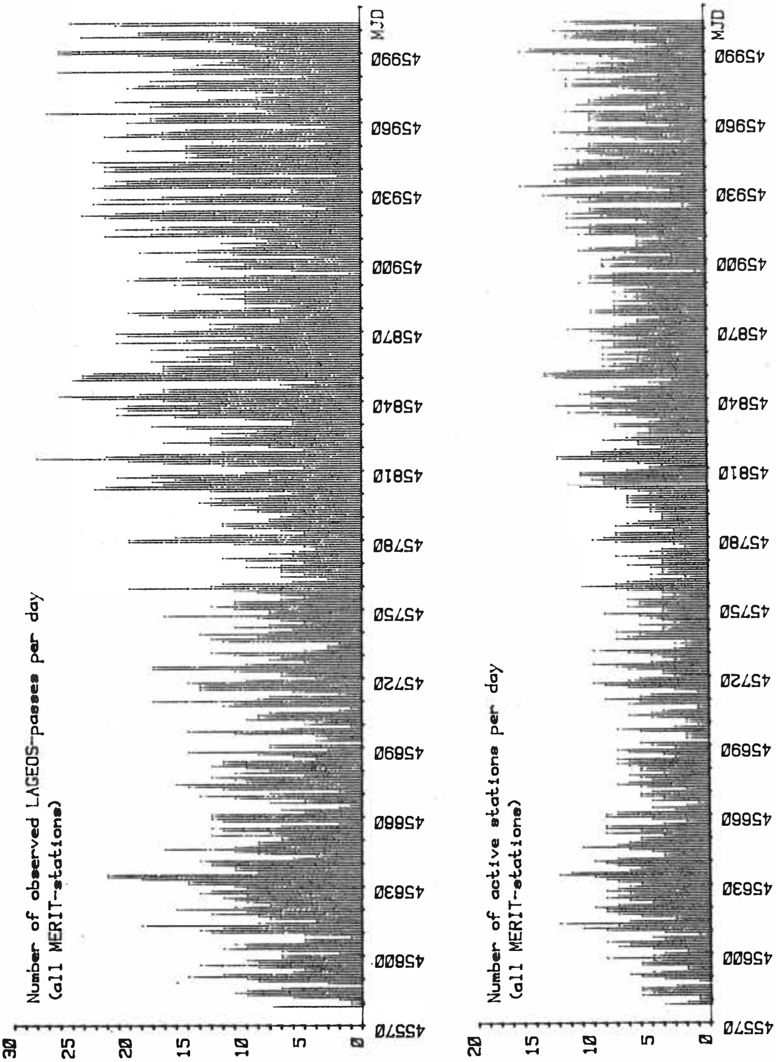

Fig. 2: Amount of SLR data during MERIT (LAGOES)

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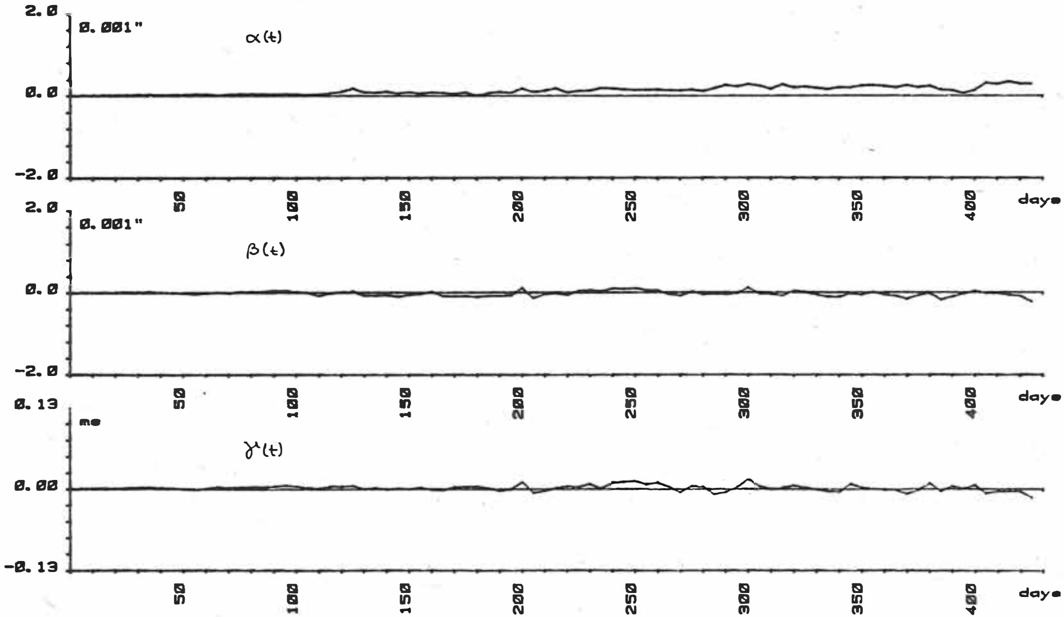

Fig. 3a: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$.
Influence of neglected plate tectonic motions on ERP.
5-day ERP solution interval.

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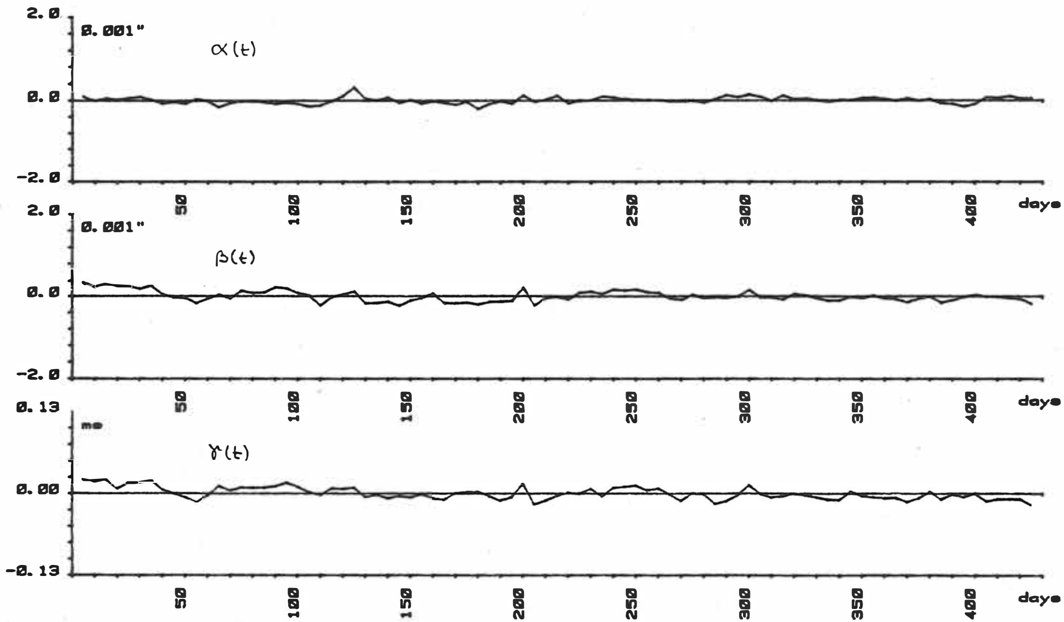

Fig. 3b: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$. (after transformation)
Influence of neglected plate tectonic motions on ERP.
5-day ERP solution interval.

DOI: https://doi.org/10.2312/zipe.1989.102.01

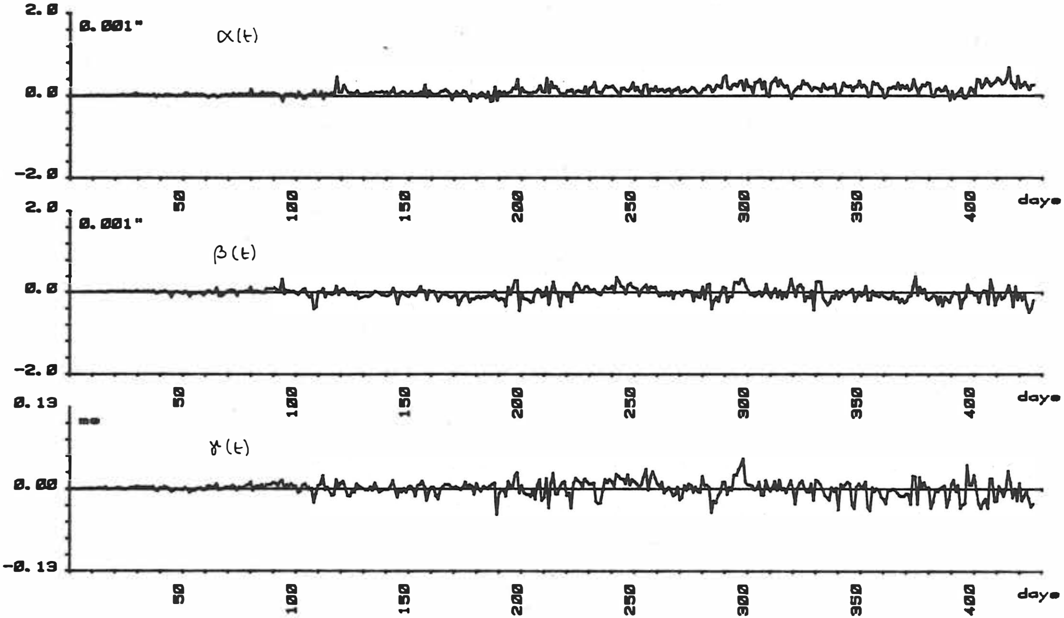

Fig. 4a: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$.
Influence of neglected plate tectonic motions on ERP.
1-day ERP solution interval.

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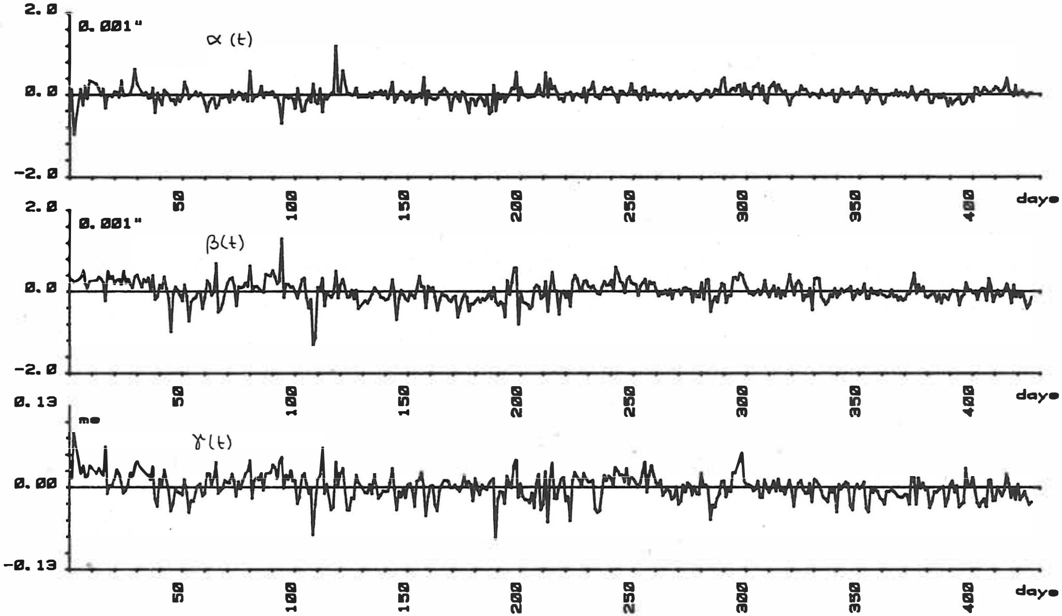

Fig. 4b: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$. (after transformation)
Influence of neglected plate tectonic motions on ERP.
1-day ERP solution interval.

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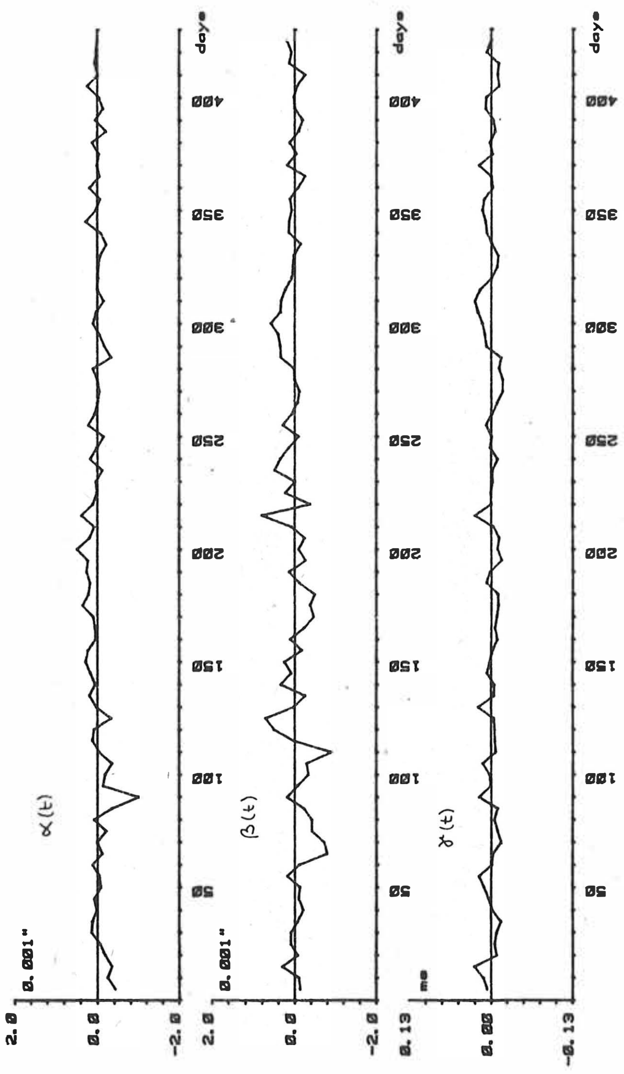

Fig. 5: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$.
Influence of random errors of station coordinates on ERP.
5-day ERP solution interval.

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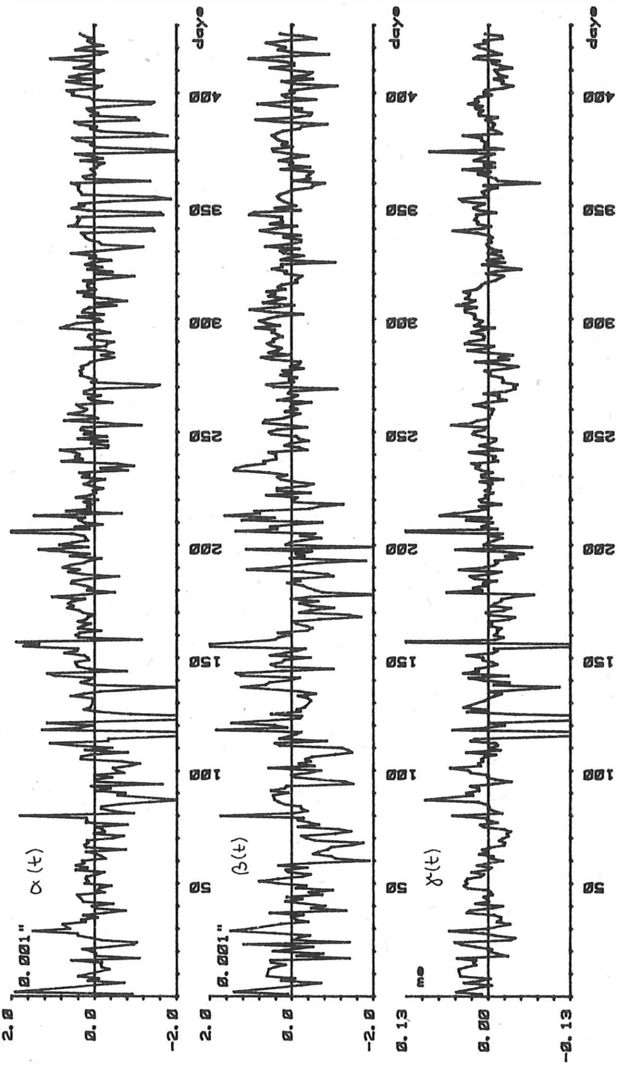

Fig. 6: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$. Influence of random errors of station coordinates on ERP. 1-day ERP solution interval.

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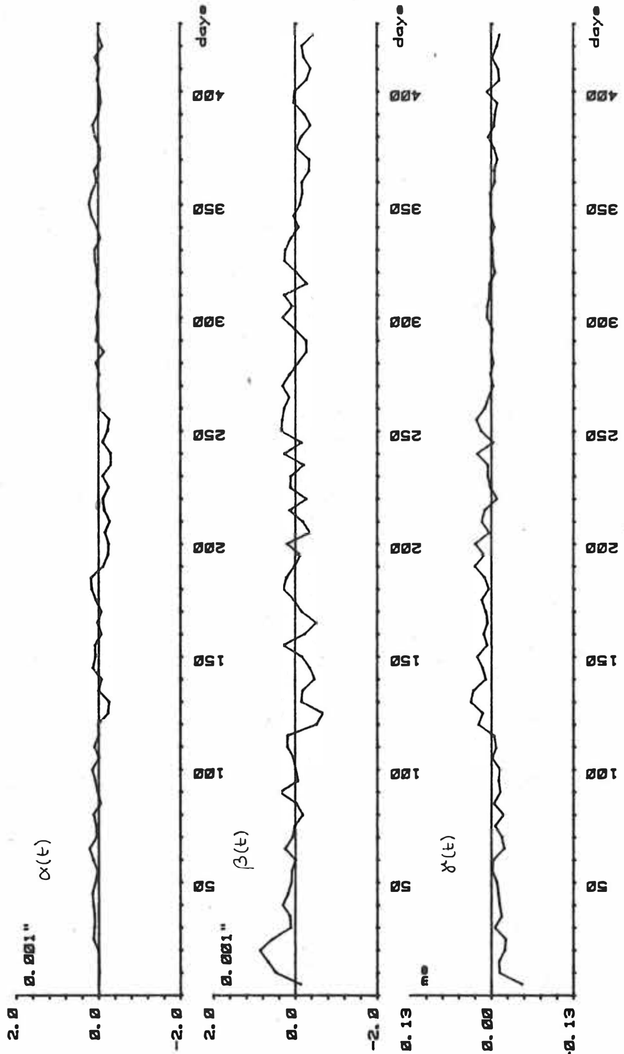

Fig. 7: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$.
Influence of sum of both effects on ERP.
5-day ERP solution interval.

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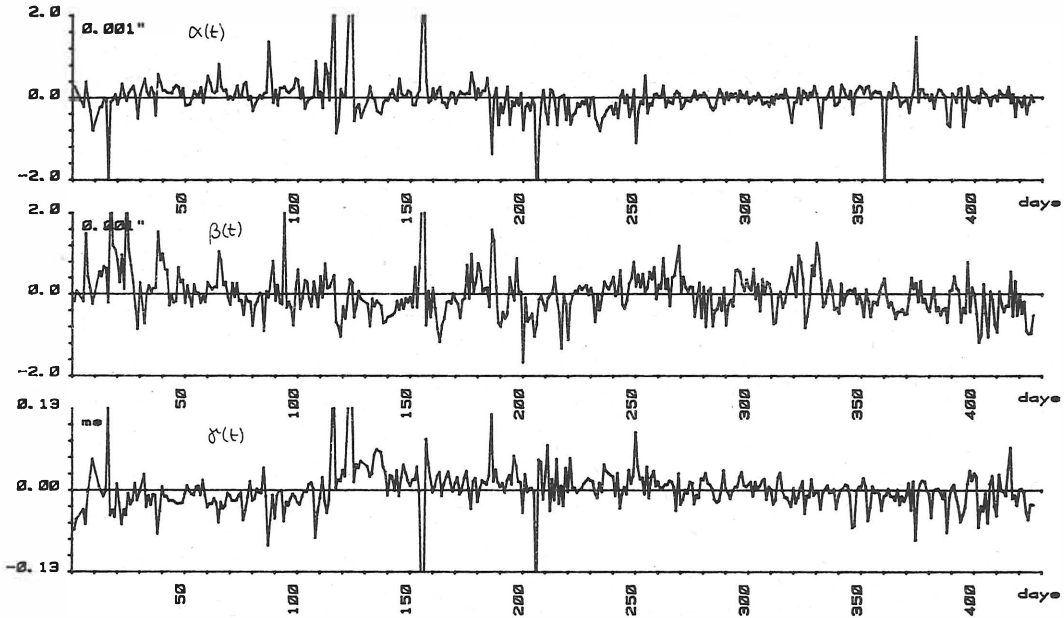

Fig. 8: Results for $\alpha(t)$, $\beta(t)$ and $\gamma(t)$.
Influence of sum of both effects on ERP.
1-day ERP solution interval.

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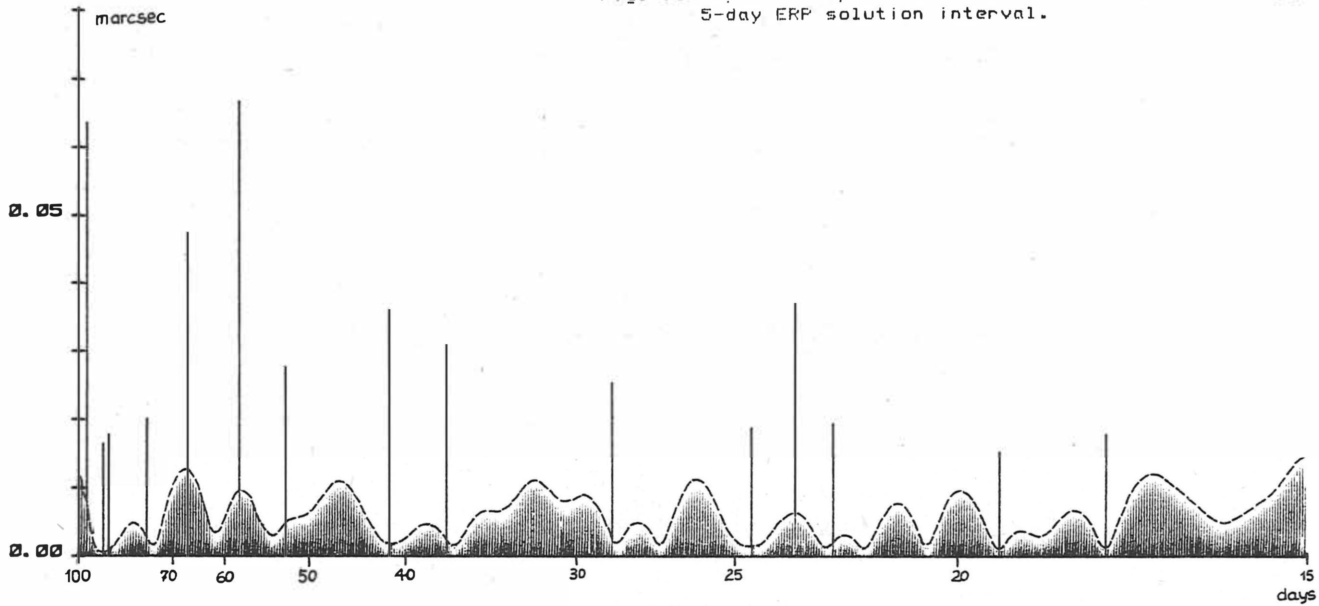
Fig. 9: Amplitude spectrum of $\alpha(t)$ (sum of both effects).
5-day ERP solution interval.



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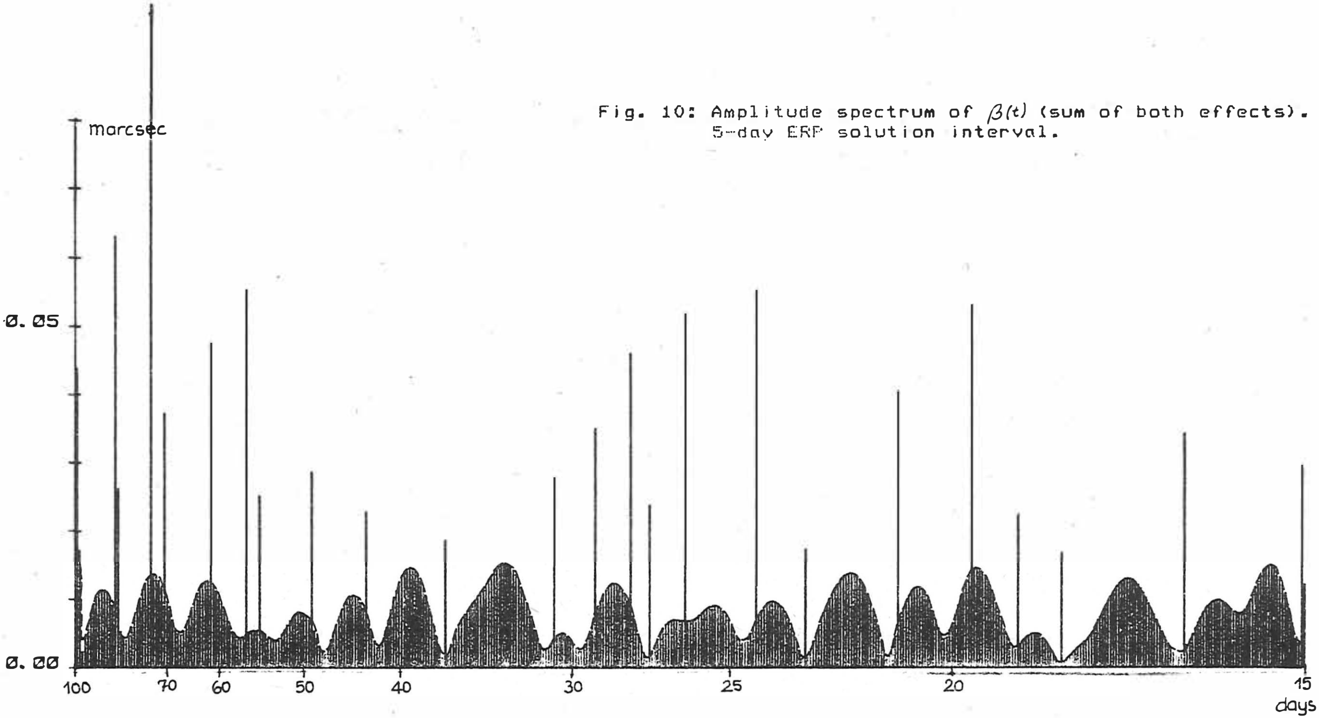

Fig. 10: Amplitude spectrum of $\beta(t)$ (sum of both effects).
5-day ERP solution interval.

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Fig. 11: Amplitude spectrum of $\gamma(t)$ (sum of both effects).
5-day ERP solution interval.

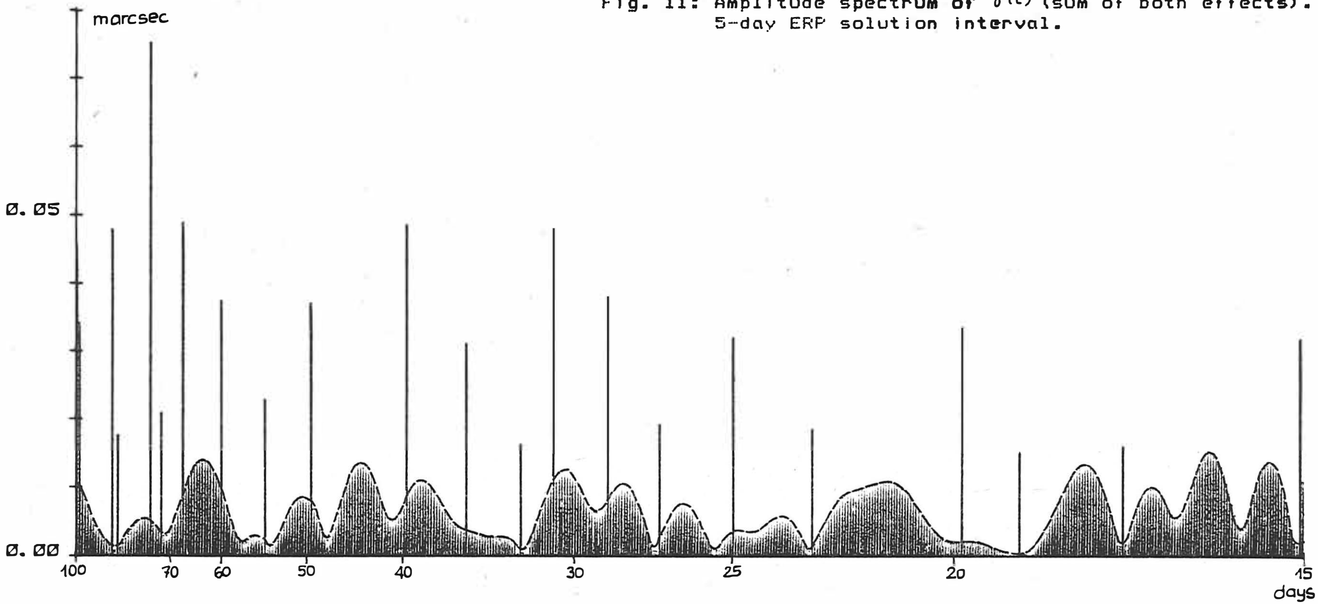

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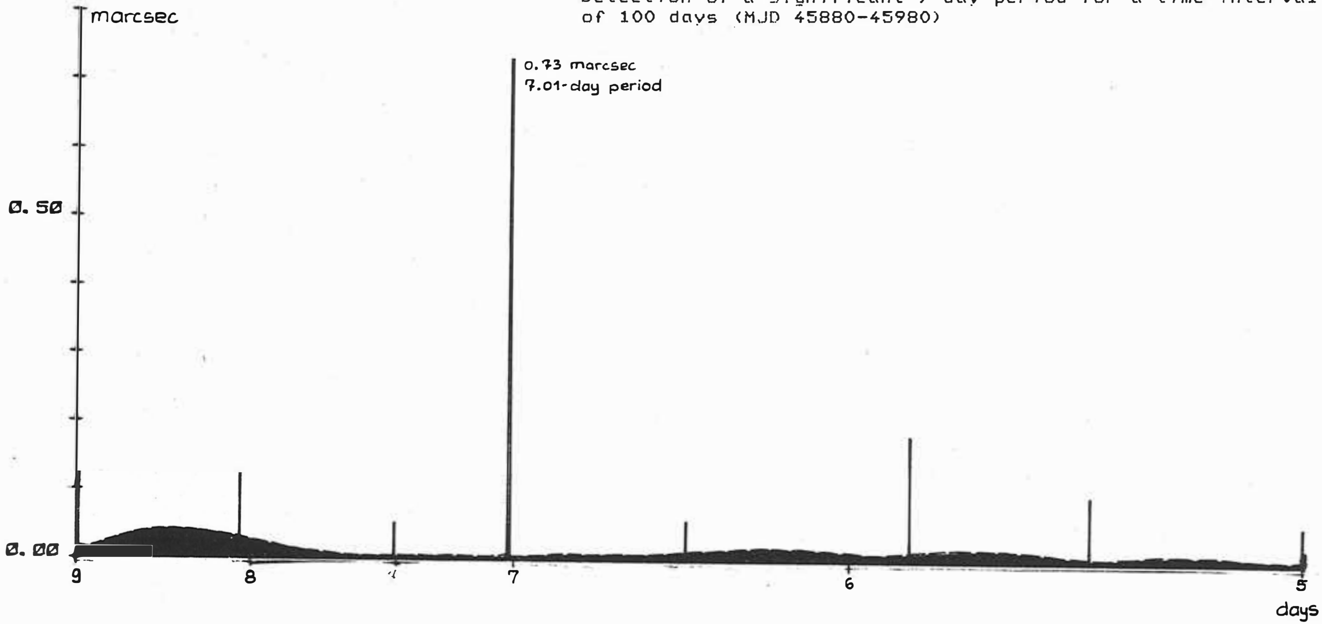
Fig. 12: Amplitude spectrum of $\alpha(t)$ (infl. of station coord. errors).
1-day ERP solution interval.
Detection of a significant 7-day period for a time interval of 100 days (MJD 45880-45980)



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THE POLE TIDE - A SPHERICAL HARMONIC APPROACH

by

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ABSTRACT. A straightforward approach based on surface spherical harmonics has been used to tackle the pole tide problem. Numerical problems arising by large matrices and complex arithmetic have been overcome. The self-consistent solution includes surface loading and mass conservation, providing finally a set of harmonic coefficients for the equilibrium pole tide. It proves to be sufficient with respect to resolution and may be used in a convenient manner to compute the equilibrium pole tide. A comparison with actual (unfortunately sparse !) tide observations reveals significant departures from computed equilibrium tides in fissured coastal areas and closed ocean basins; in general, however, good agreement between computed and observed tide values is found. Possible explanations and consequences are discussed.

1. INTRODUCTION

The variation of the Earth's rotation axis with respect to an "earth-fixed" reference frame (however this frame may be realised) induces an ocean tide, which is usually referred to as "pole tide". Particularly, we are interested in the ocean's response to the Earth's free nutation, i.e. the Chandler wobble.

First, it may be stated that the theoretical amplitude of the pole tide is very small: even its maximum amount does not exceed 1 cm. This property imposes severe constraints on the observability of the pole tide, and indeed the lack of reliable tide observations seems to be the crucial obstacle for interpretation of results. Second, the pole tide causes a global water mass variation and affects the pole path via changes in the products of inertia. This fact is indeed an essential difference to other ocean tides where such a "feed-back" mechanism may be observed only over a geological time scale. The interaction of the pole tide with the pole path gives also a key for the interpretation of the Chandler wobble's damping, a problem which has not been satisfactorily solved since the discovery of the earth's free nutation at the end of the last century. An equilibrium pole tide (in the sense that the ocean's surface remains an equipotential surface) would imply that mantle anelasticity is probably the main reason for the Chandler wobble damping. A large departure from equilibrium, however, would make the ocean be the favourite candidate for energy dissipation. A former numerical approach to this problem was given by Dickman and Steinberg (1985) who concluded that the observed pole tide is significantly enhanced in comparison to the theoretically computed pole tide. However, a recent investigation (Dickman, 1988, pers. comm.) employing a dynamic pole tide model suggests that the departure from equilibrium is small.

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2. THE BASIC IDEAS

Naturally, every attempt to get a realistic, global feature of the pole tide entails that a model of the land-ocean distribution has to be provided. A theoretically very convenient but nevertheless numerically laborious way is a spherical harmonic expansion of the ocean function. The ocean function $C(\varphi,\lambda)$ is simply defined by the condition $C(\varphi,\lambda) = 1$ where there is water and $C(\varphi,\lambda) = 0$ where there is land. Hence, it follows

$$(1) \qquad C(\varphi,\lambda) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} C_\ell^m \, Y_\ell^m$$

for the surface spherical harmonic expansion of the ocean function. Subsequently, we shall follow the phase and normalisation convention of the Y_ℓ^m as given by eq. (2.5.29) of Edmonds (1964):

$$(2) \qquad Y_\ell^m(\theta,\lambda) = (-1)^m \left[\frac{2\ell+1}{4\pi} \, \frac{(\ell-m)!}{(\ell+m)!} \right]^{0.5} P_\ell^m(\cos\theta) \, e^{im\theta}$$

$$(3) \qquad Y_\ell^{-m}(\theta,\lambda) = (-1)^m \, Y_\ell^{*m}$$

where the P_ℓ^m are the well known associated Legendre functions. It should be noted that in general the Y_ℓ^m as well as the C_ℓ^m are complex. Also, the colatitude θ instead of latitude φ has been introduced. The coefficients C_ℓ^m may be found by numerical integration, see e.g. (Munk and MacDonald, 1960, Appendix). The C_0^0 term reflects, after denormalisation, the part of the earth's surface being covered by oceans. The full advantage of spherical harmonics will be evident by considering the entire approach.

Up to now no attempt has been made to account for the imposed tidal potential. The present approach is quite general and, in principle, every tidal potential can be introduced in the subsequent derivation. However, we are only interested in the pole tide and shall confine our discussion to this phenomenon. It should be noted that this approach is only valid as far as the condition of static equilibrium is fulfilled. The present treatment is less suitable for semi-diurnal or diurnal tides, both being largely dominated by dynamic effects. The polar motion induced tidal potential can be represented by means of spherical harmonics of degree 2 and order 1:

$$(4) \qquad V(r,\theta,\lambda) = -m_1 \, \Omega^2 \, (2\pi/15)^{0.5} \, r^2 \, [\, Y_2^1 - Y_2^{-1} \,]$$
$$\qquad\qquad -m_2 \, \Omega^2 \, (2\pi/15)^{0.5} \, r^2 \, i^{-1} \, [\, Y_2^1 + Y_2^{-1} \,] \; .$$

Here, m_1 and m_2 represent dimensionless quantities (direction cosines) describing the pole position, and Ω stands for the earth's rotation rate.

It is appropriate to introduce the Newtonian equilibrium tidal height η which can be expressed in terms of the tidal potential V by

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(5) $$\eta(\theta,\lambda) = -\frac{1}{g} V(r,\theta,\lambda)$$

or, by using again a surface spherical harmonic expansion,

(6) $$\eta_\ell^m = -\frac{1}{g} V_\ell^m \quad .$$

By confining to this direct effect (the ocean's response to a variation of the centrifugal potential) the problem would be easily solvable in the spherical harmonic domain by considering only spherical harmonics of degree 2.

Unfortunately, things become intricated by accounting for the "indirect effects". This may be visualized as follows: The effect of the induced tide causes an additional potential which can ce computed using formula (5.8.1) of (Munk and MacDonald, 1960). It expresses the potential of degree n of a surface mass layer:

(7) $$U_n = \frac{4\pi G q_n a}{2n+1} \left(\frac{r}{a}\right)^n$$

with q_n being the n-th degree term of a surface load q(t) and G being the gravitational constant. By using the relationship $4\pi Ga = 3g/\rho_m$ we arrive for r=a at:

(8) $$U_n = \frac{3g}{2n+1} \left(\frac{\rho_w}{\rho_m}\right) \xi_n \quad .$$

ρ_w and ρ_m denote the mean density of sea-water (1.025 g/cm^3) and of the solid earth (5.517 g/cm^3), respectively. In addition, the perturbation in the gravitational potential due to both tide and load deformation has to be included. It has to be considered that a point on the solid surface of the earth is also displaced from its initial position. The complicated dependence of the ocean tide to a disturbing potential is described by eq. (78) of (Dahlen 1976):

(9) $$\xi(\theta,\lambda) = C(\theta,\lambda) \left[\sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} (1+k_\ell-h_\ell)\, \eta_\ell^m\, Y_\ell^m \right.$$

$$\left. + \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \frac{3}{2\ell+1} \frac{\rho_w}{\rho_m} (1+k'_\ell-h'_\ell)\, \xi_\ell^m\, Y_\ell^m + \frac{\Delta\phi}{g} \right] \quad .$$

k_ℓ and h_ℓ are the well-known Love numbers, whereas k'_ℓ and h'_ℓ are the so-called load Love numbers describing the effect of a surface load on the elastic earth (Munk and MacDonald, 1960, section 5.8). The underlying earthmodel enters via

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the Love and load Love numbers. In this equation both the irregular distribution of the continents as well as the effects of surface loading are evident. The last term, $\Delta\phi/g$, corresponds physically to the disturbance of the equipotential surface, as is clearly visible in eq. (73) of (Dahlen 1976). Due to the irregular distribution of oceans and continents the potential value of the ocean surface will be changed by an amount $\Delta\phi$. Subsequently, we shall use Dahlen's (1976) notation if nothing else is stated.

It will be useful to write explicitly a direct consequence of the normalisation according to (Edmonds 1964, eq. 2.5.4)

$$(10) \qquad \int_S Y_\ell^m Y_{\ell'}^{m'} \, dS = \delta_{\ell\ell'} \delta_{mm'}$$

$\delta_{\ell\ell}$ and δ_{mm} stand, as usual, for the Kronecker symbol.
Also, a formal simplification will be achieved by introducing

$$(11) \qquad A_{\ell rp}^{msq} = \int_S Y^{*m}_\ell \, Y_r^s \, Y_p^q \, dS \quad .$$

By using both relations and eq. (1), eq. (9) leads to an infinite system of complex linear algebraic equations. For this purpose, both sides of eq. (9) have to be multiplied consecutively with Y^{*m}_ℓ, $\ell \geq 1$, $-\ell \leq m \leq \ell$. After integration over the sphere, we finally obtain:

$$(12) \qquad \begin{pmatrix} B_{1\,1}^{-1-1} & B_{1\,1}^{-1\,0} & B_{1\,1}^{-1\,1} & B_{1\,2}^{-1-2} & \cdot \\ B_{1\,1}^{0-1} & B_{1\,1}^{0\,0} & B_{1\,1}^{0\,1} & B_{1\,2}^{0-2} & \cdot \\ B_{1\,1}^{1-1} & B_{1\,1}^{1\,0} & B_{1\,1}^{1\,1} & B_{1\,2}^{1-2} & \cdot \\ B_{2\,1}^{-2-1} & B_{2\,1}^{-2\,0} & B_{2\,1}^{-2\,1} & B_{2\,2}^{-2-2} & \cdot \\ \vdots & \vdots & \vdots & \vdots & \end{pmatrix} \begin{pmatrix} \xi_1^{-1} \\ \xi_1^{0} \\ \xi_1^{1} \\ \xi_2^{-2} \\ \vdots \end{pmatrix} = \begin{pmatrix} b_1^{-1} \\ b_1^{0} \\ b_1^{1} \\ b_2^{-2} \\ \vdots \end{pmatrix} - \left(\frac{\Delta\phi}{g} \right) \begin{pmatrix} C_1^{-1} \\ C_1^{0} \\ C_1^{1} \\ C_2^{-2} \\ \vdots \end{pmatrix}$$

where the symbols $B_{\ell p}^{mq}$ and b_ℓ^m are represented by

$$(13) \qquad B_{\ell p}^{mq} = \frac{3}{2p+1} \, \frac{\rho_w}{\rho_m} \, (1+k_p'-h_p') \left[\sum_{r=0}^{\infty} \sum_{s=-r}^{r} A_{\ell rp}^{msq} \right] - \delta_{\ell p}\delta_{\ell q}$$

and

$$(14) \qquad b_\ell^m = - \sum_{p=2}^{\infty} \sum_{q=-p}^{p} \left[\sum_{r=0}^{\infty} \sum_{s=-r}^{r} A_{\ell rp}^{msq} \, C_s^r \right] (1+k_p-h_p) \, \eta_p^q$$

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The symbols $A^{msq}_{\ell rp}$ describe triple-product integrals of surface spherical harmonics, as can be seen in eq. (11). Procedures for their numerical computation can be found in (Edmonds, 1964). Eq. (12) is not consistent because each treatment of the pole tide is subject to the condition of mass conservation in the oceans. Therefore, eq. (12) is to be solved jointly with

(15)
$$\begin{pmatrix} B^{0-1}_{0\ 1} & B^{0\ 0}_{0\ 1} & B^{0\ 1}_{0\ 1} & B^{0-2}_{0-2} & \ldots \end{pmatrix} \begin{pmatrix} \xi^{-1}_{1} \\ \xi^{0}_{1} \\ \xi^{1}_{1} \\ \xi^{-2}_{2} \\ \vdots \end{pmatrix} = b^{o}_{o} - \left(\frac{\Delta\phi}{g}\right) C^{o}_{o}$$

which has been obtained similarly by multiplying eq. (9) with Y^{*o}_{o}.
By using matrices and vectors, eq. (12) and eq. (15) may be formally described by

(16) $$B\ \xi = b - (\Delta\phi/g)\ C$$

and

(17) $$B^{o}_{o}\ \xi = b^{o}_{o} - (\Delta\phi/g)\ C^{o}_{o}\ ,$$

respectively. We shall hencefort not explicitly distinct between matrices or vectors and scalars; the nature of a quantity will be clear from the context. A solution of eq.(16) and eq.(17) for the desired pole tide ξ follows immediately:

(18) $$\frac{\Delta\phi}{g} = \frac{b^{o}_{o} - B^{o}_{o}\ B^{-1}\ b}{C^{o}_{o} - B^{o}_{o}\ B^{-1}\ C}$$

and

(19) $$\xi = B^{-1}\ b - (\Delta\phi/g)\ B^{-1}\ C\ .$$

In principle, each desired accuracy can be achieved by truncating the spherical harmonic expansion at a sufficiently high degree. However, practical restrictions are imposed by the exceedingly large matrices appearing even for a moderate degree of the spherical harmonic expansion. Numerical details will be given in section 3.

We shall use these linear complex equations, as they stand, for computing the harmonic coefficients ξ^{m}_{ℓ} of the static equilibrium pole tide. Only the symbols $B^{mq}_{\ell p}$ and b^{m}_{ℓ} will be computed in the abbreviated manner being described in (Dahlen, 1976). Neither do we follow Dahlen's advice to avoid

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complex arithmetic nor shall we use the iterative algorithm proposed by him. A unique solution using complex arithmetic seems to be most favourable in view of the enormous progress in computer facilities. In fact, IMSL-subroutine DL2NCG has been used for inversion at an IBM-3090. Fig. 2 displays the amplitude of the equilibrium pole tide. There are some deficiencies on the northern hemisphere due to the plot subroutine; the contours are in fact smooth.

3. NUMERICAL ASPECTS

As already mentioned, the size of the matrix B becomes rather large, even for a moderate degree of the spherical harmonic expansion. For an ocean function expanded up to degree and order 24 the dimension of the square matrix B will be 168. That means that a matrix consisting of 168 · 168 = 28224 complex matrix elements has to be inverted. In addition, a rather large number of triple integral products has to be computed. The harmonic coefficients of the equilibrium pole tide are computed up to degree and order 12. A higher degree of expansion of the ocean function cannot be performed by employing the straightforward approach described above; problems arising by missing storage capacity appear, and sophisticated numerical refinements would be necessary in order to handle the exceedingly large factorials. The resolution of the ocean function is displayed in Fig. 1.

The "self-consistent" approach being described in section 2 includes ocean loading, self-attraction of the ocean surface layer and mass conservation. It ensues from the foregoing discussion that the considerable numerical efforts arise mainly due to these "indirect" effects. Confining to the "direct" effect (i.e the tide driving potential) would tremendously reduce the numerical work because only (2,1)-spherical harmonics were involved. By performing some computational tests, the inaccuracy in the height of the pole tide is found to be 10% to 20%, if these "indirect" effects are neglected. There may be doubts that the "self-consistent" approach is really necessary in view of the small pole tide amplitude. However, the "direct" procedure has no real physical background: ocean mass is not conserved. Information of the earth's response to surface loading is provided by the adopted set of load Love numbers, and neglecting these effects means to use obsolete concepts.

Finally, it should be mentioned that the ocean function behaves as "step-function" at the continental boundaries by jumping from 1 to 0. It is well known that truncated spherical harmonics reproduce imperfectly these jumps. Hence, the present algorithm is not particularly well suited for computing tide values along continents. We try to diminish these disturbances of the ocean function by inserting its theoretical value 1 in eq. (9). However, it remains valid that the main disadvantage of Dahlen's (1976) algorithm is associated with the truncation of spherical harmonics, and we refer to Dahlen (1976) or Dickman and Steinberg (1986) for further details.

4. RESULTS AND DISCUSSION

Of course, each discussion on the pole tide is incomplete as long as no comparison with observed tide values is done. Unfortunately we have to realise that pole tide observations are sparse, irregularly distributed over the globe, and, moreover, not very reliable. The observed amplitudes are hardly above the noise level in most observation sites. Nevertheless, we shall use the global tide values as published by Miller and Wunsch (1973) and found our discussion on their results.

It is a well-known fact that a spectral investigation of ILS polar motion values reveals two distinct Chandler peaks at about 436 days and 428 days, see e.g (Lenhardt and Groten (1985)). The reason of this peak splitting is rather obscure and has been frequently discussed in literature. We shall not take up again this controverse topic; it has, however, to be mentioned because Miller

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and Wunsch (1973) assigned pole tide amplitudes to spectral peaks with corresponding Chandler periods ranging from 419 days to 441 days. Because no physical reason for this frequency splitting is obvious, we try to obviate all pitfalls associated with this effect by confining to pole tide amplitudes with corresponding periods from 426 days to 436 days. If in table 1 of (Miller and Wunsch (1973)) several values in this range are given, the particular one closest to 431 days will be used. All other amplitudes are assumed to be physically unexplainable or due to unknown local effects. Our choice may be only one of several possibilities but provides unique values. The theoretically computed pole tide values are gained as follows: First, an amplitude of 0.16 arcsec is assumed to represent an average Chandler amplitude for this century; a verification can be performed by a simple spectral investigation of ILS polar motion data. Unfortunately, it is not clear that the amplitude of the Earth's free nutation has been stable throughout this century. Dickman and Steinberg (1986) determined the Chandler amplitude from actual polar motion data referred to the particular time span of each tide observation. A Chandler amplitude of 0.14 arcsec would reduce the pole tide in midlatitudes by about one millimeter. Hence, there are good arguments to follow the procedure of (Dickman and Steinberg, 1986)). On the other side, a spectral analysis of the not very accurate ILS polar motion data leads to enigmatical results (see the remarks above); we hesitate to subdivide the ILS data set, and assume the aforementioned amplitude of 0.16 arcsec to be appropriate.

By inserting this value in eq. (4) and by an appropriate variation of phase angles, thus simulating one Chandler cycle, a different harmonic set of pole tide coefficients for each particular phase angle is obtained. Consecutive pole tide values for each desired site on the globe are gained via the spherical harmonic expansion. A subsequent amplitude estimation for each observation site finally provides the theoretically predicted amplitude which is to be compared with the observed one. (A phase determination gives no additional information: the equilibrium pole tide maximum, on the northern hemisphere, is shifted by 180o in phase to the earth's rotation axis, as can easily be visualized). The following table will be clear after these preliminaries :

φ [degree]	λ [degree]	Equi. Pole Tide [cm]	Observ. Pole Tide [cm]	Δ [cm]	Geographic description
Atlantic Ocean:					
28.483	343.767	0.59	0.77	-0.18	Santa Cruz (Canary Islands)
46.233	296.417	0.66	0.64	0.01	Charlottetown (Prince Edward Isl.)
45.267	293.933	0.65	1.32	-0.67	St. John (Fundy Bay)
43.667	289.750	0.64	0.53	-0.11	Portland (Maine)
42.350	288.950	0.64	0.66	-0.02	Boston (Mass.)
39.267	283.417	0.62	0.35	0.27	Baltimore (Del.)
29.317	265.200	0.52	0.48	0.04	Galveston (Texas)
Pacific Ocean:					
55.333	228.367	0.59	0.98	-0.40	Ketchikan (Alaska, Alexander Arch.)
47.600	237.667	0.62	0.30	0.32	Seattle (Washington)
37.800	237.533	0.62	0.61	0.00	San Francisco (California)
8.967	280.433	0.19	0.60	-0.41	Balboa (Panama Canal Zone)
21.300	202.133	0.46	0.56	-0.11	Honolulu (Hawai)
-33.850	151.233	0.67	0.10	0.55	Sydney (Australia)

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Other Oceans:

43.300	5.350	0.68	0.70	-0.03	Marseilles (Mediterranean)
58.783	265.800	0.52	1.29	-0.77	Churchill (Hudson Bay)
44.100	39.067	0.64	0.72	-0.07	Port Tuapse (Black Sea)
13.450	100.600	0.26	0.24	0.07	Bangkok Bar (Gulf of Thailand)
11.800	99.817	0.28	0.98	-0.70	Phrachuapkirikhan (Gulf of Thailand)

It is not easy, and perhaps impossible, to derive a general feature of the global behaviour of the pole tide from these few tide comparisons. But some cautious remarks are in order to illuminate the results. First, except Sydney all tide observations refer to the northern hemisphere. Hence, we cannot draw any conclusions being related to the southern hemisphere; this is a regrettable fact because the pole tide probably reaches its maximum amplitude in the Southern Pacific and along the South American Coast (Fig. 2).

Second, several observation sites with unexpectedly large differences between theoretically computed values and observed ones are situated in gulf zones or fissured coastal areas. This statement refers particularly to St. John, Ketchikan, Seattle, Balboa and Churchill which are observation sites with large deviations from equilibrium. The European counterpart may be found in the anomalously large non-equilibrium pole tides of the North- and Baltic Sea which have been investigated in detail by Wunsch (1986). Also, the large difference of the two observed values in the Gulf of Thailand may be interpreted in terms of inconsistent observations, rather than a departure from equilibrium. With some caution, we feel entitled to claim that it may be assumed that the pole tide on the northern hemisphere follows equilibrium.

Future work will focus on the following points: more tide observations will be included, and the resolution of the spherical harmonic expansion will be improved by truncating at a higher degree.

5. CONCLUSIONS

Based on the algorithm of Dahlen (1976) a spherical harmonic expansion of the pole tide has been computed. The set of harmonic coefficients can be used in a convenient manner to compute the self-consistent pole tide for each site on the globe. A comparison with observed values makes us inclined to assume that the pole tide follows equilibrium. However, the lack of reliable tide observations permits only a very cautious statement concerning the northern hemisphere, and none concerning the southern hemisphere.

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OCEAN FUNCTION

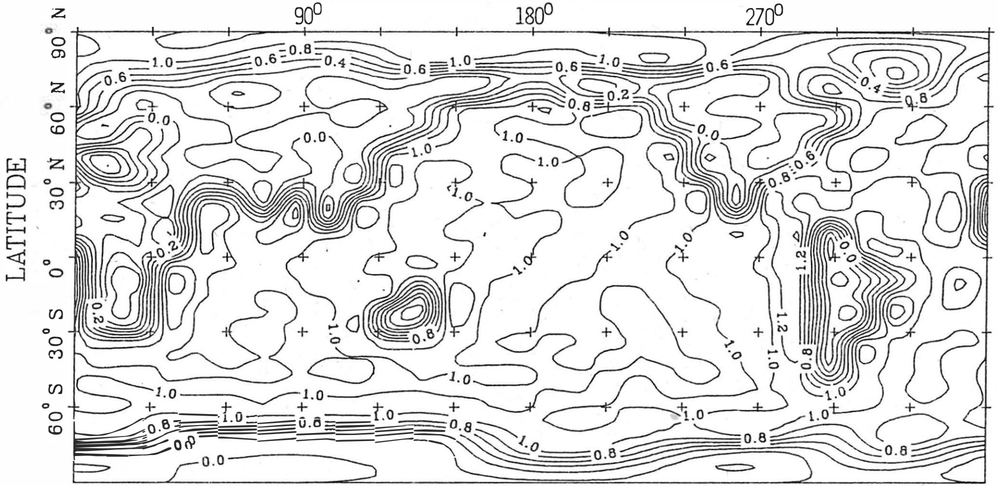

FIG. 1: SPHERICAL HARMONIC DEVELOPMENT OF THE OCEAN FUNCTION (SHOULD BE 1 FOR SEA, 0 FOR LAND) TRUNCATED AT DEGREE AND ORDER 24

PLOT : 16.15.14 THUR 11 AUG, 1988 JOB-0950BLOC, ISSCO DISSPLA 10.0

Zeichenprogrammsystem N E F K O (Version 01.86) programmiert durch W. Hausch, H. Jochemczyk u. H.-J. Euler

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PLOT 1 11.14.52 FRI 12 AUG. 1988 JOB-O950TIDE, ISSCO DISSPLA 10.0

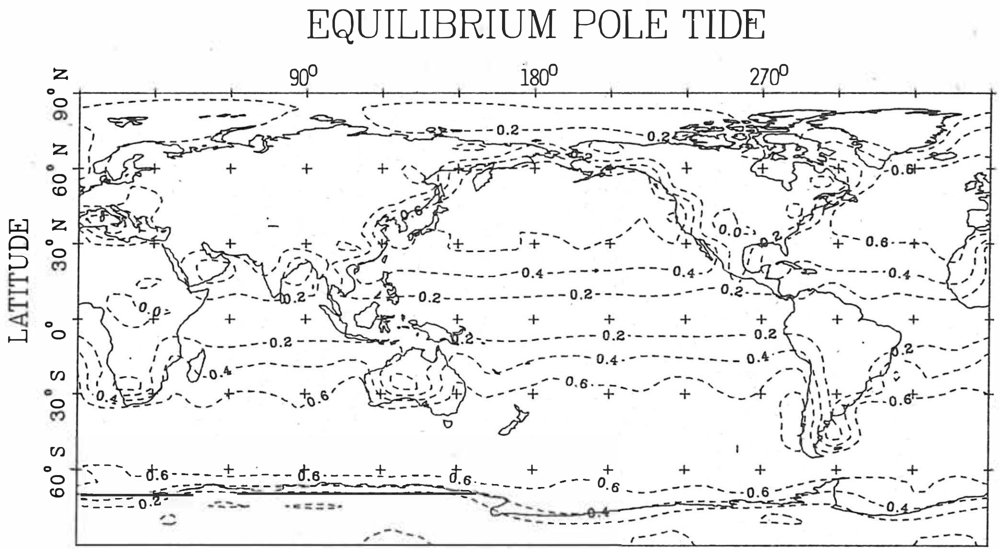

FIG. 2: AMPLITUDES OF THE EQUILIBRIUM POLE TIDE
BASED ON THE OCEAN FUNCTION GIVEN IN FIG. 2
UNIT IS CENTIMETER

ASSUMED CHANDLER AMPLITUDE 0".16

Zeichenprogrammsystem NEFKO (Version 01.86) programmiert durch W. Hausch, H. Jochemczyk u. H.-J. Euler

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Influence of Crustal Movements on the Terrestrial Reference System

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Summary

The aim of the investigations is to estimate the influence of tectonic plate motions on the realization of the global terrestrial reference system. For this reason the plate motion models AMO-2 and AM1-2 by minster and Jordan are used. The analyses are carried out for several networks (VLBI, LLR, SLR).
The annual change of the orientation of the terrestrial reference system due to the tectonic plate motions lies within 0.001" for networks with at least 5 stations.

Zusammenfassung

Die Untersuchung hat das Ziel, den Einfluß tektonischer Plattenbewegungen auf die Realisierung des globalen terrestrischen Referenzsystems zu bestimmen. Zur Modellierung der Plattenbewegungen werden die Modelle AMO-2 und AM1-2 von Minster und Jordan verwendet. Die Analysen werden für verschiedene Stationsnetze (VLBI, LLR, SLR) durchgeführt.
Die jährliche Änderung der Orientierung des terrestrischen Referenzsystems infolge der tektonischen Plattenbewegung liegt für Stationsnetze mit mindestens 5 Stationen innerhalb von 0.001".

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Starting with the Annual Report for 1986, the Bureau International de l'Heure (BIH) considered the influence of the tectonic plate motions for the realization of the BIH Terrestrial System. The BIH used the plate motion model AM0-2 by Minster and Jordan (1978). For the same purpose the analysis centre CSR at the University of Texas (USA) used another model AM1-2 also given by Minster and Jordan.

The following investigations have the aim to determine the temporal variations of the terrestrial reference systems by reason of tectonic plate motions. The analyses are carried out for two motion models and for several networks.

The following relationship was used for the calculations.

$$(1) \quad \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} = \begin{pmatrix} TX \\ TY \\ TZ \end{pmatrix} + \begin{pmatrix} D & -RZ & RY \\ RZ & D & -RX \\ -RY & RX & D \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} .$$

The quantities in this equation system have the following meaning:

X, Y, Z – Cartesian site coordinates,

ΔX, ΔY, ΔZ – changes of the coordinates due to the plate motions per year,

TX, TY, TZ – components of the translation vector of the terrestrial system due to the plate motions,

RX, RY, RZ – rotation angles of the terrestrial system due to the plate motions,

D – change of the scale factor of the terrestrial system.

The plate motion models are characterized by the components of the plate rotation vectors ωX, ωY, ωZ (in degrees per million years). These quantities are given in tables 1 and 2 for those tectonic plates on which stations are located.

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The changes of the site coordinates due to the plate motion are given by the following relations (2):

$$\Delta X = \frac{\omega Y \cdot Z - \omega Z \cdot Y}{C},$$

$$(2) \qquad \Delta Y = \frac{\omega Z \cdot X - \omega X \cdot Z}{C},$$

$$\Delta Z = \frac{\omega X \cdot Y - \omega Y \cdot X}{C}.$$

When we set X, Y, Z in metres and $\omega X, \omega Y, \omega Z$ in $^{o}/10^{6}$ years, we obtain with C = 572 987.81 the quantities ΔX, ΔY, ΔZ in centimetres.

By means of these quantities the unknowns TX, TY, TZ, D, RX, RY, RZ are determined by the method of least squares from the equation system (1) for different networks. The results are summarized in table 3. Furthermore, for each network the number of included stations is given together with the distribution of the stations over the different tectonic plates.

The first line for every network contains the results for the plate motion model AM0-2 and the second line for the model AM1-2.

The translation parameters TX, TY, TZ as well as the excess to 1 of the scale factor are of the same magnitude for the two used plate motion models. The translation parameters are generally in the order of 1...2 cm. They are noticeably greater (3...6 cm) for the network SSC(JPL)87 M 01 (only 3 stations).

The amounts of the rotation angles RX, RY, RZ are in general less than 0.001". The greatest values result again for the network SSC(JPL)87 M 01 (up to 0.002").

The differences between the rotation angles for the models AM0-2 and AM1-2 are independent of the network. They amount to

$$\Delta RX = 0.0002'',$$
$$\Delta RY = 0.0005'',$$
$$\Delta RZ = -0.0007''$$

(in the sense $\Delta R_i = R_i(AM1-2) - R_i(AM0-2)$; i = X, Y, Z).

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The following conclusion can be drawn from the obtained results. The annual change of the orientation of the terrestrial reference system due to the tectonic plate motions lies within 0.001" for networks with at least 5 stations. The differences between the results for two different plate motion models are of the same order.

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Table 1 Model AM0-2

Plate	ωX	ωY	ωZ
Eurasia	-0.03071	-0.15865	0.19605
North America	0.03299	-0.22828	-0.01427
South America	-0.05604	-0.10672	-0.08642
Pacific	-0.12276	0.31163	-0.65537
India/Australia	0.48372	0.25011	0.43132
Africa	0.05360	-0.19249	0.24016

Table 2 Model AM1-2

Plate	ωX	ωY	ωZ
Eurasia	0.03439	-0.01496	0.00046
North America	0.09842	-0.08456	-0.21017
South America	0.00948	0.03709	-0.28242
Pacific	-0.05745	0.45543	-0.85110
India/Australia	0.54942	0.39393	0.23582
Africa	0.12224	-0.04879	0.04470

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Table 3 Annual changes of the reference systems for several networks

Network	Stations: Total	EURA	NOAM	SOAM	PCFC	INDI	AFRC	TX [cm]	TY [cm]	TZ [cm]	D [10^-9]	RX [0.001"]	RY [0.001"]	RZ [0.001"]
SSC(NGS)87 R 01	12	4	7	-	-	-	1	-1.04	1.10	-0.41	1.44	0.19	-0.54	0.25
								-1.05	1.10	-0.42	1.45	0.42	-0.03	-0.45
SSC(GSFC)87 R 01	15	5	8	-	1	-	1	-0.88	2.58	0.87	0.92	0.67	-0.09	-0.27
								-0.89	2.58	0.87	0.92	0.90	0.42	-0.98
SSC(JPL)83 R 05	5	1	3	-	-	1	-	-2.76	1.12	1.73	-0.82	0.77	0.07	0.63
								-2.76	1.12	1.72	-0.81	1.01	0.59	-0.07
SSC(JPL)87 M 01	3	1	1	-	1	-	-	-2.53	5.72	2.89	0.57	1.83	0.95	-0.33
								-2.54	5.72	2.89	0.57	2.06	1.47	-1.04
SSC(CSR)86 L 01	42	11	20	4	4	2	1	-1.73	1.44	0.97	0.13	0.42	0.08	0.01
								-1.76	1.47	1.02	0.12	0.61	0.61	-0.73
SSC(DGFI)87 L 03	37	11	15	4	4	2	1	-1.76	1.49	1.00	-0.02	0.42	0.09	-0.01
								-1.79	1.52	1.06	-0.04	0.61	0.62	-0.75
SSC(ZIPE)85 L 01	24	9	7	3	3	1	1	-2.07	1.46	1.02	0.28	0.25	0.10	0.06
								-2.12	1.54	1.12	0.26	0.42	0.63	-0.71
SSC(DMA)77 D 01	38	13	17	2	3	2	1	-1.73	1.73	1.16	0.28	0.48	0.12	-0.02
								-1.73	1.74	1.16	0.28	0.71	0.64	-0.72

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Some Expriences on High Resolution ERP Determination by Means of LAGEOS Data

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Summary

The parameter estimation of the SLR method is characterized. The influence of the station distribution and the choice of the set of unknowns are discussed. Numerical results of several variants of solutions are used to estimate some relations between accuracy, resolution, distribution and number of observations. Some remarks on the new International Earth Rotation Service (IERS) are given.

Zusammenfassung

Die Parameterschätzung bei der Bestimmung von Erdrotationsparametern (ERP) auf der Grundlage von Laserentfernungsmessungen zu künstlichen Erdsatelliten (SLR) wird charakterisiert. Der Einfluß der Wahl der Unbekannten und der Stationsverteilung wird diskutiert. Hauptziel ist die numerische Untersuchung der Abhängigkeit zwischen der Anzahl und Verteilung der Meßstationen sowie der gemessenen Durchgänge einerseits und der Genauigkeit und zeitlichen Auflösung der berechneten ERP andererseits. Die Ergebnisse werden im Zusammenhang mit dem neuen Internationalen Erdrotationsdienst (IERS) analysiert.

1. Introduction

As an result of the International MERIT project a new International Earth Rotation Service (IERS) was realized by IAU and IUGG beginning with January 1, 1988 (Wilkins and Mueller, 1986). In this new IERS the astronomical observations were replaced by the cosmic-geodetic measurements Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and Very Long Baseline Interferometry (VLBI). In the Central Institute for Physics of the Earth (ZIPE) several activities in both SLR measurements and analysis are aimed to the IERS. The higher potential accuracy in time and space of all these modern methods opens new possibilities as for the realization of high precise geodetic reference systems as for the investigation of the interaction of different geodynamic processes.
The further increase of the resolution of the Earth Rotation Parameters (ERP) in time and space is a general actual task. But the optimization of the determination of ERP should be treated too. Therefore the dependency of the precision of the derived ERP

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from the amount and distribution of the measurements was investigated. This was done under the assumption of fixed station coordinates.

2. Parameter estimation in POTSDAM-5

In the orbital program system POTSDAM-5 (Gendt, 1984; Gendt, Montag, 1986) several sets of parameters including temporal variations can be improved, i.e. orbital elements, pole coordinates, station time, drag parameters, bias parameters and geodynamic parameters. In order to get a real assessment of the accuracy of the orbital model of the POTSDAM-5 programm system the number of chosen unknowns is minimized to a physical proved number. Therefore, only time independent unknowns are used in our investigations. This way it is avoided that a higher orbital accuracy is simulated by absorbing unmodeled orbital perturbations into time dependent terms of the parameter set.

There are two main variants for the parameter estimation. In the multi-pass-variant only one normal equation matrix for all selected unknowns is set up. Using this matrix all parameters included are determined directly. In this part of the programm the orbital elements together with all other parameters can be improved iteratively.
In most cases the single-pass-method is used additionally. Here a normal equation matrix is produced for every pass and every station containing all possible parameters. Using these matrices any combination of parameters can be determined off-line by the program SOLVE. This is an economical technology for obtaining many solution variants without repeating the time consuming computations of the orbital perturbations by numerical integration.
All constants are taken from MERIT Standard (Melbourne et al., 1983). Newer changes of some parameters do not influence the following numerical investigations.

3. Numerical investigations

On the basis of the SLR data of LAGEOS of the MERIT project the following subsets of data were mainly used for the parameter estimation (Table 1 and Fig. 1):

- station set A with 25 stations, 14 stations mainly relevant for the determination of x_p (λ in the zones $0°\pm45°$ and $180°\pm45°$) and 11 stations mainly relevant for y_p (λ inside $90°\pm45°$ and $270°\pm45°$),

- station set B with 13 stations, 6 mainly relevant for x_p and 7 mainly relevant for y_p,

- station set C with 7 stations, 3 mainly relevant for x_p and 4 for y_p

In any case at first the orbital elements were improved iteratively for orbital arcs of one month (initial deviations of the satellite position in the order of 30 m to 40 m). Including also the pole coordinates, the length of day (LOD) and one drag parameter the orbital fits for one-month arcs are for the station set C only slightly worse than for the others; they amount about ±10 to ±15 cm. After this procedure the maximum deviations of any

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Table 1: Used stations, arranged according to longitude zones

zones mainly relevant for x_p				zones mainly relevant for y_p			
0° ± 45°		180° ± 45°		90° ± 45°		270° ± 45°	
1				2			
$\underline{1181}$	Potsdam			7090	Yaragadee		
7805	Metsähovi			$\underline{7837}$	Shanghai		
7810	Zimmerwald						
7833	Kootwijk					Ft. Davis	$\underline{7086}$
7834	Wettzell					Greenbelt	$\underline{7105}$*
7835	Grasse					Quincy	$\underline{7109}$*
$\underline{7839}$*	Graz					Mon. Peak	$\underline{7110}$*
$\underline{7840}$*	Herstmonceux					Platteville	$\underline{7112}$*
$\underline{7939}$	Matera					Mazatlan	7122
7940	Dionysos					Santiago/Chil.	7400
8833	Kotwijk/MTLRS					Cerro Tololo	7401
						Arequipa	$\underline{7907}$
		Huahine	$\underline{7121}$				
		Maui	7210				
		Simosato	$\underline{7838}$*				

station set A: all 25 station of the table
station set B: underlined numbers
station set C: stations with star (*)

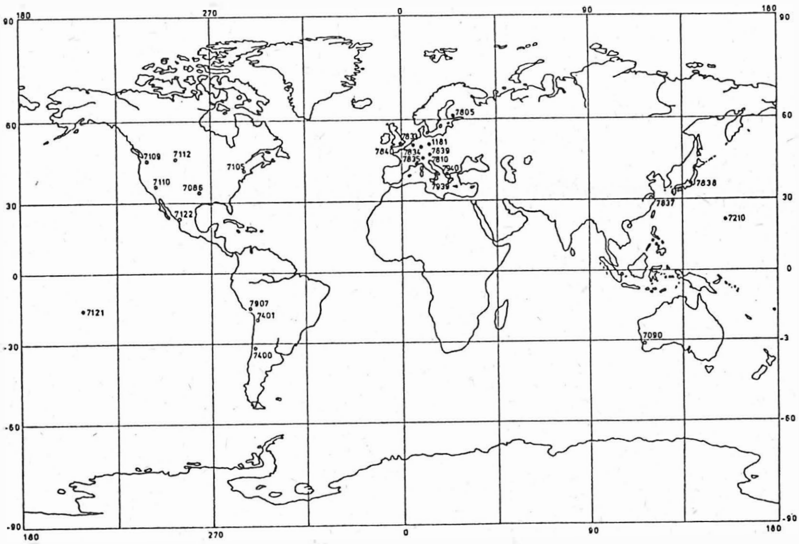

Fig. 1: Distribution of the used stations

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orbital element determined by station set A from those determined by the station set B or C are in the order of 10 cm (maximum most for station set C and for any of the angle elements). About 4 cm were obtained for the average deviations; the precision of the derived orbital elements is in the order of ± 2 cm. The correspondent maximum differences between the pole coordinates and LOD values determined by one of the three station sets for one month each amount about 5 cm and 0.02 ms, respectively (average deviations less than 2 cm and 0.01 ms, precision about ±0.8 cm and ± 0.002 ms, respectively).

By means of the single-pass method than the ERP (pole coordinates and LOD) were determined for several subintervals using the Helmert block method for the solution of the normal equations (time interval optionally different for different unknowns or groups of unknowns).
For the computations of ERP we used subintervals of 5 d, 3 d, 1.5 d, 1.0 d and 0.5 d. Several numerical investigations and experiences showed that it is quite optimal to redetermine in this part the orbital elements (6 Keplerian elements plus one drag coefficient) for arc lengths of 15 d and, using these improved orbits, to adjust the ERP inside each 15 d interval for the above mentioned subintervals. As a base for comparisons (standard) the ERP solutions by means of the station set A' (all stations observed, i.e., stations set A plus some others if there are any) for 5 d subintervals were taken. Apart from the role of this 5-d-solution as a standard in all other cases the 5-d- and 3-d-solutions were averaged because of their very small differences (Tab. 2 and 3). The influence of including the orbital elements together with the ERP as unknowns can be seen from Tab. 2. Here several deviations of the 5- and 3-d-solutions from the standard solution are shown. In col. 5 (5a for pole coordinates, 5b for LOD) the empirically obtained distribution density of the deviations is displayed for the case that the orbital elements (OE) are adjusted together with the ERP for the same time interval (5 d or 3 d). It can be seen that for the station set A (25 stations) using 7 or more relevant passes for the determination of each x_p (λ of stations 0° ± 45° and 180° ± 45°) and y_p (λ in the region of 90° ± 45° and 270° ± 45°) the probability for deviations of less than 2 mas (6 cm) for the pole coordinates is 0.99 and of less than 0.1 ms for LOD (4.6 cm at the equator) is 0.78. For the station set C these values are 0.90 and 0.73, respectively. In the line numbers 9 to 16 of Table 2 the results are given for all solutions with 4 or more relevant passes for x_p and y_p, respectively. All probabilities for the smallest deviation class are slightly worse.
In col.6 one can find the corresponding results for the case that in the SOLVE programm all orbital elements are hold fixed. Comparing col. 5 and 6 one can point out: The pole coordiates can be determined more accurate if the orbital elements are included in the parameter estimation procedure (real improvement of the orbit). But, the LOD results are worse. The reason for the latter can be seen in the correlation between LOD and $\dot{\Omega}$ (and $\dot{\lambda}$), especially because this effect is shown to be more destinct the shorther time intervals are used. Also this fact confirms that it seems to be optimal to improve the orbital elements for time intervals of 15 d (as above mentioned standard). From Table 2 it can be concluded further that in case of a high accurate orbital model the ERP can be determined quite well for 5 d or 3 d time resolution using about 7 or even 4 (not shown in Table) stations, only, provided that enough passes are observed.

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Table 2: Frequency distribution (in per cent) of the deviations of several 5- and 3-d-solutions for ERP from the standard solution

No.	Number: stations	Number: passes	class intervals: pole mas	class intervals: LOD ms	OE included: pole %	OE included: LOD %	OE not included: pole %	OE not included: LOD %
1	2	3	4a	4b	5a	5b	6a	6b
1	25 (A)	≥ 7 relevant for x_p, y_p, respectively	0-2	0.0-0.1	99	78	90	82
2			2-4	0.1-0.2	1	22	10	18
3			4-6	0.2-0.3	–	–	–	–
4			>6	>0.3	–	–	–	–
5	7 (C)		0-2	0.0-0.1	90	73	81	82
6			2-4	0.1-0.2	9	21	15	17
7			4-6	0.2-0.3	1	6	4	1
8			>6	>0.3	–	–	–	–
9	25 (A)	≥ 4 relevant for x_p, y_p, respectively	0-2	0.0-0.1	96	78	89	82
10			2-4	0.1-0.2	4	22	11	18
11			4-6	0.2-0.3	–	–	–	–
12			>6	>0.3	–	–	–	–
13	7 (C)		0-2	0.0-0.1	89	71	77	82
14			2-4	0.1-0.2	9	23	18	17
15			4-6	0.2-0.3	2	6	5	1
16			>6	>0.3	–	–	–	–

The comparison with the standard solution is also the basis for the investigation of the interaction between the accuracy and the time resolution of the ERP results on the one side and the number and distribution of the stations and the number of the observed relevant passes on the others. In Table 3 several results are shown for all three station sets. Again the frequency distributions of the deviations for the different class intervals (col. 4) are given in percent (col. 5 to 8). In col.5 we have the results for a resolution of 5 d or 3 d. Here the deviations are less than 2 mas and 0.1 ms, respectively, in practically 100% of all cases with 7 or more and almost even with 4 or more relevant passes for each pole component. The percentage is going only sligthly down with the decrease of the number of stations and relevant passes. In this connection it should be mentioned that the percentage is related to the number of solutions with the given minimum number of relevant passes. The time intervals with less than 7 or 4, respectively, relevant passes were not considered here. Therefore in the line numbers 5, 10, 15, 20, 25, and 30 of Table 3 the percentage of solutions with at least 7 or 4 relevant passes in relation to all possible solutions (time

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Table 3: Frequency distribution of the deviations of ERP solutions with different time resolution from the standard solution

No.	Number Sta-tions	Number Pas-ses	Class intervals pole mas	Class intervals LOD ms	Resolution 5^d or 3^d pole %	Resolution 5^d or 3^d LOD %	Resolution 1.5^d pole %	Resolution 1.5^d LOD %	Resolution 1.0^d pole %	Resolution 1.0^d LOD %	Resolution 0.5^d pole %	Resolution 0.5^d LOD %
1	2	3	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
1	25	≥ 7 relevant for x_p, y_p, respectively	0-2	0.0-0.1	99	100	97	95	98	80	95	85
2	(A)		2-4	0.1-0.2	1		3	5	2	12	5	10
3			4-6	0.2-0.3						8		4
4			>6	>0.3								1
5					97		80		60		25	
6	13		0-2	0.0-0.1	99	99	96	100	95	80	99	60
7	(B)		2-4	0.1-0.2	1	1	4		5	15	1	16
8			4-6	0.2-0.3						5		14
9			>6	>0.3								10
10					91		57		38		15	
11	7		0-2	0.0-0.1	97	98	94	88	94	60	85	75
12	(C)		2-4	0.1-0.2	3	2	6	7	6	35	15	20
13			4-6	0.2-0.3				5		5		5
14			>6	>0.3								
15					60		20		15		5	
16	25	≥ 4 relevant for x_p, y_p, respectively	0-2	0.0-0.1	98	100	95	95	96	78	85	76
17			2-4	0.1-0.2	2		5	5	4	11	12	12
18			4-6	0.2-0.3						7	3	7
19			>6	>0.3						4		5
20					100		98		85		58	
21	13		0-2	0.0-0.1	98	100	95	97	88	75	95	55
22			2-4	0.1-0.2	2		5	2	12	15	5	20
23			4-6	0.2-0.3				1		7		15
24			>6	>0.3						3		10
25					100		80		66		33	
26	7		0-2	0.0-0.1	94	98	89	70	88	50	80	55
27			2-4	0.1-0.2	6	2	9	17	10	35	10	25
28			4-6	0.2-0.3			2	9	2	12	7	12
29			>6	>0.3				4		3	3	8
30					88		58		42		14	

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intervals) is given. The percentage is going down from 100% in the case of 5 (or 3)-d-solutions with at least 4 relevant passes from station set A to 5% for results with a time resolution of 0.5 d and 7 relevant passes from station set C. This fact speaks for at least 15 laser stations, especially if it is aimed to a time resolution of about 2 days or less. Otherwise the gaps in the ERP series will be to large. Generally, there is another reason not to reduce the number of stations below about 15 to 20: the realization and maintenance of the terrestrial reference system. But this problem is not considered here in detail because one can assume fixed station coordinates for a longer time span (up to about 2 years or even more by including a plate motion model).

In col. 6 to 8 of Table 3 the results are given for a time resolution of 1.5 d, 1 d and 0.5 d. Of course, the percentage for the first deviation class is declining with the decrease of the number of stations and with the increase of the time resolution. But it is remarkable that using the station set A or B (and in some cases even C) one can get quite good results even for a resolution of 0.5 d, provided there are enough observations. Again it can be seen that the pole coordinates were determined more accurate than LOD, particularly for higher time resolutions. The reason for this matter seems to be the smaller accuracy for the determination of Ω in contrast to the well improved inclination i which is mainly relevant for the estimation of the pole coordinates (Montag, 1984).

4. Conclusions

The newly established IERS has brought an improvement of at least one order of magnitude for the accuracy of monitoring the earth rotation behaviour. Using these results besides the realization of a high precise reference system new possibilities are given for the investigation of the fine structure of geodynamic phenomena and the interaction of different internal and external forces.

The SLR technique is the basis for one of the most important methods. A further improvement of accuracy and time resolution can be expected in the next years by more accurate measurements and a more sophisticated analysis model.
An important aspect is the number and distribution of the laser stations. The comparisons betweeen the results of several analysis centers and different methods (Feissel, 1986; Mueller, 1985; Montag et al.,1986; Montag, 1988; IERS Bulletin A) using the data of the MERIT and Post-MERIT campaign have shown that about 30 laser stations are quite adequate to get high accurate and continuous results for ERP with a time resolution of 5 d or 3 d and better (up to 2 d and even 1 d if the measurements are fairly distributed). This was confirmed in Table 3.
For economical and other reasons it can be necessary to realize the earth rotation service with much less stations. Of course, for the determination of the pole coordinates a main condition is to have at least stations with a longitude difference of about 90°. Our investigations show that also with about 15 stations (not ideally distributed) very good results can be obtained for 5 d and 3 d resolution. Provided that there are enough observations and the reference system realized by the station coordinates can be hold fixed even with about 7 stations (Table 3) accurate ERP

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can be determined. The problem is that there are usually gaps in the observation series because of weather conditions and technical failures. This is most critical in the case of high resolution results, e.g., using 7 stations good results with time resolution of 1 d can be obtained only in about 25% to 30% of all cases. This percentage is, of course, essential better if the time resolution is not so high and the number of stations is bigger. If the gaps are not so large - let us say for 5- or 3-day solution using station set C and for 1- to 2-day solutions using station set B or A - they can be filled up by combination with other methods or by interpolation formulas. In the operational modus prediction formulas can be used. The estimated accuracies of the prediction formulas published by the IERS Bulletin A are after 10 days about ±5 mas for the pole coordinates and ±1.9 ms for LOD and after 30 days about ±9 mas and 5.6 ms, respectevely. That means that for the pole coordinates gaps up to about 2 weeks can be predicted with a small lost of accuracy, only. Because of the much less prediction accuracy for the LOD, in cases with only a small number of measurements it is recommended to use them for the determination of LOD and to fix the pole coordinates to the predicted values. So it can be concluded that even by means of about 7 fairly distributed stations in combination with interpolation or prediction formulas one can get rather good results for a longer time span. In any case even such a minimum number of laser stations brings much better results for the ERP than the former classical Earth Rotation Service.

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Variations of pole motion velocity and their correlation with variations of E.A.M. function in the period 1985 - 1987

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Abstract

The variations of the pole motion velocity in the years 1985-87 have been analysed. The velocity of pole motion was computed from x,y of CSR and of IRIS data as well as from the atmospheric equatorial effective angular momentum (E.A.M.) function χ data.

The correlation between the variations of pole motion velocity and the E.A.M. function has been investigated.

The excitation function of pole motion is computed from x,y data and is compared with the E.A.M. function as given by the ECMWF data

Short periodic oscillations in variation of χ and pole coordinates were determined and removed from the original data.

Short periodic variations of the E.A.M. function and of pole coordinates were found to be correlated.

Содержание

В работе представлены результаты анализа изменений скорости движения полюса Земли в периоде 1985-87. Скорость движения полюса была расчитана из данных x,y согласно CSR и IRIS а также по данным атмосферной возбуждающей (E.A.M.) функции χ.

Исследовано зависимость между изменениями скорости движения полюса и функции E.A.M.

Вычисьлялась функция возбуждения полюса из данных x,y и сравнивалась с оригинальной функцией χ по данным ECMWF.

Были определены короткопериодические колебания в изменениях χ и координат положения полюса, а затем усключены из оригинальных данных.

Найдены некоторые взаимные связи между короткопериодическими изменениями функции E.A.M. и положехия полюса.

1. Introduction

Variations of the Earth pole motion contain besides the long periodic oscillations, Chandler and seasonal ones. short periodic oscillations and irregular disturbances.

The analyses of the pole motion velocity presented in this paper concerns the period 1985-87, when the pole has started to move in the inward spiral. This is period especially interesting as during it the short periodic perturbations of the pole motion are most easily seen. In comparison to the previous analyses of the pole motion velocity, performed for the periods of 1977-84 (Kolaczek and Nastula 1985) and 1984-86 (Nastula 1987) we were here especially interested in the short periodic perturbations in pole motion velocity as the pole coordinates x,y data are now sufficiently accurate for such analyses.

In these analyses velocity of the pole is computed as the vector by which the pole moves on the Earth surface in the

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interval equal to 14 days (Kolaczek and Nastula 1985, Nastula 1987).

The velocity of the pole motion was computed from the two pole coordinate series : the VLBI-IRIS radiointerferometry one (solution 85-05-87) elaborated by the National Geodetic Survey - NGS (IRIS 1983-1987) and LAGEOS laser ranging (LALAR) one, (solution 84-1-02),elaborated by the Center for Space Research - CSR (Schutz B.E. 1983-87) as well as from the atmospheric effective angular momentum (E.A.M.) function χ elaborated by the European Centre for Weather Medium-Range Forecast (ECMWF).

In order to get equally spaced data all data series were smoothed with the Gauss filter with FWHM = 5 days and steps of two days.

To get a more complete comparison between pole motion variations and variations in atmospheric excitation the pole motion excitation function were computed from the x,y coordinate data.

In order to remove the short periodic variations from both the x,y series of the pole and the function χ, the short periodic model of oscillations was obtained by the methods analogous to those used in the works of Kolaczek and Kosek (1985, 1987).

2. The short time variations of the pole velocity

The variations of the pole motion velocity V, computed from x,y coordinates obtained by two different observational techniques IRIS and CSR filtered by the Butterworth filter with the cutoff period of 140 days are shown in Figure 1. A good agreement of diagrams of velocities computed from the data from both observational techniques indicates the real, physical character of short time variations of the pole motion. The correlation coefficient between the velocity V(IRIS) and the velocity V(CSR) is equal to about 0.71. The maximum amplitude values of the pole velocity vary from several to twenty thousand of arcs.

In the hodograph ofvelocity V (Fig.2) the short time perturbations of the pole velocity in the beginning and in the middle of 1985, in the second half of 1986 and in the period of 1987-88 can be seen against the background of long periodic oscillations. A good agreement between the perturbations of velocity computed from both IRIS and CSR data can be seen. The pole velocity presented in the hodographs seems to be especially perturbed during the periods of 1987-88 when the pole moves slowly on the trajectory with small radius. Anyhow the amplitude of these variations is comparable and even smaller than the amplitude of the variations in the remaining periods.

3. The atmospheric excitation of the pole motion variations

Variations of the pole position excited by the atmosphere $x(\chi)$,$y(\chi)$ were computed according to the known 'integration' approach of Barnes and others (Barnes at. al 1983), showing the dependence between variations of x,y and atmospheric excitation function χ. This comparison is given only to the end of 1986 year. For these analysis the influences of wind and pressure was

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considered in the function χ. Initial conditions for integration were adopted on the basis of pole coordinates series x,y determined by observations. The coordinates $x(\chi), y(\chi)$ obtained from the atmospheric excitation will be called the 'atmospheric' coordinates of the pole. The 'atmospheric' coordinates were smoothed by the Gaussian filter with the FWHM = 5 days. The correlation coefficient between the variations of 'atmospheric' coordinates of the pole and the observed coordinates , filtered by the high pas Butterworth filter with the cutoff period of equal to 140 days , was found to be equal to 0.5. It proves the existence of correlation between short periodic variations in the pole motion and the function χ.

The pole motion velocity excited by the atmospheric variations, so - called 'atmospheric', velocity of the pole, V(ATM) was computed from $x(\chi), y(\chi)$. In the hodographs of velocities (Fig. 3) as in the diagrams of the absolute value of the velocities (Fig.4) certain similarity between V(ATM), V(CSR) and V(IRIS) can be seen. The correlation coefficient between investigated velocity (filtered by the Butterworth filter with the cutoff period of 140 days) amounts to approximately 0.3. The observed close convergence between V(ATM), V(CSR) and V(IRIS) in the period of 46000-46200 MJD is seen. In these period the oscillations have highest amplitudes. The amplitude of the velocity variations computed from the atmospheric excitation is sufficient enough to explain the magnitude of amplitude of the pole motion velocity variations V(IRIS), V(CSR) in short period part of their spectra.

Additionally, excitation functions χ(IRIS), χ(CSR) were estimated from x,y coordinates data , according to Barnes 'differential' approach (Barnes at. all 1983). This method omits problems with initial conditions of integration but due to the differentiation it results in an increased noise level. These computed excitation functions contain contributions from all sources perturbing the observed pole motion , not only the atmospheric ones as in the case of the atmospheric function χ. The computed function of the excitation of pole from both observational techniques data χ(IRIS),χ(CSR). show a good similarity to each other and the correlation coefficient is equal to 0.6.

The comparison of computed components of the geodetic excitation functions χ(CSR) with the observed function χ(ECMWF) is presented in Figure 5. The correlation coefficient between the atmospheric and geodetic functions is equal to approximately to 0.3 and 0.25 for χ_1 and χ_2 respectively.

4. The short periodic oscillations of the x,y coordinates of the pole and of the excitation atmospheric function

An analysis of short periodic oscillations in the x,y series of IRIS and CSR, was carried out in order to explain the character of the short time pole velocity variations given in Figures 1, 2. These analyses were carried out according to the methods applied by Kolaczek and Kosek (Kolaczek and Kosek 1985, 1987). The purpose was to establish whether the variations have periodic or irregular character. The oscillations with periods

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larger than 140 days were removed from the considered series by using the high-pass Butterworth filter. Then the autocovariance estimations were computed for each series. The Maximum Entropy Spectral Analysis - (MESA) were carried out in order to detect short periodic oscillations of the autocovariance estimations of x,y IRIS and x,y CSR. The detected short periodic oscillations were then computed by the Ormsby narrow band pass filter from the x,y series of the pole coordinates (Ormsby 1961). The periodic oscillations have been selected in such a way as to minimize the variation of the autocovariance estimation of the pole coordinates series obtained after elimination of the short periodic oscillation model. The sum of the selected short periodic oscillations, computed by the Ormsby filter created the model of short periodic oscillations in x,y (the so-called deterministic part) (Table 1.).

Table 1. Periods of short periodic oscillations creating the models

Data series	Period in days																	
X IRIS	105		61	48	40	35			26	22	19		17	15				
X CSR	105		62	48		35			24	22		18		15		12		
Y IRIS	106		64	47	39			29		22	19	18	17		13			
Y CSR	106	70			38			29	25	22		18	17	15				
χ_1	93		56		42		31	28		22	20		17	15		11	8.7	7.7
χ_2	94		54			36	30			22	21		17	14	13.6	10	8.3	7.4

Subtracting the short periodic model from the observed x,y data reduces their standard deviation by three times and eliminates most of the short periodic oscillations of the autocovariance estimation. The diagrams of the absolute value of the pole motion velocity and the velocity hodographs are also smoother (Figs. 6, 7). After subtracting the short periodic model from the original x,y data amplitude of maximum variations of the pole motion velocity in the short period range is 0.004 arcs. The majority of perturbations existing in the velocity variations disappears or is being smoothed out. It means that the majority of perturbation existing in the velocity variations can be modelled as the sums of short periodic oscillations. The amplitude of the remaining variations is around 0.004 arcs and hence amplitudes of irregular variations should not exceed this range.

The analogous analyses of short periodic oscillations as for the pole coordinate series were carried out for the χ series of the atmospheric excitation function. The periods of short periodic oscillations selected for computation of the model are given in Table 1. Similarly as in the case of pole coordinates variations elimination of the short periodic oscillations from

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the original data χ diminishes the standard deviation nearly three times.

Variations of the pole coordinates x(χ-det),y(χ-det) were computed from the excitation function from which the short periodic deterministic model was removed. The velocity of the pole obtained from these 'atmospheric' pole coordinates data, V(ATM-det) is smoother than the velocity V(ATM) computed from x(χ),y(χ) data (Figs. 8, 9). The large perturbations of the pole motion velocity in the beginning of the 1985 year disappeared. It means that these perturbations were caused by the sum of the short periodic atmospheric influences.

The pole velocity variations computed from the atmospheric excitation function from which deterministic part was removed, V(ATM-det), are smoother than velocity variations obtained from x,y data without their short period deterministic model V(IRIS-det) and V(CSR-det) (Fig. 10). The amplitude variations of observed and atmospheric velocities of the pole motion have the same order. Moreover V(IRIS-det),V(CSR-det) and V(ATM-det) demonstrate a common perturbation in the period 46350-46800 MJD ,which proves the existence of common irregular perturbations in the function χ and the pole motion after the short periodic oscillations model is subtracted from the data.

The hodographs of V(IRIS-det), V(CSR-det) and V(ATM-det) are also similar (Fig. 11). The majority of perturbations in hodographs of V(IRIS-det), V(CSR-det) as well as in hodographs of V(ATM-det) disappear or are diminished after removing the short periodic deterministic model.

The comparison of excitation functions computed from geodetic data after elimination of the short period deterministic model χ(IRIS-det),χ(CSR-det) and atmospheric excitation function from which the deterministic part was removed χ(ECMWF-det) reveals a considerable smoothing of atmospheric excitation referring to the function computed from geodetic data. Supposedly it is connected with worse modeling of short periodic variations in the x,y series then in the χ_1 , χ_2 or with the influence of other than atmospheric perturbing factors. The comparison of χ(CSR-det) and χ(ECMWF-det) is shown in Figure 12.

5. Conclusions

The performed analysis of pole motion velocity demonstrated the existence of the real short time velocity variations with maximum amplitudes from several to 20 thousand of arcs. Hodographs of the pole motion velocity seem especially perturbed when the pole moves on trajectory with small radius. Anyhow the amplitude of these perturbations is comparable with the amplitude of the variations in the remaining period of time.

The similarity between the diagrams of the velocities V(ATM), V(IRIS), V(CSR) (Figs. 3,4) as well as correlation coefficient equal to 0.3 point out to correlation of the pole motion velocity and the atmospheric excitation in this range of spectra of their variations Similar conclusion was found from the comparison of the computed χ(IRIS), χ(CSR) and observed χ(ECMWF) function.

The majority of pole motion perturbations can be modelled as a sum of short periodic oscillations, obtained by the MESA method

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computed by the Ormsby filter in the x,y coordinates of the pole. The removal of the short periodic oscillations model from the x,y coordinates results in the pole motion velocity variations with the maximum amplitude of about 0.004 arcs. These value limits any possible short time irregular perturbations. Similarity of such perturbations V(ATM-det), V(IRIS-det) and V(CSR-det) (Figs.10, 11) indicates their atmospheric origin. Certainly, the influence of other phenomena perturbing the pole motion should be taken into consideration. The assumption of the influence of earthquakes on the polar motion becomes more realistic when we consider magnitudes of amplitudes of perturbations which are left, after subtracting the short periodic oscillations.

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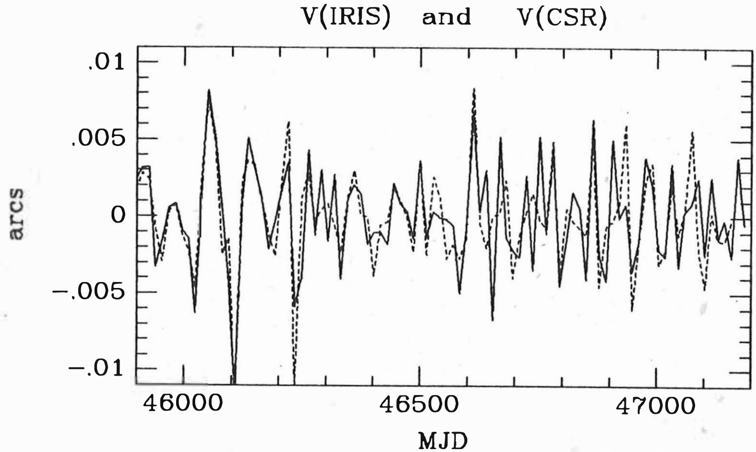

Fig. 1 The pole motion velocity, computed from x,y of IRIS(——) data and from x,y of CSR(- - -) data , after removing long periodic oscillations by the Butterworth filter with cutoff period of 140 days.

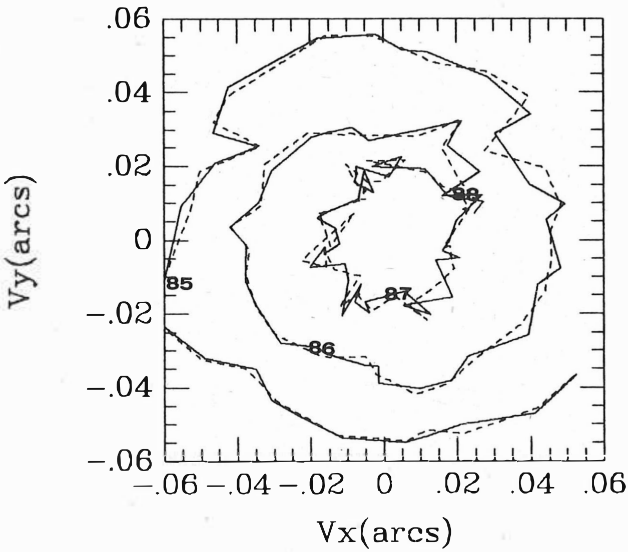

Fig. 2 Hodographs of the pole motion velocity computed from x,y of IRIS(——) data and from x,y of CSR(- - -) data .

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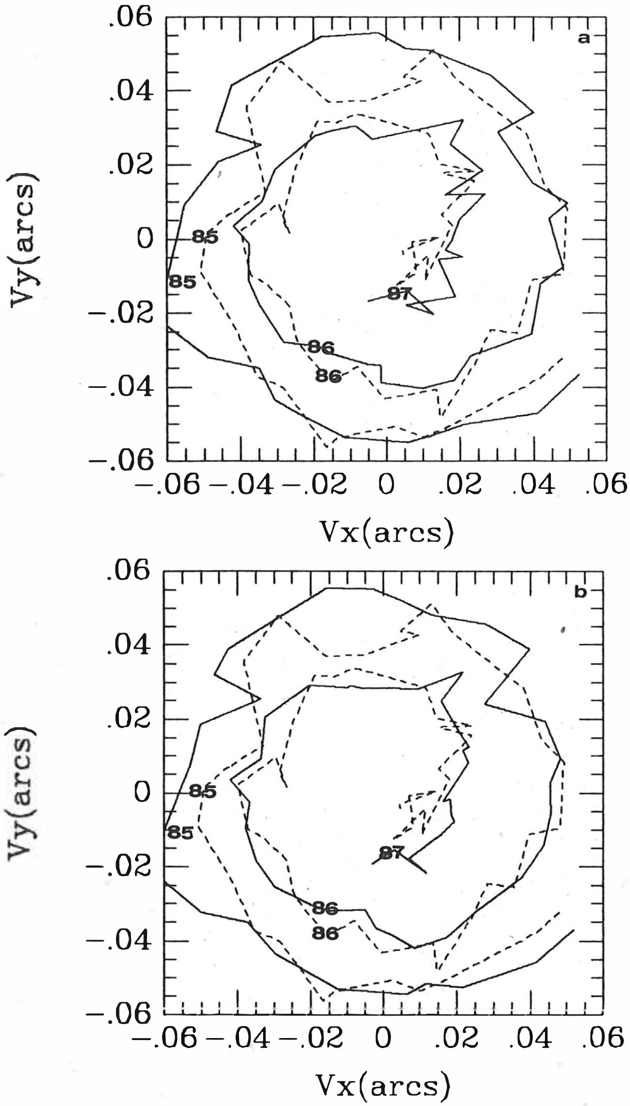

Fig.3 Comparison of hodographs of the pole motion velocity computed from x,y of IRIS(——) data (3a) and x,y of CSR(——) data (3b) with the velocity hodograph computed from the atmospheric function χ(---).

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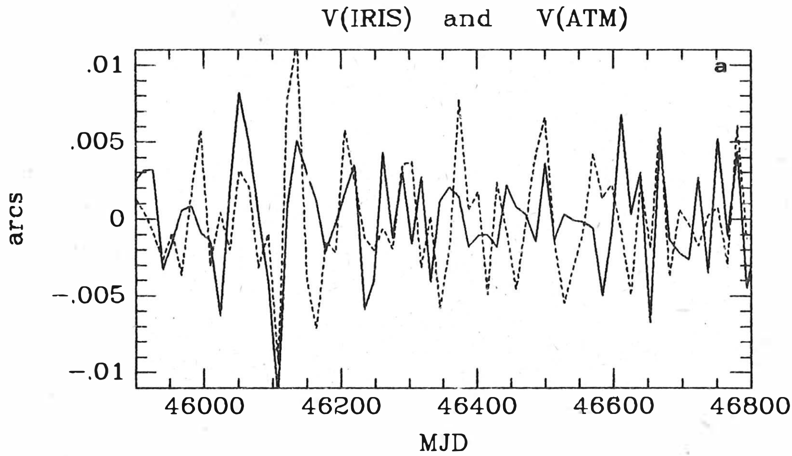

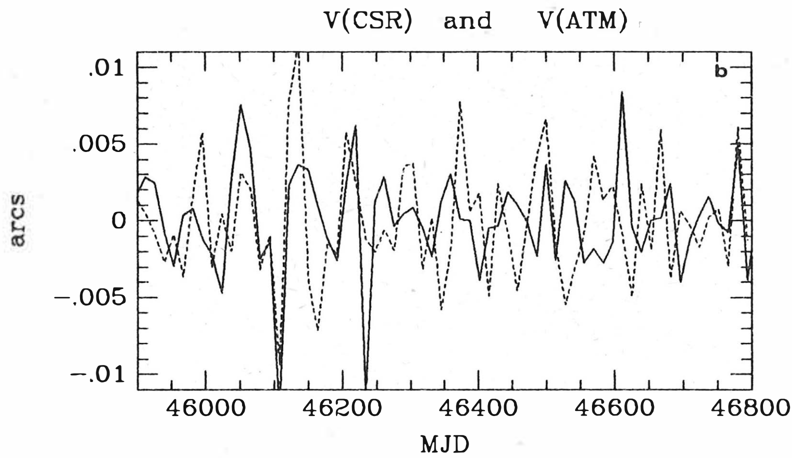

Fig. 4 Comparison of the pole motion velocity computed from x,y of IRIS(——) data (4a) and from x,y of CSR(——) data (4b) with the one computed using atmospheric excitation function χ(---). Long periodic oscillations (larger than 140 days) were removed.

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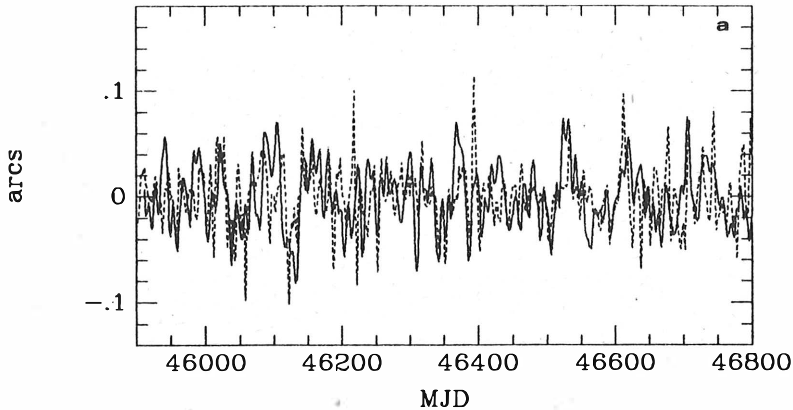

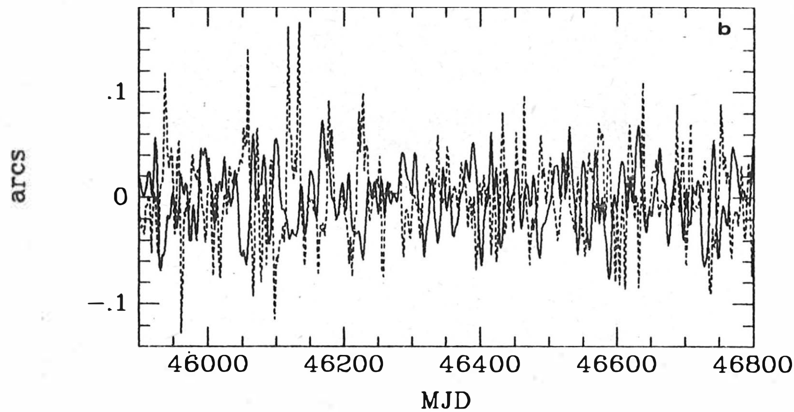

Fig.5 Comparison of the components of excitation function χ_1 (——) (5a) and χ_2 (——) (5b) computed from x,y of CSR data with the components of atmospheric function χ(ECMWF)(- - -). Long periodic oscillations (larger than 140 days) were removed.

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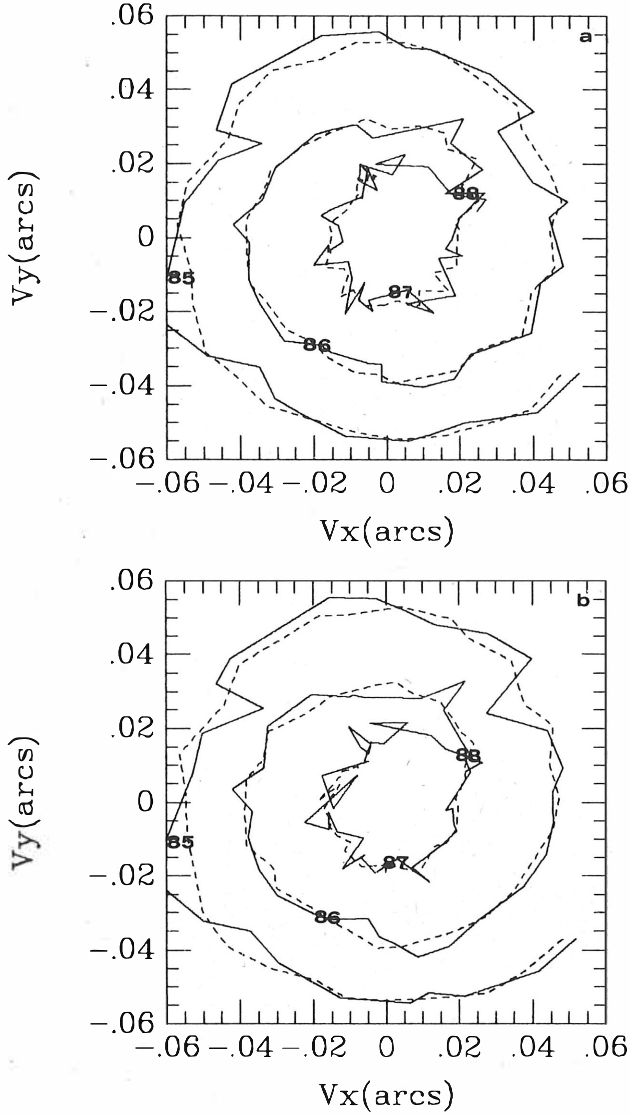

Fig.6 Comparison of hodograph of the pole motion velocity according to x,y of IRIS data (6a) and x,y of CSR data (6b) before (——) and after (- - -) removing the short periodic deterministic model.

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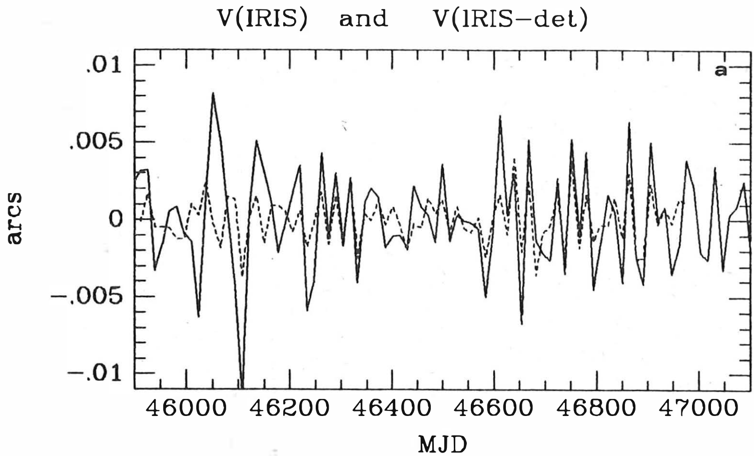

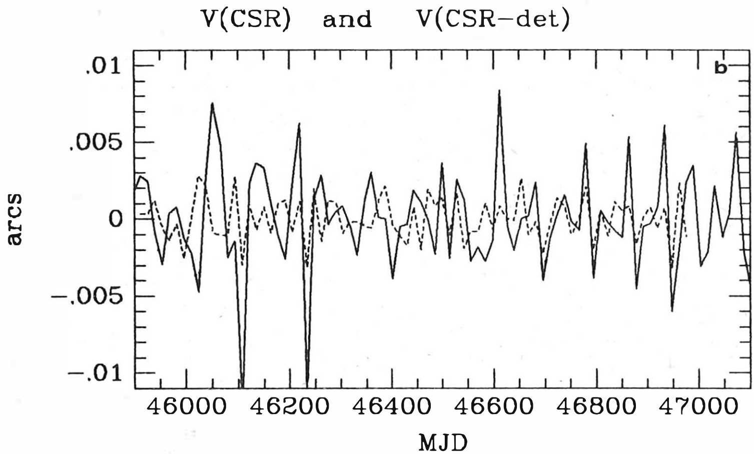

Fig.7 Comparison of the pole motion velocity computed from x,y of IRIS data (7a) and x,y of CSR data (7b) before (——) and after (- - -) removing the short periodic deterministic model. Long periodic oscillations were removed.

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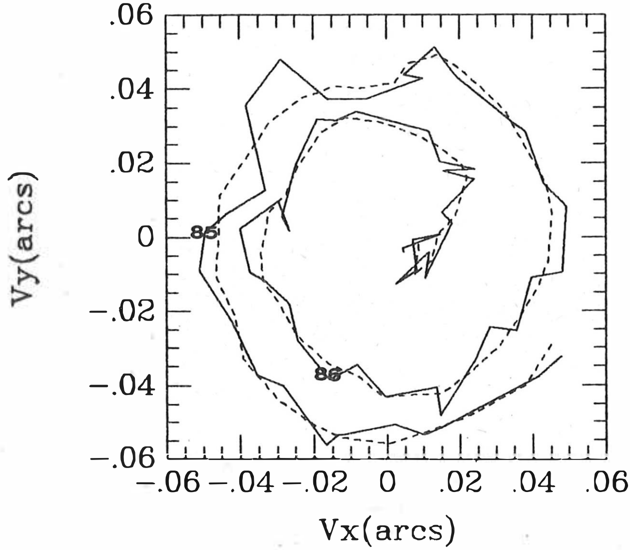

Fig.8 Comparison of hodographs of the pole motion velocity computed from the atmospheric excitation function before (——) and after (- - -) removing the short periodic deterministic model from function χ.

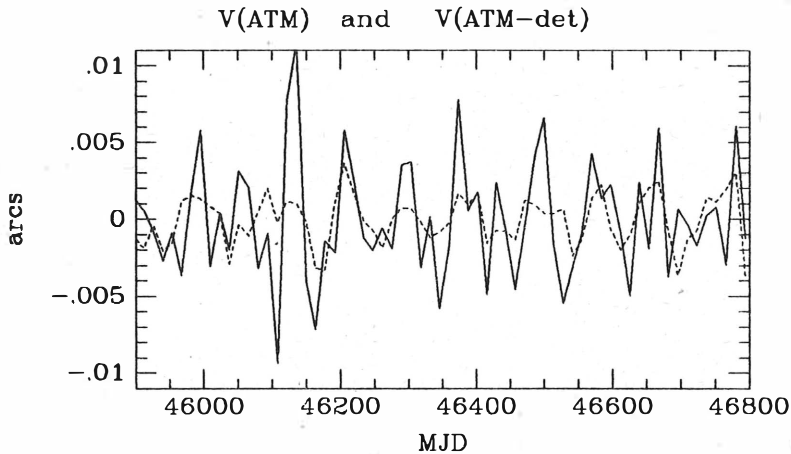

Fig.9 Comparison of the pole motion velocity computed from the atmospheric excitation function before (——) and after (- - -) removing the short periodic deterministic model from function χ. Long periodic oscillations were removed.

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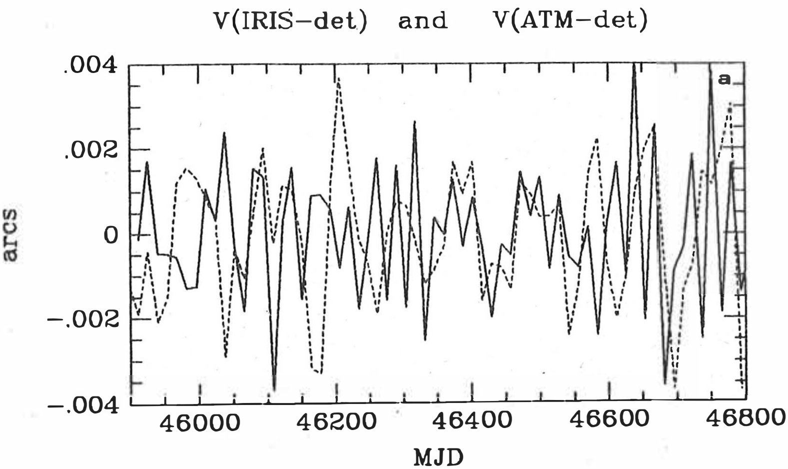

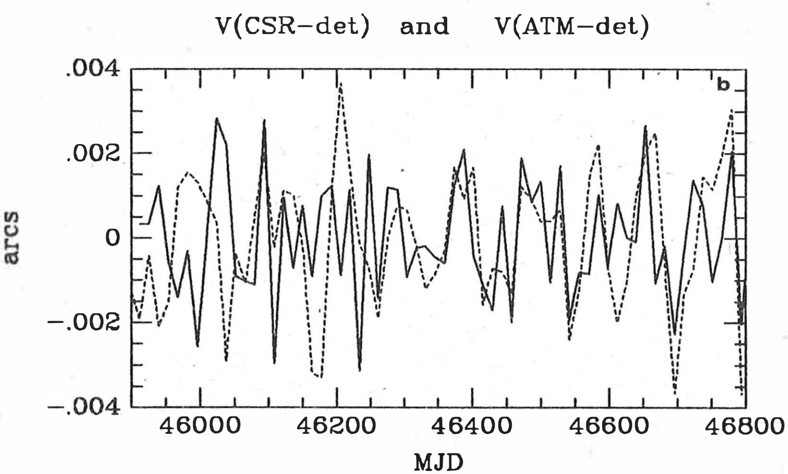

Fig. 10 Comparison of the pole motion velocity according to x,y of IRIS(——) data (10a) and x,y of CSR(——) data (10b) with the ones computed from atmospheric excitation(- - -), after removing the short periodic deterministic models from x,y and χ series. Long periodic oscillations were removed.

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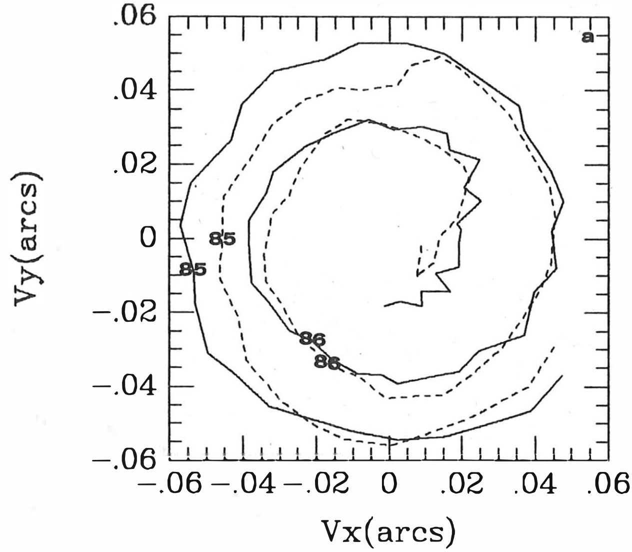

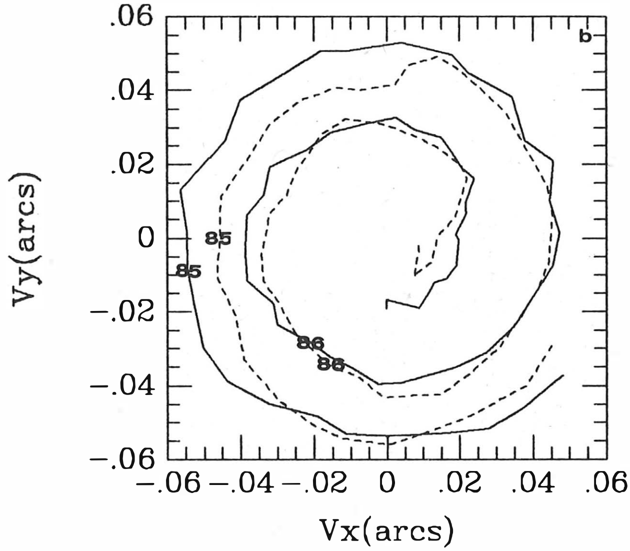

Fig.11 Comparison of hodographs of the pole motion velocity according to x,y of IRIS(——) data (11a), of CSR(——) data (11b) and function χ(- - -) data, after removing the short periodic deterministic models from x, y and χ seris.

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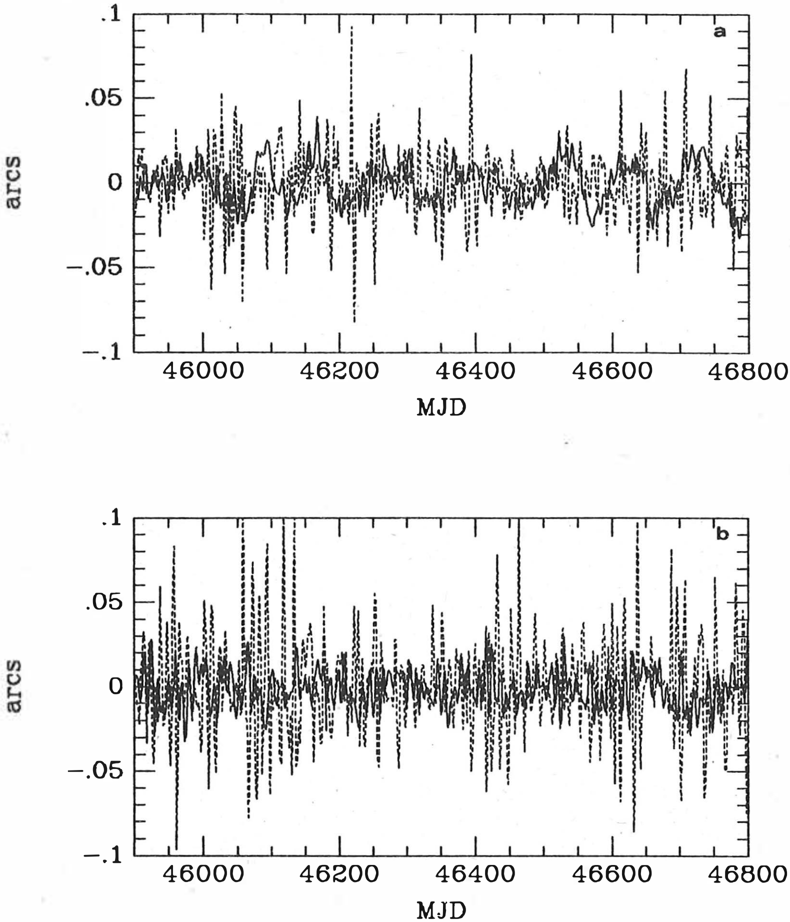

Fig.12 Comparison of components of excitation functions χ_1(——) (12a) and χ_2(——) (12b) with the ones computed from x,y of CSR(- - -) data after removing the short periodic deterministic models. Long periodic oscillations were removed.

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POLAR MOTION: OBSERVATIONS AND ATMOSPHERIC EXCITATION

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SUMMARY: Observed polar motion in 1976.5-1986.0 is compared with the pole excited by transfer of mass within the atmosphere. It is found that additional excitations are needed to explain the difference between the two data sets. The differences consist mainly in a constant phase shift of the annual term, small fluctuations of the phase of Chandler wobble and a slow secular increase of the total polar motion amplitude. A search for the excitations that could explain these effects is made. The most promising candidates are global groundwater storage changes and non-equilibrium response of the oceans.

key words: polar motion, atmospheric and groundwater excitation, variable Chandler frequency

1. INTRODUCTION

It has become a well-known fact that the atmosphere has a dominant effect on the changes of the Earth-rotation parameters (ERP), namely length-of-day changes and polar motion. The variations of the length-of-day have been shown by many authors to be caused, for the periods up to several years, mainly by the combined effects of the seasonal changes of zonal winds and tides of the solid Earth. Polar motion exhibits (except for the free Chandlerian nutation with period of about 435 days and a variable amplitude) a dominant annual motion which is known to be caused by the atmosphere. However, this component is shifted in phase with respect to atmospheric excitation by about 30 degrees, or one month (see e.g. [6], [7] or [9]). This phase difference can be almost fully explained by the additional excitation excerted by the groundwater storage changes ([7], [9] or [11]). The combination of both excitations (i.e. atmospheric and groundwater storage, represented by a simple annual term) has recently been used to integrate polar motion on the interval of 9 years ([11]) and found to agree quite well with the astronomically observed path of the pole. For the atmospheric excitation, only the pressure term with inverted barometer correction was used, from the daily values of equatorial components of the effective angular momentum functions (EAMF) of the atmosphere whose conception was introduced in [1]. Three variants of the solution have been studied:

i) atmospheric excitation only,

ii) excitation caused by the atmosphere plus groundwater storage after Van Hylckama [5],

iii) excitation caused by the atmosphere and groundwater storage after Kikuchi [7].

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The best agreement with the observed polar motion was achieved for the variant iii). Nevertheless, there still remained some unexplained systematic differences between the integrated and observed polar path, consisting in minor differences in phase and a secular increase in amplitude of the observed polar motion with respect to the amplitude of the integrated polar motion. Tri-axial Earth model with fluid core, visco-elastic mantle and equilibrium ocean was used to calculate the Earth's response to these excitations, as proposed in [8]. The model used gives a constant frequency of the free Chandlerian term. Since there is a strong evidence, based on a long-term study of polar motion, that the frequency of the free nutation is variable and amplitude-dependent (see e.g. [10]), we decided to test this hypothesis also on a short time scale and modern data for both polar motion and atmospheric excitation.

2. THEORETICAL BACKGROUND

For the sake of simplicity, let us confine to a rotationally symmetric Earth model. Then the first two Liouville equations in a linearized form will read (in complex notation)

(1) $$m + i\,\dot{m}\,A/\Omega(C-A) = \Psi \quad ,$$

where A, C are the principal moments of inertia of the Earth, Ω the mean rotational velocity of the Earth and Ψ the excitation function. The excitations depending on m should be, prior to solving the eq. (1) transferred from the rhs to lhs of the equation. These excitations are caused by

a) the fluid core: $\Delta\Psi_c = i\,\dot{m}\,A_c/\Omega(C-A)$,

where A_c is the moment of inertia of the core,

b) the visco-elastic mantle: $\Delta\Psi_m = k(m - i\,\dot{m}/\Omega)(1 - iQ^{-1})/k_s$,

where k and k_s denote the elastic and secular Love numbers and Q is the quality factor of the mantle,

c) the ocean: $\Delta\Psi_o = \xi\, m$,

where ξ is a factor, dependent on the amplitude of polar motion. For the equilibrium ocean, it is a constant equal to 0.064. Here we shall assume that the non-linear reaction of the ocean is responsible for the dependence of Chandler frequency on the amplitude.

Hence we obtain

(2) $$m[1 - \xi - k(1 - iQ^{-1})/k_s] + \\ + i\,\dot{m}\,[A_m/(C-A) + k(1 - iQ^{-1})/k_s]/\Omega = \Psi' \quad ,$$

where Ψ' denotes the remaining part of the excitation function. The homogenous solution to this equation for a constant ξ then

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reads

(3) $m = m_0 \exp[(\alpha + i\sigma)t]$,

where

$$\alpha \doteq -k\Omega Q^{-1}/k_s[A_m/(C-A) + k/k_s]$$

and

$$\sigma \doteq \Omega(1 - \xi - k/k_s)/[A_m/(C-A) + k/k_s].$$

If we further consider the numerical values $k/k_s = 0.3173$, $A_m/(C-A) = 269.66$ and $\Omega = 6.3004$ rad/day, we arrive at

(4) $\alpha \doteq -0.0074\ Q^{-1}\ \text{day}^{-1}$

$$\sigma \doteq 0.01593 - 0.0233\xi\ \text{rad/day} .$$

In order to approximate the dependence of σ on the total amplitude of polar motion M, empirically found in [10], it is sufficient to put

(5) $\xi = 0.064[1 - \exp(-20M)]$,

where M is expressed in arcseconds; this value leads to the expression for the Chandler frequency

(6) $\sigma = 0.01444 + 0.00149 \exp(-20M)$,

which is an excellent approximation of the empirically obtained graph drawn in Fig. 3 in [10]. The solution (3) holds only in case when the amplitude M is constant. The existence of any excitation Ψ' on the rhs of eq. (2) necessarily causes changes of its value and, consequently, also the variations of σ. Therefore the argument σt has to be replaced by the expression

(7) $\varphi = \int_0^t \sigma\, d\tau = \sigma_0 t + 0.00149\int_0^t \exp(-20M)\, d\tau$,

in which the integral is to be estimated numerically from the known values of M. If we further use the EAMF of the atmosphere χ instead of the excitation function Ψ' and integrate the equation (2), we arrive at the solution

(8) $m = \exp(\alpha t + i\varphi)[m_0 - i\sigma_0(1 + \sigma_0/\Omega)\int_0^t \chi \exp(-\alpha\tau - i\varphi)d\tau] -$

$$-(\sigma_0/\Omega)[\chi - \chi_0 \exp(\alpha t + i\varphi)] ,$$

in which m_0 is the complex constant of integration, defining the initial pole position. It should be noted that m and m_0 are given in a coordinate system whose origin is defined by the mean position of the principal axis of Earth's inertia and its axes are directed along the meridians 0° and 90°E. The mean position of the pole is identical with the mean excitation pole, given by the mean value of χ. On the other hand, the observed pole position is given in a system whose origin is chosen conventionally and whose y-axis is directed to 90° W. Therefore the x and y coordinates to be directly comparable with the observed values should be calculated from the integrated values

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$m = m_1 + im_2$ using the formulas

(9) $x = m_1 + \Delta x, \quad y = -m_2 + \Delta y$,

where the values Δx, Δy express the shift between the two origins.

3. THE RESULTS

The daily values of equatorial components of EAMF of the atmosphere χ_1, χ_2 as calculated by the NMC were used to estimate numerically the integral in eq. (8) needed to calculate the excited pole position. The amplitudes M, necessary to calculate the instantaneous Chandler frequency σ from the formula (6) and its integral from eq. (7) were calculated simultaneously as the distance between the integrated pole position and a chosen mean position of the pole, i.e. from the formula

(10) $M^2 = (x - x_{01})^2 + (y - y_{01})^2$.

The values x_{01}, y_{01} were chosen so that the fit to the observed polar motion would yield the best agreement in a least-squares sense. The constant shifts Δx, Δy were estimated à priori from the mean values of the pole coordinates and EAMF and put equal to $\Delta x = 0.02''$ and $\Delta y = 0.58''$. The initial position of the pole

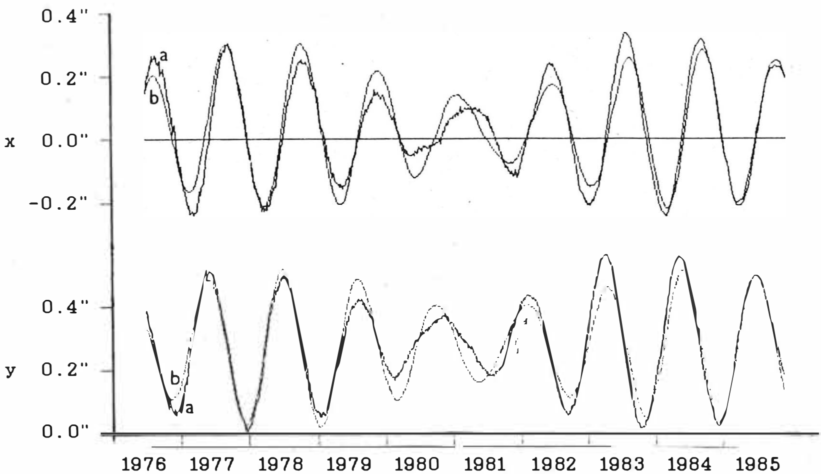

Fig. 1 Observed (a) and excited (b) polar motion. The atmospheric pressure term with inverted barometer correction and amplitude-dependent Chandler frequency have been used to integrate the excited polar path.

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at the beginning of the interval studied, i.e. 1976.5, was adjusted by the method of least squares to fit the integrated polar path to the observations. Both EAMF as calculated at the NMC and observed pole positions as determined from the BIH combined solution [2] were used in the interval 1976.5 - 1986.0. Integrated polar motion was calculated in three versions, identical with the study [11]. The resulting curves and their agreement with the observations are shown in Figs 1 - 3. Fig. 1 represents the integration using only the pressure term with inverted barometer correction, while the other two are obtained when combination with annual excitation by groundwater storage changes after Van Hylckama [5] and Kikuchi [7] was used.

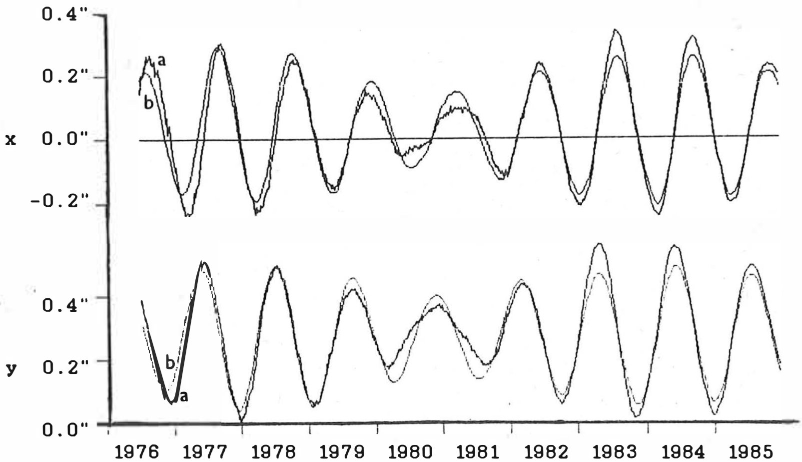

Fig. 2 The same as Fig. 1, but the groundwater storage excitation after Van Hylckama has been added to atmospheric excitation.

In order to estimate the obtained fits numerically, the root-mean-square deviations were calculated from the formula

(11) $\delta = \pm\sqrt{\Sigma(v_x^2 + v_y^2)/2n}$,

where $v_x = x_{BIH} - x$, $v_y = y_{BIH} - y$ and n is the number of data compared. They are given in Tab. 1, together with the other estimated parameters - initial position of the pole x_0 , y_0 and the mean position of the pole x_{01} , y_{01} For comparison, the values obtained with the same data by identical method but assuming the Chandler frequency constant, are also displayed.

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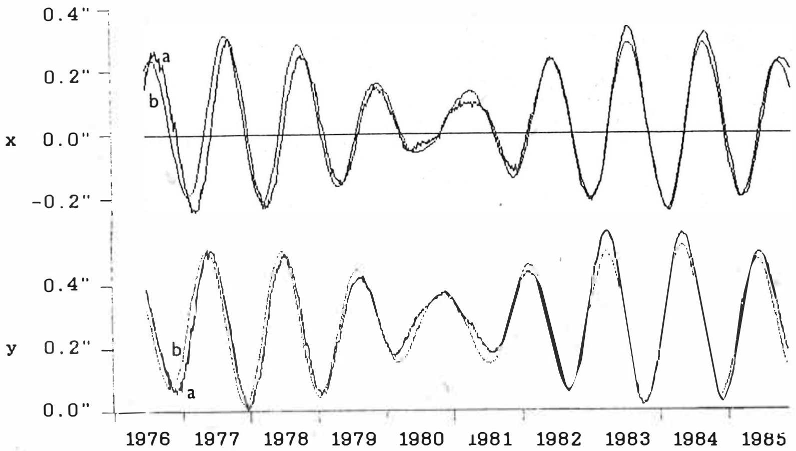

Fig. 3 The same as Fig. 1, but the groundwater storage excitation after Kikuchi has been added to the atmospheric excitation.

Table 1

	σ variable					σ constant		
	δ	x_o	y_o	x_{o1}	y_{o1}	δ	x_o	y_o
χ^P	±0"048	0"112	0"250	0"055	0"285	±0"057	0"108	0"292
$\chi^P + \Delta\chi_{VH}$	40	145	265	28	270	52	142	300
$\chi^P + \Delta\chi_K$	36	170	255	18	290	46	162	283

4.CONCLUSIONS

From Figs. 1 - 3 it can be seen that there is a very good agreement of the integrated polar motion with the observations; the use of additional excitation from the groundwater storage changes, though modelled only by a simple annual term, improves the fit significantly. This is true especially if the groundwater excitation after Kikuchi is used. The substantial improvement in all three variants is obtained when the Earth model with variable Chandler frequency is used, which is demonstrated by the values of δ displayed in Tab. 1 (compare the values in the left and right half of the table). This very fact supports the hypothesis that Chandler frequency is not constant, even on such a short time interval as studied in the present

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work. Its dependence on amplitude, found from the long-term changes of polar motion in [10], seems to be valid also in a short-periodic sense. On the other hand, there still exists a secular increase of the amplitude that cannot be explained by any of the excitations in question. It is obvious that there should exist an excitation, yet unknown, with frequency nearly equal to the Chandler frequency. Such an excitation could be present in groundwater storage changes (see e.g. [12]); more detailed knowledge of these changes is necessary for further study in this field.

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Klaus-Harro Tiemann

Zur Entstehungsgeschichte des Internationalen Breitendienstes (1888 - 1899)

Unter dem unscheinbaren Titel "Neue Methode zur Bestimmung der Aberrations-Constante nebst Untersuchungen über die Veränderlichkeit der Polhöhe" berichtete vor 100 Jahren, im Juni 1888, der 31jährige Observator Friedrich Küstner (1856 - 1936) im Heft 3 der Beobachtungsergebnisse der Königlichen Sternwarte zu Berlin mit dreijähriger Verspätung über eine zum Zwecke der praktischen Anwendbarkeit der Horrebow-Talcottschen Meßmethode für die Bestimmung der Aberrationskonstante im Zeitraum 2. April 1884 bis 28. Mai 1885 durchgeführte Beobachtungsreihe, deren Auswertung ihn zu der unbeabsichtigten Schlußfolgerung führte, daß es nicht mehr

> "gestattet sei, die Polhöhe von vornherein als constant anzunehmen, daß im Gegentheil alle Anzeichen dafür sprechen, daß sie in kürzeren Zeitintervallen unregelmäßige Schwankungen bis zu einigen Zehntelsekunden erfahren kann". [1, S. 59]

Die Ursache für dieses Naturphänomen sah er

> "in den gewaltigen, der Energie der Sonne entstammenden Vorgängen in der Atmosphäre und Hydrosphäre der Erde, mit ihrem gesammten Einfluß auf die luftförmigen, flüssigen und festen Theile der Peripherie des Erdballs, durch welchen unablässig Winkelausschläge zwischen der Hauptträgheitsachse und der momentanen Rotationsachse nothwendig hervorgerufen werden müssen". [1, S. 52]

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Küstners Zufallsentdeckung, nach der Entdeckung des Planeten Neptun im Jahre 1846 durch Johann Gottfried Galle (1812 - 1910) die zweite herausragende Forschungsleistung, welche im 19. Jahrhundert an der Berliner Sternwarte vollbracht wurde, fand nicht sofortige Anerkennung in der Fachwelt.

> "Der Glaube an die Unveränderlichkeit der geographischen Breiten innerhalb der Grenze der Wahrnehmbarkeit wurzelte" - wie Friedrich Robert Helmert (1843 - 1917), Direktor des Königlichen Geodätischen Institutes zu Berlin und Direktor des Zentralbüros der Internationalen Erdmessung, im Frühjahr 1890 rückblickend schrieb - "zu fest. Ich selbst, der ich doch in dem Beobachtungsplan für das neu zu erbauende Institut (in Potsdam - K.-H. T.) bereits 1886 fortlaufende Untersuchungen der Breite, aufgenommen habe, mußte in meinem oben erwähnten Werke (Höhere Geodäsie, Teil II, Kap. 5 - K.-H. T.) 1884 auf Grund sorgfältiger Berechnungen feststellen, daß diejenigen Ursachen, aus welchen am naheliegendsten Veränderungen zu erwarten sind, nämlich die durch meteorologische Prozesse erzeugten Massenbewegungen auf der Erdoberfläche und die damit verbundenen Verschiebungen der Drehaxe der Erde, Änderungen der Breite von mehr als einigen Hundertstelsekunden kaum erklären lassen".
> [2, Bl. 343/344]

Weitere Beobachtungen, über die noch zu berichten sein wird, veranlaßten Helmert jedoch, sein ursprüngliches Urteil zu revidieren. So bewertete er in seinem zitierten Brief das gründliche Studium der Lage der Erdrotationsachse als eine Sache, die von

> "fundamentaler Bedeutung für die Physik der Erde (ist), da wir ggw. nur ziemlich vage Vermutungen über die Ursachen der Erscheinung haben. Selbstredend" - fuhr er fort - "ist die Angelegenheit auch epochemachend für die Methoden der Erdmessung". [2, Bl. 345]

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Es vergingen hingegen noch 9 Jahre, bis Ende 1899 mit dem Internationalen Breitendienst ein wissenschaftlich und ökonomisch zweckmäßiger Beobachtungsdienst aufgenommen wurde. Entscheidenden Anteil daran hatten Helmert und der geodätisch interessierte Astronom Wilhelm Julius Foerster (1832 - 1921), einer der bedeutendsten Wissenschaftsorganisatoren des vorigen Jahrhunderts. [Vgl. 3, S. 12 - 67 bzw. 4, S. 21 - 29]

Foerster, seit 1865 Direktor der Berliner Sternwarte und seit 1886 Mitglied der 11köpfigen Permanenten Kommission der Internationalen Erdmessung, war derjenige, der gewissermaßen den Stein ins Rollen brachte. Ohne große Zeit verstreichen zu lassen, nutzte er taktisch klug die günstige Gelegenheit der im September 1888 in Salzburg stattfindenden Jahrestagung der Permanenten Kommission, um das Expertengremium zu bewegen, dem notwendigerweise unverbindlichen Wunsche Küstners,

> "durch geeignete und zweckmäßig organisirte Beobachtungen, welche an verschiedenen Orten gleichzeitig anzustellen sein würden, die Frage der Polhöhen-Schwankung noch näher zu untersuchen" [1, S. 59],

möglichst unverzüglich Folge zu leisten und diese neuartige Problematik als eine Forschungsaufgabe der internationalen Geodätenvereinigung zu bestimmen. Fünf Momente waren es, die Foersters Initiative auslösten:

Zum einen begriff er als einer der wenigen Wissenschaftler sofort die große wissenschaftliche Relevanz der Polhöhenvariationen.

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Zurückzuführen war das zweitens zu einem nicht geringen Teil darauf, daß präzise Ortsbestimmungen zum bevorzugten Interessenfeld Foersters gehörten. Von Zeitgenossen wird übereinstimmend bezeugt, daß ihm "die höchste Verfeinerung der Beobachtungs- und Meßkunst" [5, S. 42] und im Zusammenhang damit "die gründliche Kritik und Ausarbeitung der Methoden zur Erzielung möglichst vollkommener Beobachtungsergebnisse auf dem Gebiet der Astrometrie" [6, S. 6] als "wichtigste" [5, S. 52] Aufgaben der Sternwarte galten. Bereits auf der Generalversammlung der Astronomischen Gesellschaft 1877 in Stockholm war ihm nach eigenen Worten "der Gedanke für den Nachweis periodischer Lagenänderungen der Drehungsachse im Erdkörper 'helle' geworden". [7, S. 167] Kurz danach ließ er nach seinen Plänen [Vgl. 8 und 9] den Universaltransit bauen, das neuartige Instrument, mit dem Küstner seine spektakulären Messungen vornahm. Da jener einer der "letzten großen Meister der astrometrischen Beobachtungskünstler" [10, S. 47] war, kann man durchaus davon sprechen, daß in materieller und personeller Hinsicht die Berliner Sternwarte für den Nachweis der Polhöhenschwankungen prädestiniert gewesen ist und insofern Küstners Leistung nur bedingt den Charakter einer Zufallsentdeckung trägt.

Anlaß, sich aktiv zu engagieren, hatte Foerster drittens auch deshalb, weil es sich um die Entdeckung eines seiner Mitarbeiter handelte und weil viertens mit der allgemeinen Anerkennung dieser Forschungsleistung zugleich das internationale Renommee der Berliner Sternwarte stieg.

Daß er sich fünftens an die Geodätenvereinigung und nicht an die ebenfalls in Frage kommende Astronomische Gesellschaft wandte, denn das Phänomen der Polhöhenschwankungen ist bekannt-

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lich sowohl von astronomischem als auch von geodätischem Interesse, ist keinesfalls dem Umstand geschuldet, daß die Permanente Kommission eher tagte als die Astronomische Gesellschaft, sondern Resultat seines weitsichtigen Denkens. Um das ins Auge gefaßte Ziel, einen speziellen internationalen Beobachtungsdienst einzurichten, Realität werden zu lassen, hatte Foerster richtig erkannt, daß dazu die Internationale Erdmessung als zwischenstaatliche Organisation, die überdies ein größeres Finanzbudget besaß, besser geeignet war als die sich aus den Beiträgen ihrer Mitglieder finanzierende nichtstaatliche Astronomische Gesellschaft. [Vgl. 11, S. 70]
Die Geodätenvereinigung zu wählen, bot sich ferner auch deshalb an, weil sie sich bereits 1883 auf ihrer 7. Generalkonferenz mit dem Antrag des italienischen Astronomen Emmanuele Fergola (1830 - 1915)

> "auf Untersuchung der Veränderlichkeit der Erdaxe in Bezug auf die feste Oberfläche des Sphäroids durch die säcularen Änderungen der Polhöhe einiger auf beiden Hemisphären passend vertheilten Sternwarten" [12, S. 46]

beschäftigen mußte und einige zustimmende Beschlüsse gefaßt hatte. [Vgl. 12, S. 101 ff.]

Wie die Beratungsprotokolle der Permanenten Kommission beweisen, nutzte Foerster letzteren Aspekt geschickt als Einstieg, um am zweiten Beratungstag, dem 19. September 1888, den klug formulierten Antrag zu stellen,

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"diesmal eine Commission zu ernennen, welche sich auf's Neue mit dem Stande dieser Frage beschäftigt und der Permanenten Commission nöthigenfalls zur Förderung des Studiums derselben weitergehende Vorschläge macht." [13, S. 30]

Da "von keiner Seite Widerspruch erhoben" [13, S. 30] wurde, wählte man eine 5köpfige Spezialkommission, der neben Foerster und Helmert der Holländer Hendricus van de Sande-Bakhuyzen (1838 - 1923), stellvertretender Vorsitzender der Astronomischen Gesellschaft, der Franzose François Tisserand (1845 - 1896), Mitglied der Pariser Akademie der Wissenschaften, sowie der Österreicher Edmund Weiss (1837 - 1917), Vorstandsmitglied der Astronomischen Gesellschaft, angehörten. Noch am selben Tag, auf der Nachmittagssitzung der Permanenten Kommission, legten die 5 Experten ihren Bericht vor. Nachdem sie einleitend konstatierten,

"daß keinerlei Mittheilungen erheblicher Art, geschweige denn irgend welche Ergebnisse über die 1883 empfohlenen korrespondirenden Polhöhen-Beobachtungen vorliegen" [13, S. 33],

unterbreiteten sie folgende drei Beschlußempfehlungen:

"1. Die Permanente Commission erklärt es für eine wichtige und dringliche Aufgabe der internationalen Erdmessung, nunmehr auch mit eigenen Mitteln und Kräften zur Aufklärung der Frage der Veränderlichkeit der Lage der Erdaxe im Erdkörper beizutragen.

2. Um die hierzu erforderliche Organisation von korrespondirenden Polhöhen-Bestimmungen an mindestens 4, über den ganzen Umkreis der Erde vertheilten Stationen vorzubereiten, insbesondere um die noch erforderlichen Vorarbeiten zum Zwecke der Feststellung der geeignetsten Methoden der Beobachtungen und der Her-

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stellung der entsprechenden völlig gleichartigen Instrumente auszuführen, wird für das Centralbureau, dessen Direktor die Mitwirkung einiger astronomischer und geodätischer Beobachtungsinstitutionen bei diesen Vorarbeiten für gesichert erklärt hat, ein Geldbetrag bis zu 4000 Mark, welcher nach dem Berichte des Centralbureaus jedenfalls disponibel ist, dem Bureau der Permanenten Commission zur Verfügung gestellt.

3. Über die volle oder teilweise Verwendung dieses Betrages und über die Ergebnisse der Vorarbeiten ist in der nächsten Session der Permanenten Commission Bericht zu erstatten". [13, S. 30]

Wie im Beratungsprotokoll weiter zu lesen ist, erfolgte eine "einstimmige Annahme" [13, S. 31] der Beschlußempfehlungen. Dieser scheinbar glatte Beratungsablauf, den das Protokoll vermuten läßt, entspricht jedoch nicht dem realen Sachverhalt. Helmerts o.g. analoge Aussage bestätigend, berichtete Foerster 1890 über die damals herrschende Meinungslage zu Küstners Entdeckung:

> "Die Fachgenossen, mit Ausnahme von Auwers (der Astronom der Berliner Akademie der Wissenschaften - K.-H. T.), wollten daran nicht glauben, Es gelang mir aber doch im Herbst 1888 bei der Versammlung der Permanenten Commission in Salzburg durchzusetzen (und zwar mit Hilfe von Helmert, der die Notwendigkeit gründlichster Weiterführung der Sache erkannte), daß auf Kosten der Erdmessung eine Beobachtungsreihe feinster Art über die Lage der Erdaxe ... organisirt wurde. Von da ab übernahm Helmert die Führung der Untersuchung als einer bedeutungsvollen Aufgabe des Centralbureaus der Erdmessung." [14, Bl. 349]

Trotz dieser geschilderten Verhältnisse unterschied sich die Situation von 1888 in wesentlichen Punkten von der des Jahres 1883. Konnte Fergola nur allgemein an das wissenschaftli-

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che Interesse appellieren, so lag 1888 mit Küstners Entdeckung ein erster greifbarer praktischer Beleg vor. Desweiteren engagierten sich mit Foerster und Helmert nunmehr zwei Persönlichkeiten, die als Kommissionsmitglieder den nötigen Einfluß und das erforderliche Renommee besaßen sowie als Institutsdirektoren über eine leistungsstarke Forschungsbasis verfügen konnten. Letztlich war die Geodätenvereinigung seit 1887 in der Lage, geplante Forschungsarbeiten nicht nur moralisch, sondern auch finanziell - wenngleich bei einem Jahresbudget von 16 000 Mark [Vgl. 15, S. II] in recht bescheidenem Maße - zu unterstützen.

Auf der ein Jahr später, im Oktober 1889, in Paris stattfindenden 9. Generalkonferenz setzte Helmert im Bericht des Zentralbüros die Tagungsteilnehmer über den zwischenzeitlich erreichten Bearbeitungsstand in Kenntnis. Als wichtigste Ergebnisse konnte er vermelden,

- daß ab dem 1. Januar 1889 auf der Berliner Sternwarte und dem Astrophysikalischen Observatorium Potsdam zwei zusammenhängende Beobachtungsreihen begonnen wurden,
- daß sich die Straßburger und die Prager Sternwarte dem Beobachtungsprogramm angeschlossen haben,
- daß man bei den vier Meßreihen die Methode von Horrebow-Talcott anwendete und
- daß unter Leitung seines Mitarbeiters Carl Theodor Albrecht (1843 - 1915) die Auswertung der Beobachtungsergebnisse erfolgt. [Vgl. 16, S. 83/84]

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Da aus den neuen Meßreihen noch keine exakten Schlüsse zu ziehen waren, fand keine größere Diskussion zu der Polhöhen-Problematik statt, und die Fortsetzung der in Angriff genommenen Maßnahmen wurde gebilligt. Kennzeichnend für die Beratungsatmosphäre war, daß die anwesenden Astronomen noch "fast ausnahmslos" die Ansicht weiterhin vertraten, "die Veränderungen wären ... zu klein, um erkannt werden zu können." [2, Bl. 34]

Auf der im September 1890 in Freiburg stattfindenden Jahrestagung der Permanenten Kommission hatte das von Foerster und Helmert vorangetriebene Forschungsprojekt seine erste kritische Phase zu überstehen. In seinem obligatorischen Jahresbericht vermeldete Helmert zunächst mit Genugtuung,

- daß die von Januar 1889 bis April 1890 in Berlin und Potsdam durchgeführten Beobachtungen eine übereinstimmende Schwankung der geographischen Breite von 0,5 Bogensekunden ergaben und

- daß die bei der Veröffentlichung der Meßresultate in der Nr. 2963 der Astronomischen Nachrichten geäußerte Bitte, ähnliche Beobachtungen überall anzustellen und dem Zentralbüro mitzuteilen, von 5 Wissenschaftlern aufgegriffen wurde.

Seine abschließende Bemerkung,

> "es wird wohl keinen Widerspruch finden, wenn ich behaupte, daß die neuesten Erfahrungen in der Frage der Veränderlichkeit der geographischen Breite dazu drängen, die Beobachtungen auf diesem Gebiete mit allem Nachdruck fortzusetzen" [17, S. 14],

führte zur erneuten Einsetzung einer Spezialkommission. Zu

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ihren Mitgliedern wurden wiederum Bakhuyzen, Foerster, Helmert und Tisserand gewählt. Neu kamen hinzu der italienische General Annibale Ferrero (1840 - 1902), Präsident der italienischen geodätischen Kommission, sowie der Schweizer Sternwartendirektor Adolph Hirsch (1830 - 1901), ständiger Sekretär der Internationalen Erdmessung, Wie bereits 1888, so geben auch die Protokolle von 1890 nur bedingt Auskunft über den realen Verlauf der zweitägigen Beratungen in der Spezialkommission und über die anschließende Diskussion im Plenum. Ein genaueres Bild vermitteln die beiden Berichte, die Helmert am 30. September 1890 sowie Foerster am 22. Oktober 1890 dem preußischen Kultusminister übergaben. So teilte Helmert mit:

> "Die vom Centralbureau beobachteten Breitenänderungen beschäftigten die Delegirten lebhaft. Die Wichtigkeit der Wahrnehmung wurde anerkannt, aber in der Erklärung ging man weit auseinander und demgemäß in den einzuschlagenden weiteren Schritten. Foerster suchte als Referent der Spezial-Commission für diese Frage mit Glück zu vermitteln." [17, Bl. 24]

Noch detaillierter schilderte Foerster die Situation:

> "Es war sehr merkwürdig zu sehen, wie das große Gewicht und die wissenschaftliche Evidenz des von dem Centralbureau vorgelegten Beobachtungsmaterials über diese Erscheinung in den Gemütern der den verschiedenen Nationen angehörenden Fachmänner mit einer gewissen Abneigung gegen diese 'Berliner Sache und mit einer gewissen Bedrängnis in Folge der Neuheit und überwältigenden Wichtigkeit dieser Angelegenheit kämpfte. In den ersten Tagen der Versammlung" - fuhr er fort - "überwog trotz aller vertraulichen und schlichten Beweisführung von Helmert und meiner Seite die abgeneigte Stimmung in Gestalt der Ansicht, daß es noch verfrüht sei, auf gemeinsame Kosten eine Expedition zur einheitlichen Verfolgung der bezüg-

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lichen Erscheinung zu organisieren. Man müsse sich doch erst mit den heimischen Astronomen über die ganze Angelegenheit beraten, bevor man sich entscheiden könne, und eigentlich müßten doch auch die übrigen Sternwarten erst auf Grund eigener Beobachtungen ihr entsprechendes Votum über die Sachlage abgeben ... Auf Grund fortgesetzter Erläuterungen und Beweisführungen ... wurde denn endlich in den letzten Tagen eine einstimmige Beschlußfassung erzielt ... Um überhaupt" - endete Foerster seinen Bericht - "die kleinen nationalen Widerstände gegen die ganze Unternehmung zu vermindern, ist in Freiburg von uns auch noch in's Auge gefaßt worden, aus den Dotationsfonds der Permanenten Commission auch für einige andere gemeinsame Aufgaben der Erdmessung baldmöglichst Mittel herzugeben." [18, Bl. 48 - 52]

Ein Vergleich mit den Beratungsprotokollen zeigt, daß die Schilderungen Helmerts und Foersters den Tatsachen entsprachen. Klar erkennbar ist erstens, daß die schließlich einstimmige Beschlußfassung in der Spezialkommission und im Plenum eindeutig auf das zähe Verhandlungsgeschick dieser beiden Männer zurückzuführen ist. Eine diplomatische Meisterleistung stellte allein schon die für die Diskussionsrichtung und das Diskussionsklima wichtige Eröffnungsrede Foersters dar. Nachdem er einen kurzen Überblick über die Entwicklung seit 1888 gegeben hatte, stellte er die entscheidende Frage:

"Was hat die Permanente Commission angesichts dieser Thatsachen zu thun? Soll sie einfach diese wichtigen Ergebnisse und die Dokumente dieser Untersuchungen veröffentlichen und die Arbeit, sowie das Verdienst, aus dem vorhandenen Material die bedeutendsten Folgerungen zu ziehen, den Sternwarten oder anderweitigen wissenschaftlichen Institutionen überlassen? Oder soll sie, in ihrer Eigenschaft als Centrum einer großen wissenschaftlichen Organisation, nicht vielmehr diese kost-

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> baren Elemente, welche sie aus eigener Initiative erworben hat, selber so weit verfolgen, als ihre finanziellen und wissenschaftlichen Mittel es erlauben?"
> [19, S. 42/43]

Der Auffassung, die Breitenvariationen wären lediglich eine regionale Erscheinung, begegnete er geschickt mit dem Argument:

> "Um aber den regionalen Charakter dieser beobachteten Erscheinung zu beweisen, sollten in den verschiedensten Gegenden gleichzeitige und gleichwerthige Beobachtungen ausgeführt werden. Anderentheils müßte man aber auch in den entferntesten Gegenden, und womöglichst unter den Europa entgegengesetzten Längengraden, ähnliche Beobachtungen anstellen, um die andere Alternative, welche von einigen kompetenten Astronomen aufrecht erhalten wird, beweisen zu können ... Sollten sich" - schlußfolgerte er abschließend - "bei völligem Wechsel von Methode, Beobachter und Station dieselben Breitenänderungen constatiren lassen, dann wäre allerdings kein Zweifel mehr erlaubt, und dann wäre es auch angezeigt, Zahl und Ort der entfernten Stationen zu bestimmen, an welchen in einer gegebenen Zeit Beobachtungen vorgenommen werden sollten, um mit der größten Genauigkeit die Elemente der Bewegung der Erdaxe bestimmen zu können."
> [19, S. 43]

Die anschließende Diskussion war zweitens dadurch geprägt,

- daß als noch strittig angesehen wurde, ob es sich bei den Breitenverschiebungen um eine regionale Erscheinung oder um eine allgemeine Tatsache handelt (Tisserand),
- daß man von der Veränderlichkeit der geographischen Breiten noch nicht völlig überzeugt war (Hirsch),

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- daß wenigstens zwei vollständig verschiedene Meßmethoden angewendet werden sollten, um wirklich genaue wissenschaftliche Resultate zu erhalten (Bakhuyzen),
- daß die Breitenproblematik mehr von astronomischem als geodätischem Interesse wäre und man deshalb die der Internationalen Erdmessung zur Verfügung stehenden Geldmittel nicht für diese, sondern vielmehr für dringliche geodätische Forschungsaufgaben, z. B. die Anschaffung eines Normalstabes aus Platin-Iridium, verwenden sollte (Bassot, 1841 - 1917). [Vgl. 19, S. 44/45 und 47]

Die trotz all dieser Bedenken schließlich einstimmig zustande gekommene Entschließung umfaßte 8 Punkte, von denen die ersten drei sowie der sechste die wichtigsten waren:

"1. Die Permanente Commission erachtet es für nothwendig, die Breitenbeobachtungen auf den Sternwarten von Berlin (oder Potsdam), Prag, und wenn möglich auch in Straßburg fortzusetzen ...

2. Außerdem ist das Bureau der Permanenten Commission beauftragt, eine wissenschaftliche Expedition nach den Sandwich-Inseln vorzubereiten, zu dem Zwecke, in jenen Gegenden Breiten-Beobachtungen vorzunehmen, welche den in Centraleuropa gleichzeitig stattfindenden Beobachtungen entsprechen ...

3. Das Bureau der Commission ist ... ermächtigt, sich mit der Coast-and Geodetic Survey der Vereinigten Staaten und andern wissenschaftlichen Instituten in Verbindung zu setzen, deren persönliche oder finanzielle Mithülfe erwünscht scheinen könnte ...

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6. Nachdem die Mitglieder der Permanenten Commission alle ... Mittheilungen des Centralbureaus (= kurze Übersichtstabellen der bis dahin vorliegenden Beobachtungsreihen - K.-H. T.) erhalten haben, steht jedem derselben das Recht zu, innerhalb einer gewissen, vom Bureau der Commission zu bestimmenden Frist, welche aber in keinem Fall über 1 - 2 Monate ausgedehnt werden darf, - zu verlangen, daß die Beschlüsse betreffend eine Expedition nach den Sandwich-Inseln einer nochmaligen, schriftlichen Abstimmung unterworfen werden. Wenn bei dieser Abstimmung die Mehrheit der Permanenten Commission sich gegen eine Expedition aussprechen sollte, so würde die endgültige Entscheidung bis zur nächsten Session vertagt werden ..." [19, S. 46/47]

Wesentlich ruhiger als die Freiburger verlief die im Oktober 1891 in Florenz abgehaltene nächste Tagung der Permanenten Kommission.

In seinem Jahresbericht teilte Helmert mit,

- daß sich gegen die definitive Absendung einer Expedition nach den Sandwich-Inseln kein Einwand erhob, da die übersandten vorläufigen Beobachtungsresultate von überzeugender Güte und Zuverlässigkeit waren,
- daß als Expeditionsziel Honolulu ausgewählt wurde,
- daß unter Foersters Leitung und Mitwirkung die Expeditionsvorbereitung erfolgte und
- daß am 1. April 1891 Foersters Mitarbeiter Adolf Marcuse (1860 - 1930), welcher bislang die Berliner Breitenbeobachtungen ausführte, nach Honolulu abreiste und inzwischen mit den Messungen begonnen habe. [Vgl. 20, S. 62/63]

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Die sich anschließende Diskussion nutzte Foerster, um unter Hinweis auf die ersten, den globalen Charakter der Erdachsenrotationsbewegungen bestätigenden Beobachtungsresultate aus Honolulu den Vorschlag zu unterbreiten,

> "daß ein besonderer Dienst von regelmäßigen und fortgesetzten Breitenbeobachtungen eingerichtet werden sollte, der auf eine gewisse Anzahl von passend gelegenen Sternwarten über die ganze Erde vertheilt würde." [20, S. 70]

Zu diesem Zweck stellte er den Antrag,

> "in dieser Conferenz eine Spezial-Commission aus mehreren besonders mit dieser Frage vertrauten Mitgliedern zu ernennen, welche dem Bureau der Permanenten Commission beigegeben würde, um der nächsten General-Conferenz einen vollständigen Entwurf für regelmäßig organisirte Breitenbeobachtungen vorzulegen." [20, S. 71]

Nach kurzem Meinungsstreit darüber, ob man aus zeitlichen und finanziellen Gründen zunächst nur die temporären Veränderungen beobachten solle und erst später die säkularen sowie nach nochmaliger Auseinandersetzung mit der bereits 1890 aufgeworfenen Frage,

> "ob dieses Problem, welches im Wesentlichen astronomischer Natur sei, die praktische Geodäsie genügend interessire, um eine Verwendung der verfügbaren Mittel der Association gerechtfertigt erscheinen zu lassen" (Bassot) [20, S. 72],

nahm man einstimmig Foersters Antrag an und wählte ihn sowie Bakhuyzen und Tisserand als Mitglieder der Spezialkommission. [Vgl. 20, S. 73]

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Ihrer Aufgabe nachkommend, legte die Spezialkommission im Anschluß an die Berichterstattungen von Helmert und Marcuse einen Beschlußentwurf auf der im Herbst 1892 in Brüssel sich versammelnden 10. Generalkonferenz vor. Das nach einer - nicht näher erläuterten - "längeren Discussion" [21, S. 98] unverändert angenommene Arbeitspapier hatte folgenden Wortlaut:

> "Die von der Permanenten Commission während der letzten drei Jahre organisirten oder veranlaßten Beobachtungen in Berlin, Potsdam, Straßburg, Prag und Honolulu, sowie die neuerdings mit den in Berlin und Honolulu gleichzeitig in Washington ausgeführten Beobachtungen, und endlich die in Pulkowa nach wesentlich anderen Methoden unternommenen Beobachtungen haben mit einem hohen Grade von Wahrscheinlichkeit die Existenz merklicher und mehr oder minder periodischer Schwankungen der Rotationsaxe im Inneren des Erdkörpers festgestellt. In der That liefern die einfachen Beziehungen, welche man zwischen dem Gange der gleichzeitigen Breiten-Änderungen an den verschiedenen Beobachtungsorten und zwischen den geographischen Längen dieser Orte gefunden hat, den Beweis, daß die zufälligen und systematischen Beobachtungsfehler nur einen geringen Einfluß auf die Beobachtungsreihen geübt haben, und daß die hauptsächliche und gemeinschaftliche Ursache dieser Breiten-Änderungen wirklich in einer geringen Schwankung der Erdaxe zu suchen ist.
>
> In Anbetracht dieses Resultats ermächtigt die Conferenz die Permanente Commission, ihre Bemühungen fortzusetzen, um diese wichtige Frage so vollständig als möglich an's Licht zu ziehen, und um für die astronomischen und geodätischen Arbeiten der Erdmessung so bald und genau als möglich die Correctionen zu ermitteln, welche künftig an die Breiten-, Längen- und Azimut-Beobachtungen anzubringen sind, um dieselben auf ein und dieselbe, ursprüngliche oder mittlere Lage der Erdaxe zu beziehen, und auf diese Weise die in verschiedenen Zeiten ausgeführten Bestimmungen dieser Elemente genau vergleichbar zu machen.

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Da es gegenwärtig noch nicht möglich scheint, eine spezielle Organisation für diese zugleich wissenschaftlich und praktisch wichtigen Arbeiten zu gründen, so dürfte es für jetzt genügen, daß das Centralbureau der Erdmessung, welches übrigens über die Resultate der regelmässigen, im geodätischen Institut zu Potsdam begonnenen, Breitenbeobachtungen verfügt, auch ferner als vermittelndes Organ verschiedenen Sternwarten dient, welche, wie Pulkowa, Straßburg, Washington u.s.w., an diesem Unternehmen sich betheiligen und daß vom Centralbureau die Resultate dieser Beobachtungen zusammengefasst und publicirt werden. Zu diesem Zwecke wird demselben ein Kredit von 3000 M. = 3750 fr. für das nächste Jahre zur Verfügung gestellt.

Doch dürfte die Permanente Commission nicht umhin können, auch die fernere Zukunft dieser Untersuchungen in's Auge zu fassen; denn es handelt sich darum, die genauesten Methoden, sowie die rationellste Arbeits-Vertheilung und Organisation zu ermitteln, nicht nur um die vollständige Untersuchung dieser wichtigen Erscheinungen, mit Einschluss der Säcular-Änderungen, sondern auch um die baldige und sichere Benutzung der Resultate derselben für die verschiedenen wissenschaftlichen und praktischen Arbeiten, im Besonderen für die Geodäsie festzustellen. Zu diesem Zwecke dürfte es nützlich sein, daß die Erdmessung sich mit anderen ähnlichen wissenschaftlichen Institutionen, z. B. mit der internationalen astronomischen Gesellschaft in Verbindung setzt, indem sie denselben die verschiedenen Pläne mittheilt und sie um ihre nützliche Beihilfe angeht.

Wahrscheinlich werden alle diese Schritte zur Überzeugung führen, daß es nützlich, wo nicht nothwendig werden wird, auf internationalem Wege die Gründung und den Unterhalt einer gewissen Anzahl von, auf demselben Parallel unter verschiedenen Längen gelegenen Beobachtungsstationen zu organisiren; dies wäre namentlich wichtig, um die Thatsache der Schwankungen der Erdaxe gänzlich unabhängig von

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den Eigenbewegungen der Sterne festzustellen. Zu diesem Zwecke würde die Permanente Commission zu ermächtigen sein, sich an die Regierungen der Erdmessungsstaaten zu wenden und denselben ein besonderes Projekt für die nöthigen Maasregeln zu unterbreiten.

Schon jetzt läßt sich erkennen, daß vier Stationen erwünscht wären, von welchen drei nöthigenfalls genügen würden, um die Componenten der Axenbewegung, sowie die Änderungen der Stern-Declinationen festzustellen, während die vierte Station eine unabhängige Controlle liefern würde. Für die Wahl einer solchen Gruppe von Stationen könnte man z. B. eine in Sicilien, eine zweite in Japan, eine dritte in Californien, und die vierte in Virginien vorschlagen." [21, S. 97/98]

Mit der Annahme dieses Beschlußentwurfes wurde die Untersuchung der Breitenvariationen auf eine neue Stufe gehoben. Allgemein anerkannt war nunmehr, daß das 5 Jahre zuvor von Küstner erstmals registrierte Naturphänomen real existierte, daß es globalen Charakter besaß und daß im Rahmen der Geodätenvereinigung seine tiefere Erforschung fortzusetzen war. Als hemmend für die angestrebte wissenschaftlich und ökonomisch zweckmäßigste Beobachtungsform erwies sich jedoch die zu schmale Finanzbasis der Internationalen Erdmessung. Die notwendigen Gelder bedingten eine beträchtliche Erhöhung des 1886 vereinbarten Jahresetats. Ein derartiger Schritt war aber satzungsgemäß erst ab 1897 möglich [Vgl. 15] und konnte nur durch die nächste Generalversammlung beschlossen werden.

Foerster, von dem Bestreben erfüllt, einen speziellen internationalen Beobachtungsdienst zu begründen, nutzte deshalb die 1893 stattfindende Jahrestagung der Permanenten Kommission, um die entsprechenden Schritte langfristig vorzubereiten. Grundlage

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für die Beratungen war wiederum der Jahresbericht von Helmert. Er enthielt die "erfreuliche" Mitteilung, "daß die astronomische Welt in eifriger Weise sich dieser Frage (der Breitenmessungen - K.-H. T.) bemächtigt hat" [22, S. 62] und endete mit der Orientierung:

> "Für die Zukunft muß man danach streben, die Untersuchungen über die Veränderungen der Breite in mehreren, wesentlich verschiedenen Meridianen so zu führen, daß für jedes Jahr einzeln die Bewegung der Erdaxe mit Sicherheit hervorgeht, und nicht erst für das Mittel mehrjähriger Perioden, denn dies würde eine der interessantesten Thatsachen der Erscheinung verdunkeln und die Forschung hemmen." [22, S. 63]

In seinem anschließenden Diskussionsbeitrag verwies Foerster zunächst auf die Mängel der gegenwärtigen Vorgehensweise.

> "Es genügt nicht" - argumentierte er - "daß eine gewisse Anzahl Sternwarten gute Reihen von Polhöhen-Beobachtungen angefangen haben ...; denn im Anfang dürfte es, trotz des besten Willens, unvermeidlich sein, daß ein Theil dieser Beobachtungen nicht den für diesen Zweck nöthigen Genauigkeits-Grad besitzen." Desweiteren fiele "dem Centralbureau die in der That nicht leichte Aufgabe zu ...., die Breiten-Variations-Beobachtungen zusammenzustellen, um daraus die von jetzt an für die Geodäten und Astronomen unentbehrlichen Reductions-Konstanten abzuleiten. Die auf solche Weise mit vieler Mühe und mit Benutzung sehr verschiedener Instrumente und Methoden erhaltenen Elemente, " - fuhr Foerster fort - "werden nothwendiger Weise wenig homogen sein, so daß man bald genöthigt sein wird, an andere, rationellere und systematischere Mittel zu denken." Für erforderlich hielt er deshalb "eine vollständige und specielle Organisation". [22, S. 82/83]

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Da die "Zeit schon ziemlich vorgeschritten" [22, S. 83] war, setzte man die Beratung am nächsten Tag fort. Als erster ergriff nochmals Foerster das Wort. Er wiederholte seine Ansicht,

> "daß man sich angesichts der Schwierigkeiten einer baldigen und umfassenden Organisation der Breiten-Bestimmungen zwar in nächster Zeit mit den freien Leistungen der einzelnen Sternwarten begnügen müsse, aber doch sobald als irgend möglich von dieser regellosen und desshalb auch unökonomischen Behandlung der Aufgabe zu einer gemeinsam mit den Astronomen zu ordnenden, systematischen Behandlung übergehen solle." [22, S. 90]
> Selbst wenn es gelänge, "ein freies, genügend vollständiges Zusammenwirken von Sternwarten hierfür zu organisiren und auch ihre Ergebnisse genügend schnell und regelmäßig mitgetheilt zu erhalten, wird sich doch in wenigen Jahren schon herausstellen, daß die Resultate nicht homogen genug sind, falls es nicht gelingt, die Eigenbewegungen der bei den Breitenbeobachtungen benutzten Sterne dabei vollständig zu eliminiren. Das letztere ist aber " - setzte er fort - "nur dann, bei der Anwendung der genauesten Methode, möglich, wenn mindestens drei Sternwarten bis auf wenige Kilometer einem und demselben Parallel angehören. Eine solche Kombination aber existirt eben nicht. Sie muß also ad hoc geschaffen werden. Und das ist unser (Hervorhebungen durch Foerster - K.-H. T.) Plan, den man als unnöthig und übertrieben bezeichnet, und auf den die Logik der Thatsachen und die sorgfältige Kritik doch mit Nothwendigkeit hinführt. Die bezügliche Organisation wird schließlich" - begründete er zu Ende kommend - "auch wirthschaftlich zweckmäßiger sein, als die bekannte Akkumulation organisationsloser, heterogener Arbeiten, in denen sich ... die Sternwarten noch immer gefallen, vorübergehend und zusammenhangslos die Arbeit für gewisse Zwecke unkritisch häufend und andere Gebiete ganz liegen lassend." Er schlug deshalb vor, "für die energische weitere Verfolgung der Verhandlungen betreffend eine rationelle Organisation der Breiten-Beobachtungen die in Flo-

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renz 1891 eingesetzte Commission wieder in Thätigkeit treten zu lassen." [22, S. 90/91]

Im Anschluß an Foerster verlas Ferrero einen an ihn gerichteten Brief seines Landsmannes Giovanni Schiaparalli (1835 - 1910) vom 5. September 1893. Darin teilte dieser mit, daß er das zur Kenntnis erhaltene

"Projekt des Herrn Marcuse zum Studium der Breiten-Änderungen" in den "Grundgedanken ... vollständig billige ... Man hat schon öfter gesagt und wird es wahrscheinlich noch weiter behaupten, daß es zu diesem Zwecke nicht nöthig sei, besondere Beobachtungs-Stationen zu gründen, und daß die bestehenden Sternwarten das nöthige Material für die vollkommene Ergründung des Phänomens auf eine beliebige Zeit zu liefern im Stande seien. Zweifellos ist es möglich, mit Hilfe von unter verschiedenen Längen (leider auch unter verschiedenen Breiten) gelegenen Sternwarten eine annähernde Kenntniss dieser Thatsachen zu erlangen ... Indessen" - argumentierte Schiaparalli wie Foerster - "läßt sich doch nicht leugnen, daß diese Methode bedeutende Schwierigkeiten darbietet. In erster Linie, den Übelstand der unvermeidlichen Verschiedenartigkeit der angewandten Methoden und Instrumente. Ferner die geringe Wahrscheinlichkeit, unter mehreren Sternwarten während einer langen Reihe von Jahren eine dauernde Übereinstimmung aufrechtzuerhalten, Endlich die Unmöglichkeit, mehrere Fehlerquellen zu beseitigen, wie z. B. die Unsicherheit betreff der Aberrations-Constante, die systematischen Fehler der Declinationen, und gewisse periodische Unregelmäßigkeiten der Refraction. Diese verschiedenen Gründe bringen mich" - bemerkte Schiaparelli zusammenfassend - "zu der Ansicht, daß eine dauernde Controlle des Phänomens durch speziell organisirte Stationen nöthig ist, welche so zu wählen sind, daß die erwähnten Übelstände beseitigt werden; wobei vor allem im Auge zu halten ist, daß alle diese Stationen auf dem gleichen Parallel liegen und daß in allen dieselben

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Sterne auf dieselbe Weise zu beobachten sind."
[22, S. 91/92]

Nach dem Verlesen des Briefes hielt Ferrero es ebenfalls

"für rathsam, abermals eine Spezial-Commission, aber aus weniger Mitgliedern als die in Florenz gewählte, zu beauftragen, die Frage zu studieren und der nächsten General-Conferenz formelle Vorschläge zu unterbreiten." [22, S. 94]

Die danach einsetzende Diskussion war von einem lebhaften Meinungsstreit gekennzeichnet. So vertrat Helmert die konträre Ansicht,

"daß man bei der Organisation der Untersuchung der Bewegung der Erdachse im Erdkörper an die bereits vorhandenen Beobachtungsstationen der Sternwarten anschließen solle ... Ohne Zweifel bietet das Projekt durch vier Breitenstationen auf demselben Parallel die Untersuchung zu führen, eine klare und einfache Lösung dar. Wenn man sich aber auch dabei an eine vorhandene Sternwarte anlehnt, so sind doch noch drei neue Stationen zu schaffen und es ist sehr die Frage, ob deren Unterhaltung wegen des Zwanges der Innehaltung des Parallels nicht sehr kostspielig werden wird." Zudem schien ihm "noch nicht nachgewiesen, daß man nicht auf anderem Wege mit weniger Kosten wesentlich dasselbe erreichen kann."
[22, S. 94]

Da auch von anderen Kommissionsmitgliedern eine ähnliche Auffassung vertreten wurde, schälten sich am Ende der Diskussion zwei Fraktionen heraus; die um Foerster, welche die Einrichtung eines speziellen Beobachtungsdienstes für notwendig hielt, und die um Helmert, welche aus wissenschaftlichen und ökonomischen Gründen es für zweckmäßiger und völlig ausreichend ansah, die

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bisherige, auf dem freiwilligen Zusammenwirken der bestehenden Sternwarten basierende Vorgehensweise fortzusetzen. In dieser scheinbar ausweglosen Situation erwies sich der Vermittlungsvorschlag des Schweizer Delegierten Hirsch als nützlich, welcher meinte,

> "es kann sich nun nicht darum handeln, heute durch eine Abstimmung zu entscheiden, welche von beiden Ansichten die richtige ist. Die Frage muß vorerst noch weiter durch das Centralbureau und die von Herrn Ferrero vorgeschlagene Spezial-Commission klargestellt werden, damit alsdann die Permanente Commission, auf all' diese Voruntersuchungen gestützt, der nächsten General-Conferenz von 1895 endgültige Vorschläge machen kann."
> Ausgehend davon schien es ihm "angezeigt, vorläufig eine Spezial-Commission zu ernennen, die Anzahl der Mitglieder zu bestimmen, und schließlich diese letztern zu wählen." [22, S. 96]

Von den Versammlungsteilnehmern wurde dieser Vorschlag gebilligt und in offener Abstimmung die Bildung einer Spezialkommission mit 5 gegen 3 Stimmen beschlossen. Mit 7 gegen 1 Stimme beschränkte man die Mitgliederzahl auf 3. Per Stimmzettel wurden Schiaparelli (7 Stimmen), Tisserand (6 Stimmen) und Foerster (5 Stimmen) als Kommissionsmitglieder gewählt, Bakhuyzen und Helmert scheiterten mit 4 bzw. 2 Stimmen. [Vgl. 22, S. 96/97]

Auf der nächsten, im September 1894 in Innsbruck abgehaltenen, Tagung der Permanenten Kommission konnte nur ein geringfügiger Fortschritt erzielt werden. Der von der dreiköpfigen Spezialkommission - bezeichnenderweise allerdings nicht einstimmig - unterbreitete Vorschlag zur Einrichtung eines gesonderten internationalen Beobachtungsdienstes, welcher von Foerster

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zu Beginn der Diskussion nochmals erläutert und mit den Argumenten ergänzt wurde, daß für die

"rein astronomischen Aufgaben ... keine unablässig fortlaufende Anordnung der Beobachtungen erforderlich (ist)" und daß "bei dem freien Zusammenwirken beliebig gelegener Sternwarten zwar die Stern-Örter, aber nicht die Sternbewegungen aus den Ergebnissen zu eliminiren sind, so daß nur der feste Dienst auf einem und demselben Parallel, der von Sternörtern und Sternbewegungen unabhängig macht, die fortschreitenden Polbewegungen genügend sicher ergeben kann" [23, S. 34] ,

fand auch im Plenum keinen ungeteilten Zuspruch. Nach wie vor wurden Bedenken in wissenschaftlicher, vor allem aber in administrativ-finanzieller Hinsicht geäußert. Auf Initiative von Ferrero gelang es jedoch immerhin, den im Vorjahr erzielten Konsens zu festigen und diesmal sogar einstimmig folgende drei - unübersehbar mit den Muttermerkmalen eines Kompromisses gezeichnete - Beschlüsse zu fassen:

"1. Die Permanente Commission, im Anschluß an die von der Spezial-Commission gemachten Vorschläge, drückt den Wunsch aus, daß die weiteren Untersuchungen über die Breiten-Variationen einer internationalen Organisation übertragen werden.

2. Die Permanente Commission ersucht die Spezial-Commission, im Verlauf von zwei bis drei Monaten einen vollständigen und ausführlichen Plan für eine solche Organisation vorzulegen, und zugleich die dafür erforderlichen Kosten anzugeben.

3. Die Permanente Commission wird alsdann, auf Grund dieses Plans, auf dem Wege der Korrespondenz, die Vorschläge ausarbeiten, welche der nächsten Generalkonferenz zu unterbreiten sind." [23, S. 42 ff.]

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Auf der 11. Generalkonferenz, sie fand vom 25. September bis 12. Oktober 1895 in Berlin statt, stand die Frage der Breitenbeobachtungen nicht im Vordergrund der Beratungen. Auf der zweiten Plenartagung am 2. Oktober gab Helmert als Direktor des Zentralbüros lediglich einen summarischen Überblick über die bislang gewonnenen Ergebnisse, welcher von Albrecht und Marcuse durch sogenannte Spezialberichte ergänzt wurde. [Vgl. 24, S. 21 ff]

Das Hauptinteresse der Diskussion galt aber der anstehenden Erneuerung der vertraglichen Grundlagen der Internationalen Erdmessung. Daß dieses komplizierte Ziel erreicht wurde, ist nicht zuletzt das persönliche Verdienst von Foerster. Sein verantwortungsvolles und viel Fingerspitzengefühl erforderndes Wirken als Präsident der Generalkonferenz würdigte der österreichische Delegierte Weiss im Namen der Tagungsteilnehmer mit den Worten:

> "Meine Herren, wir stehen im Begriff, eine der schwierigsten und für die weitere Ausgestaltung der Erdmessung bedeutungsvollsten General-Conferenzen zu schließen. Auf derselben waren große Meinungsverschiedenheiten auszugleichen und wiederholt Gegensätze zu überbrücken, welche zunächst unausgleichbar erschienen. Wenn es trotzdem gelungen ist, das für ein ferneres Gedeihen unseres schönen internationalen Unternehmens nicht hoch genug anzuschlagende Ziel zu erreichen, das Votum zu einem einstimmigen zu gestalten, so haben wir das wesentlich der umsichtigen, liebenswürdigen und taktvollen Art zu danken, in welcher Herr Geheimrath Foerster unsere Sitzungen geleitet hat." [24, S. 96]

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Für die Beschlußfassung über die künftige Organisation der Breitenbeobachtungen war speziell der Artikel 7 der neuen Übereinkunft von unmittelbarer Relevanz, denn er sah die nicht unbeträchtliche Erhöhung des Jahresbudgets der Internationalen Erdmessung von 16 000 auf 60 000 Mark vor. [Vgl. 24, S. 281] In Wegfall geriet dadurch das die Entscheidungsfindung bis dahin nachhaltig erschwerende finanzielle Hindernis. Einen unmittelbaren persönlichen Anteil daran hatte Foerster. Die Einrichtung eines internationalen Breitendienstes vor Augen habend, hatte er gemeinsam mit dem ständigen Sekretär der Internationalen Erdmessung, Adolph Hirsch, den Vertragsentwurf der Permanenten Kommission ausgearbeitet und u. a. das neue Budget von 60 000 Mark vorgeschlagen [Vgl. 24, S. 16 ff.], während der von den Delegierten Badens, Frankreichs, der Niederlande, Österreich-Ungarns, Spaniens und Württembergs unterbreitete Gegenentwurf die Beibehaltung des alten Etats von 16 000 Mark vorsah. [Vgl. 24, S. 274] In einer allen Konferenzteilnehmern [Vgl. 24, S. 67] überreichten "Denkschrift zur Begründung der in dem Entwurfe einer neuen Übereinkunft für die Internationale Erdmessung vorgeschlagenen Dotationserhöhung" vom Juni 1895 erläuterte Foerster darüber hinaus die ihm besonders am Herzen liegende Finanzangelegenheit. Bereits mit dem ersten Satz kam er auf das Wesen der Sache zu sprechen, indem er darauf hinwies,

> "die in dem Entwurf ... vorgeschlagene Erhöhung ... wird dadurch erforderlich, daß aus den in den letzten sechs Jahren von der Erdmessung theils angeregten theils subventionirten oder unmittelbar veranstalteten Reihen von Polhöhen-Beobachtungen der zweifellose Nachweis merklicher Lagen-Änderungen der Erdaxe hervorgegangen ist, und daß es der Organisation der Erdmes-

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sung nunmehr obliegt, dauernd für die Einrichtung eines möglichst zweckmäßigen und sparsamen Beobachtungssystems zur unablässigen Bestimmung der Lage der Erdaxe Fürsorge zu treffen und hierdurch zugleich die ursprüngliche Dotation von 16 000 M wieder in vollem Maaße verwendbar zu machen für experimentelle oder theoretisch-rechnerische Arbeiten gemeinsamen Interesses auf dem Gebiete der Lotabweichungsstudien, der Nivellements, der Schweremessungen u.s.w." [25, Bl. 82]

In seinen weiteren Ausführungen hob Foerster nochmals die umfassende wissenschaftliche und praktische Bedeutung der Breitenbeobachtungen hervor, begründete er die wissenschaftliche und ökonomische Zweckmäßigkeit eines aus vier Stationen bestehenden und auf 37° 5' nördlicher geographischer Breite gelegenen Beobachtungsdienstes, veranschlagte er die erforderlichen Investitionskosten mit insgesamt 44 000 Mark und die jährlichen Betreibungskosten mit 34 000 Mark sowie 10 000 Mark für die Auswertung und Publikation der Meßdaten, gab er schließlich einen kurzen Rückblick über die Verhandlungen der im Herbst 1893 eingesetzten Spezialkommission, wobei insbesondere das zustimmende Votum des Vorstandes der Astronomischen Gesellschaft vom August 1894 betreffs der Zweckmäßigkeit der Begründung eines regelmäßigen Beobachtungsdienstes sowie die bekundete Mitwirkungsabsicht der Leiter der amerikanischen und der japanischen Landesvermessung als wichtige Erfolge genannt wurden. [Vgl. 25, Bl. 82 ff.]

Daß Foerster und nicht die Spezialkommission die Denkschrift verfaßte, lag - wie aus den Konferenzprotokollen hervorgeht - daran, daß dieselbe nach der letzten Jahrestagung keine Beratungen abgehalten hatte,

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> "weil sich bei näherer Betrachtung der Sachlage ergab, daß zu den in Innsbruck bereits unterbreiteten Vorschlägen ... wesentliche Ergänzungen nicht möglich waren, bevor ein Beschluß in Betreff der Beobachtungsmethode gefaßt werden konnte." [24, S. 67]

Hierbei handelte es sich um die von Foerster in Alternative zur Horrebow-Talcottschen Meßmethode im April 1894 angeregte und seitdem in Erprobung befindliche Eignungsfähigkeit der in der Astronomie bereits mit Erfolg angewendeten Fotografie. [Vgl. 23, S. 9 ff.] Angesichts der erklärten Beschlußunfähigkeit der Spezialkommission mußte Foerster, wollte er die mit der 11. Generalkonferenz sich bietende günstige Gelegenheit, bei der Verabschiedung der neuen Übereinkunft auch die finanziellen Erfordernisse des beabsichtigten Breitendienstes mitzuberücksichtigen, nicht ungenutzt verstreichen lassen, die Initiative ergreifen, um weitere erhebliche Verzögerungen zu verhindern. Von der Mehrheit der Mitglieder der Permanenten Kommission wurden die in der Denkschrift enthaltenen Grundzüge, welche im Prinzip mit den 1894 von der Spezialkommission unterbreiteten Vorschlägen identisch waren, nachträglich befürwortet, wenngleich bemängelt wurde, daß

> "sie an Vollständigkeit und Ausführlichkeit im Einzelnen zu wünschen übrig lassen; sie bewegen sich nur in größeren summarischen Aufstellungen". [24, S. 67]

Diese beinahe obligatorische Pauschalkritik war für Foerster unerheblich, denn sein Hauptziel, die finanzielle Absicherung des geplanten Breitendienstes, konnte er mit der Denkschrift realisieren, wenngleich es zu heftigen Diskussionen um den Artikel 7 kam [Vgl. 24, S. 67 ff. und 200 ff.], die auch nach

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Abschluß der Generalkonferenz anhielten, so daß Foerster Anfang 1896 sich veranlaßt sah, eine im Dezember 1895 ausgearbeitete und aktualisierte "Begründung der Erhöhung der Dotation für die Internationale Erdmessung" an alle Konferenzteilnehmer zu verschicken. [Vgl. 26, Bl. 268 ff.] Parallel dazu konnte er noch auf der letzten Sitzung der Permanenten Kommission am 12. Oktober 1895 durchsetzen, daß die Bildung einer neuen, aus Helmert, Schiaparelli, Tisserand und ihm bestehenden, Spezialkommission beschlossen wurde. Zu deren Aufgabe bestimmte man die Ausarbeitung eines "detaillirten Programms des Breitendienstes mit beigefügtem, ungefährem Kostenanschlag." [24, S. 219]

Die als Expertengremium im Oktober 1896 in Lausanne letztmalig zusammentretende Permanente Kommission (mit der 1897 in Kraft tretenden neuen Übereinkunft wurde sie durch ein vierköpfiges Präsidium ersetzt, welchem als beratendes Gremium in Verwaltungssachen eine aus Delegierten sämtlicher Vertragsstaaten zusammengesetzte Permanente Kommission beigeordnet war [Vgl. 24, S. 280]) beschäftigte sich vornehmlich mit der Frage der Einsatzmöglichkeit der Fotografie und mit der Auswahl der zu errichtenden vier Beobachtungsstationen. Mit knapper Mehrheit (5 : 4 Stimmen) wurde dabei Foersters Vorschlag angenommen,

> "es ist wünschenswerth, im Laufe des Winters und des nächsten Sommers eine dritte vergleichende Reihe von photographischen und optischen Beobachtungen anzustellen, deren Resultate der General-Conferenz des nächsten Jahres mitgetheilt werden könnten, welche alsdann in der Lage wäre, eine auf genügendes Material gestützte Entscheidung zu treffen." [27, S 95]

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Helmert, der die Überlegenheit der fotografischen Meßmethode bezweifelte, da Untersuchungen in seinem Institut zu dem Resultat führten,

> "daß das Gelingen der ganzen Operation wesentlich gesisicherter erscheint, wenn man für den geplanten internationalen Polhöhendienst das bewährte optische Beobachtungsverfahren, unter entsprechender Erhöhung der Leistungsfähigkeit der Instrumente, beibehält"
> [27, S. 178],

gelang es jedoch mit 8 : 1 Stimmen den ergänzenden Beschluß herbeizuführen:

> "Die Instrumente sollen zunächst so ausgeführt werden, daß sie für die optische Methode dienen können, jedoch in der Weise, daß sie später mit Leichtigkeit für die Anwendung der photographischen Methode umgeformt werden können." [27, S. 95]

Grundlage für die Diskussion um die Auswahl der geeignetsten Beobachtungsstationen war ein Schreiben Helmerts vom 20. Juni 1896. Darin teilte er - inzwischen "mehr und mehr" von Foersters Plan "begeistert, weil derselbe eine einfache, durchsichtige Lösung des Problems der Feststellung der Erdaxen-Schwankungen biete" [27, S. 101] - mit:

> "Obwohl ein formeller Beschluß über die Ausführung der Organisation eines ständigen Beobachtungsdienstes für die geographische Breite durch Besetzung von mehreren Stationen auf demselben Parallel noch nicht vorliegt, so schien es doch dem Centralbureau wichtig, die Auswahl geeigneter Stationen schon jetzt zum Gegenstand einer Studie zu machen. ... Auf Veranlassung des Herrn Professor Foerster, von dem der erweiterte Fergola'sche Plan herrührt, hatte schon früher Herr Dr. Marcuse sich mit der Wahl einer günstigen Combination von 4 Stationen desselben Parallels befaßt. In einem mir gefälligst

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mitgetheilten Bericht vom Januar 1896 empfiehlt er die Stationen Licata in Sicilien, Shirakawa in Japan, Felton an der Westseite und Petersburg an der Ostseite von Nordamerika ... Der grundlegenden Bedeutung der Frage schien es nun nach der Meinung des Centralbureaus zu entsprechen, ihre eingehende Erörterung nochmals selbständig durchzuführen und sodann das zur Beurtheilung der Frage gesammelte Material den Delegirten der Erdmessung vorzulegen. Herr Professor Dr. Albrecht hat sich unter Mitwirkung des Herrn Dr. Hecker dieser Arbeit unterzogen, wobei ich mit besonderem Danke der Unterstützung zu gedenken habe, welche ihm durch werthvolle Mittheilungen von Seiten des Herrn Professors Celoria, Vice-Präsident der italienischen Gradmessungs-Commission, und des Herrn Dr. Omori, japanischen Delegirten bei der Berliner Conferenz, zu Theil geworden ist. Mit Zustimmung" – fuhr Helmert fort – "der aus den Herren Foerster, Schiaparelli, Tisserand und dem Unterzeichneten bestehenden, im Oktober 1895 in Berlin von der Permanenten Commission eingesetzten Breiten-Commission werde die Abhandlung des Herrn Professors Albrecht schon jetzt gedruckt. Indem ich den Herren Delegirten der Erdmessung dieselbe nunmehr überreiche, ersuche ich die geehrten Herren, womöglich schon bis zur nächsten Sitzung der Permanenten Commission mit ihren Bemerkungen hervorzutreten."
[27, S. 72/73]

Diesem Wunsche wurde Rechnung getragen, allerdings kam es nicht zu einer definitiven Beschlußfassung. [Vgl. 27, S. 98 ff und S. 127 ff.]

Auf der im Oktober 1898 in Stuttgart stattgefundenen 12. Generalkonferenz der Internationalen Erdmessung konnte Foerster dann mit Genugtuung erleben, wie seine 10jährigen unermüdlichen Bemühungen von Erfolg gekrönt wurden. Mit Ausnahme des Punktes 6, der neugefaßt werden mußte, beschlossen die Dele-

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gierten einstimmig, die von einer 6köpfigen Breitenkommission (ihr gehörten als alte Sachkenner Bakhuyzen und Foerster an) unterbreiteten 8 Vorschläge, anzunehmen:

"1. Die Conferenz beschließt, daß die im Paragraph 4 des Artikels 6 der Convention von 1896 vorgesehene internationale Untersuchung über die Breiten-Änderungen mit dem Jahre 1899, unter der Direction und Verantwortlichkeit des Centralbureaus, und unter der Kontrolle des Präsidiums der Erdmessung (Siehe Art. 7 der Uebereinkunft) zu beginnen hat.

2. Zu diesem Zwecke billigt die Commission das vom Director des Centralbureau's vorgelegte Programm, worin 6 unter demselben Parallel gelegene Stationen vorgeschlagen werden; 4 dieser letzteren sollen gänzlich auf Kosten der internationalen Erdmessung gegründet und unterhalten werden, während die Erdmessung für die Station Tchardjui und diejenige in Cincinatti einen Beitrag gewährt. Die Commission spricht Rußland und den Vereinigten Staaten den lebhaftesten Dank für die zu Gunsten dieser beiden Stationen so freundlich zugestandene Mitwirkung aus.

3. Die Kosten für dieses Unternehmen werden durch die im Paragraph 4 des Art. 6 der Übereinkunft vorgesehene Dotation bestritten.

4. Die General-Conferenz beschließt, daß die zu dieser Untersuchung dienenden Beobachtungen zunächst während eines Zeitraumes von 5 Jahren fortzusetzen sind. Am Ende dieser Periode wird die Generalkonferenz über die weitere Fortführung der Beobachtungen, sowie über etwaige, von der Erfahrung angegebene Änderungen an den benützten Methoden Beschluß fassen.

5. Während der ersten 5 Jahre sind die Beobachtungen nach der Talcott'schen Methode auszuführen, gemäß den Angaben, welche in dem Berichte über die Vorbereitungen für den internationalen Polhöhendienst der Herren Hel-

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mert und Albrecht enthalten sind.

6. In Anbetracht der jetzigen Sachlage, und mit Rücksicht darauf, daß die Anwendung der photographischen Methode vielleicht die für dieses Unternehmen ausgeworfenen Summen überschreiten könnten, beschließt die Conferenz, daß während der ersten 5 Jahre die optische Methode ausschließlich verwendet werden soll.

7. Da es für die Bestimmung der jährlichen periodischen Erdaxen-Änderungen von großem Interesse ist, die systematischen Jahresfehler so viel als möglich durch eine große Anzahl der benutzten Stationen zu eliminiren, beschließt die Conferenz, daß das Präsidium diejenigen Sternwarten, welche sich besonders für dieses Unternehmen interessiren, einladet, ihre Beobachtungen über die Breiten-Änderungen fortsetzen oder baldmöglichst beginnen zu wollen, wobei denselben völlige Freiheit in der Wahl der Instrumente und Methoden gelassen wird.

8. Die General-Conferenz ist einverstanden, daß das Centralbureau die Organisation des Unternehmens so bald als möglich an die Hand nimmt. Ebenso ist das Centralbureau ermächtigt, die Installations- und Ausführungs-Bedingungen für die Breiten-Stationen, mit Einbegriff des Eigenthums-Rechtes an den Instrumenten und Einrichtungen, festzusetzen. Für den Fall, daß hierzu eine Verständigung mit den betreffenden Regierungen nöthig sein sollte, wird das Erdmessungs-Präsidium gemäß Art. 4 der Übereinkunft, die Correspondenz und die Annahme der vereinbarten Abmachungen besorgen."
[28, S. 40 ff.]

Die nicht namentliche Nennung der 6 Beobachtungsstationen wurde - wie in den Konferenzprotokollen nachzulesen ist -

> "absichtlich unterlassen ..., um dem Centralbureau mehr Freiheit zu lassen, seiner Zeit den sich etwa noch zeigenden Hindernissen und Umständen Rechnung zu tragen."
> [28, S. 42]

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Es zeichnete sich jedoch bereits zu diesem Zeitpunkt ab, daß nicht die von Foerster 1895 angeregte geographische Breite von 37° 05' [Vgl. 24, Bl. 83], sondern die von Albrecht 1896 vorgeschlagene Breite 39° 08' [Vgl. 27, S. 127 ff.] gewählt werden würde.

Auf der vom 25. September bis 6. Oktober 1900 in Paris abgehaltenen 13. Generalkonferenz wurden dann die Delegierten davon in Kenntnis gesetzt, daß - in der Reihenfolge Cincinatti (1.9.), Tchardjui (10.9.), Gaithersburg (2.10.), Ukiah (11.10.), Carloforte (24.10.) und Mizusawa (16.12.) - bis Mitte Dezember 1899 sämtliche 6 Beobachtungsstationen in Italien, Japan, Rußland und den USA ihren Betrieb aufgenommen hatten. [Vgl. 29]
13 Jahre später würdigte Helmert die Funktionsweise und die Bedeutung des Internationalen Breitendienstes mit den Worten:

> "Die Wahl der vier internationalen Stationen auf der Nordhalbkugel der Erde hat sich als eine recht glückliche in den nun fast 13 Jahren ihrer Benutzung erwiesen. Auch die Instrumente funktionierten ausreichend, und ihre Installation hat keine Mängel gezeigt. Es dürfte vorläufig zweckmäßig sein, an dem gegenwärtigen Dienst nichts zu ändern.
> Noch sind allerdings die Ursachen der zeitlichen Breitenvariationen nicht völlig aufgeklärt, trotz der Bemühungen mehrerer Astronomen. Aber es unterliegt wohl keinem Zweifel mehr, daß ohne einen fortdauernden Beobachtungsdienst eine scharfe Angabe der geographischen Breiten für einen gewissen Normalzustand oder mittleren Zustand der Erde niemals möglich sein wird." [30, S. 139/140]

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Dem ist heute kaum anderes hinzuzufügen. Die vor 100 Jahren von dem Berliner Sternwartendirektor Wilhelm Foerster initiierte systematische Erforschung der Bewegung der Erdrotationsachse ist trotz zwischenzeitlicher Änderung der Organisationsformen, der Stationen, Instrumente, Meßanordnungen und Methoden unverändert - wie die seit dem 1. 1. 1988 neu geschaffene Einrichtung des International Earth Rotation Service beweist - von hohem wiseenschaftlichen Interesse. [Vgl. 31, S. 113]

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Astronomical constants in the relativistic framework

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ABSTRACT. The system of astronomical constants has been inspected from the view point of the theory of general relativity. Astronomical constants are affected by relativity in three ways. (1) Basic conceptual change. For instance, Kepler's third law has to be adapted to the theory of relativity. Consequently, the relationship between the Gaussian gravitational constant k^2, unit distance, and heliocentric gravitational constant, GS, must undergo a corresponding revision. (2) Definitions and numerical values of some constants, such as a_e, J_2, etc., depend on reference frames. If their values are known in one frame, the corresponding values in another frame can be derived through coordinate transformation. (3) Modification of units cause constants like GE, A etc., having different numerical values in various frames. Intrinsically, it is not relativistic effects, it is artificially introduced by the conventional requirement, that there is no scale difference between TAI and TDB.

1. Introduction

The IAU (1976) System of Astronomical Constants is, in principle, based on Newtonian theory. In the last decade, space techniques applied to astrometry and geodesy have already reached the 10^{-8} accuracy level or even better. As a result, more accurate astronomical constants could be estimated by using the data acquired from observations of these techniques. For instance, in comparison with the

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IAU (1976) System, quite a few constants in the MERIT Standards (Melbourne et al., 1983) have already been improved significantly. To match this technical progress and to exploit this high accuracy, relativistic theory has entered modelling and data processing of astronomical and space-geodetic observations. As a natural step of development the current conception of astronomical constants has to be adapted to relativity theory. In fact, this problem has already been recognized a few years ago. Murray (1983), for example, dedicated a whole section (§ 1.9 in his book) to astronomical units and constants; in addition, he pointed out at the end of chapter 6 that the unit of length will be affected by the modification of the unit of time. Later on, this problem of unit was further studied in detail by Fukushima et al. (1986b) stating that some constants, such as GE, A, may have different values in different reference frames due to the modification of units.

When reflecting a little more on this subject further problems are found. Firstly, according to the principle of equivalence GE and A should have identical values in various frames. Currently they do have different values, the reason is the units in various frames are different, which is caused by the definition problem of TAI and TDB. Secondly, the actual relativistic effects on astronomical constants are twofold: the basic conceptual change; the definition and numerical value of some constants depend on frames.

Many astronomical constants have already more than 8, some even as much as 11 significant digits while the relativistic effect could amount to 10^{-8}. From this fact one can see, that the identified problems have not only theoretical importance but also practical implications, especially for disciplines such as astrometry, celestial mechanics, space navigation and geodesy in which highly accurate constants have to be used. Besides, this seems to be a critical and not completely understood problem, which needs to be discussed widely.

In this paper only the conceptual framework and the philosophy for treating this problem are presented. Some part of the paper strongly depends on the conception of reference frame, text books and relevant papers such as Will (1981), Fujimoto et al. (1982), Murray (1983), Fukushima et al. (1986a) can be referred. The most important frames for us are the barycentric frame (BF) and geocentric terrestrial frame

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(TF). Depending on the accuracy requirements relativistic models can be very complicated or rather simple. Here only the first order relativistic effects are considered, in order to avoid unnecessary complications of the relativistic model. Accuracy requirement of the treatment is at the order of 10^{-10} . Einstein's general relativity is adopted here.

2. Basic conceptual change: relations between defining, primary and derived constants

In the IAU (1976) System of Astronomical Constants the Gaussian gravitational constant k^2 is a defining constant. In Newtonian sense astronomical unit A is defined as the radius of the orbit of a particle of negligible mass which moves in a circular orbit around the sun with constant angular velocity k radians per day. The relationship between k, A and the heliocentric gravitational constants (GS) is

$$GS = A^3 k^2 / d^2 , \qquad (1)$$

which is identical with Kepler's third law:

$$GS = A^3 n^2 \qquad (2)$$

with n=k/D. A definition of this form has been used since the time of Gauss. The same formal definition can be retained in relativistic sense when standard Schwartzschild coordinate is adopted, since in this case Kepler's third law takes the same form as in Newtonian case, see (Murray, 1983). But the commonly adopted spatial coordinate (as used by JPL in a PPN treatment of planetary radar observations) is isotropic. For these coordinates Kepler's third law reads (see Murray, 1983):

$$n^2 a^3 = GM\,(1 - 3GM/c^2 a), \qquad (3)$$

which is different from its original form of eq.(2) by a scale factor $(1 - 3GM/c^2 a)$ that approximately amounts to $(1 - 3 \times 10^{-8})$. Definition or at least the explanation of the definition is thus affected. The following table clarifies the situation.

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	Newtonian sense	Relativistic sense
Kepler's third law:	$n^2a^3=GS$	$n^2a^3=GS(1-3GS/c^2a)$
define:	a=1(unit) S=1(unit) time unit=1 day	a=1(unit) S=1(unit) time unit=1 day
from above:	$n^2=G$	$n^2=G(1-3GS/c^2a)$
implication:	n=k(radians per day) is equivalent to $k^2=G$	<u>if</u> n=k(radians per day) then $k^2\neq G$; <u>if</u> $k^2=G$ then n≠(radians per day)

Consequently, if eq.(1) is still used to link GS with k^2 and A, then the meaning of k^2 will be different from Newtonian sense.

With k as defining constant the heliocentric gravitational constant GS remains as a derived constant, whose value can be obtained from equation (3), instead of eq.(1). If k is disregarded, then GS value could possibly be directly estimated from planetary observations, in like manner as the value of GE is estimated by satellite ranging. In the latter case GS becomes a primary constant.

3. The effect of the units of time and length on the astronomical constants

The relation between coordinate times dt_B in BF and dt_T in TF is

$$dt_T/dt_B=1-(\phi+v^2/2)/c^2, \quad (4)$$

see Fukushima et al. (1986a), in which

$(\phi + v^2/2)/c^2$ contains a secular part $\langle\phi+v^2/2\rangle/c^2$ and a periodic one $\langle\phi+v^2/2\rangle_P/c^2$. Roughly, one gets

$$\langle\phi + v^2/2\rangle/c^2 =1.5*10^{-8},$$

and the amplitude of the periodic part amounts to $3*10^{-10}$. The secular

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difference between the two time scales dt_T and dt_B seemed to be inconvenient in practical application. Consequently, it has been suggested by IAU that TDB and TAI should be defined in such a way that they only differ by periodic terms. In other words, the above secular difference is superficially removed by introducing a change of the time unit. This creates a new time scale denoted by t_{TB}. Its relation with t_T is

$$dt_T/dt_{TB} = 1 - \langle \phi + v^2/2 \rangle /c^2 = \eta \tag{5}$$

where η is a constant scale factor, and the differential relation between t_B and t_{TB} is

$$dt_{TB}/dt_B = 1 - \langle \phi + v^2/2 \rangle_p /c^2 \tag{6}$$

The constant c in the T-frame has the same value as in the B-frame when (ct_T, x_T^i)are the coordinates in the T-frame. Once the time unit undergoes a scale change the corresponding change of the unit of length must be introduced to keep the numerical value of c invariant. The spatial coordinates obtained after this unit change are denoted by x_{TB}^i; it holds

$$x_T^i/x_{TB}^i = \eta \tag{7}$$

and (ct_{TB}, x_{TB}^i) are the coordinates after the unit modification.

In analogy to the constant c the constant GE in the T-frame retains the same value as in the B-frame when (ct_T, x_T^i) are used as coordinates. If GE is expressed by the coordinates (ct_{TB}, x_{TB}^i) its numerical value must be adapted to these units of time and length. Since GE $\propto x^3/t^2$, the value of GE becomes

$$(GE)_T B = (GE)_T/\eta = (GE)_B/\eta, \tag{8}$$

according to equations (5) and (7).

Essentially, this is the main argument in Fukushima et al. (1986b). Note that GE does not undergo an intrinsic change from one frame to another, merely its numerical value varies in different frames due to the change of units.

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The necessity of the IAU convention deserves some reconsideration. The secular difference between dt_B and dt_T is a kind of time dilation. In the theory of relativity all those time dilations, Lorentz contractions etc. are derived under the implicit condition that the units of time and of space remain the same in various frames. Time dilation is a reality. By modifying the unit one can only superficially but not actually remove this time dilation. Moreover, by modifying the unit of the space coordinate along with the unit of time one can only keep the value of c invariant with respect to the change of unit. Any other quantity will change its numerical value in connection with the modification of unit, provided its dimension differs from $(x/t)^k$, k=0, ±1, ±2, although it has no intrinsic variation at all. GE is only one of the examples. These are the inconveniences brought about by unit modification. If not treated carefully misunderstanding and errors are caused.

4. The effect of time-space relations on length definition and on astronomical constants-reference frame dependent constants

In analogy to the difference between coordinate time and proper time the spatial cordinates and vectors in various frames are also different. From coordinate transformation equation given in Fukushima et al. (1986a), one can determine the spatial coordinate difference of the same interval in two different frames. But these relations are not directely applicable to space vectors. Commonly, a spatial vector is defined by a pair of simultaneous events, which form a space-like interval. The difficulty arises when the two events are simultaneous in one frame but not in the other. However, this difficulty is removable. If one first defines a vector $\bar{r}_T$ in the T-frame, the corresponding vector $\bar{r}_B$ in the B-frame can be expressed by

$$\bar{r}_B=(1-\phi/c^2)\bar{r}_T-(\bar{v}\cdot\bar{r}_T)\bar{v}/2c^2-(\bar{v}\cdot\bar{r}_T)\bar{v}_1/c^2, \qquad (9)$$

where $\bar{v}_1$ is the velocity of the end point of the vector w.r.t. the geocenter. For details of this expression see Appendix. If the IAU convention is taken into account then the relation becomes

$$\bar{r}_B=(1-(\phi+\langle\phi+\bar{v}^2/2\rangle)/c^2)\bar{r}_{TB}-(\bar{v}\cdot\bar{r}_{TB})\bar{v}/2c^2-(\bar{v}\cdot\bar{r}_{TB})\bar{v}_1/c^2 \qquad (10)$$

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From these equations the absolute values of the vectors are obtained

$$r_B=(1-\phi/c^2-(\bar{v}\cdot\bar{r}_T)^2/2c^2r_T^2-(\bar{v}\cdot\bar{r}_T)(\bar{v}\cdot_1\bar{r}_T)/c^2r_T^2)r_T \qquad (11)$$

and

$$r_B=(1-(\phi+\langle\phi+\bar{v}^2/2\rangle)/c^2-(\bar{v}\cdot\bar{r}_{TB})^2/2c^2r_{TB}^2-(\bar{v}\cdot\bar{r}_{TB})(\bar{v}\cdot_1\bar{r}_{TB})/c^2r_{TB}^2)r_{TB} \qquad (12)$$

Equations (11) and (12) demonstrate that the length of the corresponding vector in the B-frame is shorter than that of the original vector in the T-frame. The shortening in equation (11) is an intrinsic one, it is not attributed to the modification of unit. As a consequence astronomical constants related to length may be affected.

Typical examples are the size and shape of the earth, namely the equatorial radius a_e, flattening factor f and dynamical form factor J_2. Due to tidal deformation, plate tectonic motion, etc. size and shape of the earth are varying with time. Nevertheless, within certain limits one can define these constants for a quasi-rigid earth. In principle, the constants can be defined either in the B- or in the T-frame. According to the above discussion the definitions in the two frames are different. a_e and J_2 being primary constants are derived from observations. Their definition in the T-frame is clear as the determination of these constants is usually performed in this frame. Definitions in the B-frame, however, are difficult. The special relativity components vary at a diurnal period. In addition, the general relativity term ϕ/c^2 changes as the earth moves along its orbit. These constants now become time variable in the B-frame. By analyzing observational data in the B-frame one can determine these "constants" in the B-frame. Even if there are no observational and other errors, the values will be different from those in the T-frame. Residents on the earth are certainly interested in its size and shape measured in the T-frame rather than in the B-frame. Moreover, the size and shape of the earth can be accurately estimated by processing the observations acquired on the earth or in its vicinity in the T-frame, whereas observations carried out in the planetary space are of little use for this purpose. Consequentely, these constants are better determined and defined in the T-frame. For applying them to the B-frame careful transformation is necessary by using eq. (9) or (10), otherwise errors will occur; see ,e.g., Vincent (1986).

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5. Concluding remarks

When dealing with astronomical constants in connection with high precision data processing one should always aim at coherence of the constants and the reference frame in which they are employed.

The basic physical constants such as c, G and GE remain constant in different reference frames. Only their numerical values may undergo changes due to the modification of units in time and length. A typical example is GE. The IAU convention introduced for TDB and TAI is the reason for this modification. The necessity of this convention is worth being reconsidered.

Vectors and distances may have different values in various frames affecting the definitions of relevant astronomical constants. Constants such as those representing the size and shape of the earth are preferably defined and determined in the terrestrial frame. For using them in the B-frame, careful coordinate transformation should be applied.

Appendix

In the relativistic framework vectors are commonly defined by the interval of a pair of simultaneous events, E_P and E_Q. First, only special relativity is concerned. Up to terms of the order $1/c^2$, the Lorentz transformation between the L-frame and L'-frame yields

$$dt'=(1+v^2/2c^2)dt-(d\underline{x}\cdot\underline{v})/c^2 \qquad \text{(A-1)}$$

$$d\underline{x}'=d\underline{x}+(d\underline{x}\cdot\underline{v})/2c^2-dt(1+v^2/2c^2)\underline{v} \qquad \text{(A-2)}$$

If the vector is defined in L-frame, so that $d\underline{x}$ is the vector and $dt=0$, then in the L'-frame the spatial coordinate of the interval is

$$d\underline{x}'=d\underline{x}+(d\underline{x}\cdot\underline{v})\underline{v}/2c^2.$$

But $d\underline{x}'$ is not the corresponding vector in L'-frame, since now $dt'\neq0$. In other words, the two events in the L'-frame are not simultaneous. To define the corresponding vector in L'-frame a third

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event E_Q, should be created, which is simultaneous with E_P in L'-frame. From eq.(A-1) follows

$$dt'=-(d\underline{x}\cdot\underline{v})/c^2 .$$

In this time interval the end point of the vector moves w.r.t. the head point by the distance

$$-\underline{v}dt'=(d\underline{x}J\underline{v})\underline{v}/c^2 \cdot$$

The corresponding vector in L'-frame should be defined as

$$(d\underline{x})'=d\underline{x}+\underline{v}dt'=d\underline{x}-(d\underline{x}\cdot\underline{v})\underline{v}/2c^2 \qquad \text{(A-3)}$$

For the length of the vector one gets

$$(dx)'=(1-(d\underline{x}\cdot\underline{v})^2/2c^2dx^2)dx. \qquad \text{(A-4)}$$

This is the Lorentz contraction. Generally, points P and Q are not at rest in the L-frame. Taking the geocentric vector to a satellite (Q) as example the end point Q of the vector moves in the L-frame. Let the velocity of Q in the L-frame be v_1, then eqs.(A-3) and (A-4) become

$$(d\underline{x})'=d\underline{x}-(d\underline{x}\cdot\underline{v})\underline{v}/2c^2-(d\underline{x}\cdot\underline{v})\underline{v}_1/c^2 \qquad \text{(A-5)}$$

$$(dx)'=(1-(d\underline{x}\cdot\underline{v})^2/2c^2dx^2-(d\underline{x}\cdot\underline{v})(d\underline{x}\cdot\underline{v}_1)/c^2dx^2)dx \qquad \text{(A-6)}$$

Finally, the effect of general relativity can be incorporated. If $d\underline{x}$ is originally defined in the T-frame the corresponding vector in the B-frame is

$$d\underline{x}_B=d\underline{x}_T(1-\phi/c^2)-(d\underline{x}_T\cdot\underline{v})\underline{v}/2c^2-(d\underline{x}_T\cdot\underline{v})\underline{v}_1/c^2 \qquad \text{(A-7)}$$

If the original vector is defined in B-frame, then the corresponding vector in T-frame is

$$d\underline{x}_T=d\underline{x}_B(1+\phi/c^2)-(d\underline{x}_B\cdot\underline{v})\underline{v}/2c^2-(d\underline{x}_B\cdot\underline{v})\underline{v}_1/c^2 \qquad \text{(A-8)}$$

The length relation is easily obtainable, and the unit modification can be incorporated, too.

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EARTH TIDES

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TIDAL EVOLUTION OF THE MARS-PHOBOS SYSTEM

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Summary

On the basis of the observed tidal acceleration of the mean motion of Phobos or the secular decrease in the semi-major axis of its orbit, the tidal evolution of the gravity field of Phobos has been investigated. It has been demonstrated that the secular tidal variations will generate zero-gravity at the surface of Phobos in the equatorial region up to latitudes $\pm 60^{o}$ and that the body will desintegrate after the semi-major axis of the orbit of Phobos has reached the critical value $\bar{a}$ = 6 552.2 km.

Резюме

Исходя из наблюденного значения приливного ускорения среднего движения Фобоса или векового уменьшения большой полуоси его орбиты, исследуется приливная эволюция поля силы тяжести Фобоса. Показывается, что вековые приливные вариации вызовут нулевое значение ускорения силы тяжести на поверхности Фобоса в области от экватора до широт $\pm 60^{o}$, и что тело Фобоса перестанет существовать как единое целое после того, как большая полуось его орбиты достигнет критического значения $\bar{a}$ = 6 552,2 км.

1. TIDAL FORMING POTENTIAL

At any potential point $P(\rho, \phi, \Lambda)$ on the surface of Phobos tidal forming potential V_t can be expressed as

$$(1)\quad V_t = \frac{GM}{a}\left(\frac{\rho}{a}\right)^2 \Big[P_2^{(o)}(\sin\phi)\, P_2^{(o)}(\sin\phi_o) + \frac{1}{3} P_2^{(1)}(\sin\phi)\, P_2^{(1)}(\sin\phi_o)\cos(\Lambda - \Lambda_o) + \frac{1}{12} P_2^{(2)}(\sin\phi)\, P_2^{(2)}(\sin\phi_o)\cos 2(\Lambda - \Lambda_o)\Big]\, ;$$

$GM = 42\,828.3 \times 10^9\ m^3\ s^{-2}$ is the areocentric gravitational constant,

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a = 9 378 500 the semi-major axis of the orbit of Phobos (the actual value), ρ, ϕ, Λ are the phobocentric spherical coordinates of the potential point (radius vector, latitude, East longitude respectively), ϕ_0, Λ_0 phobocentric latitude and longitude of the Mars' mass center respectively; $P_2^{(k)}(\sin\phi)$, k = 0,1,2 are the Legendre functions of the 2nd degree and kth order.

The orbital plane of Phobos is close to the plane of the Martian equator ($i = 1.02^o$) and the plane of the prime meridian of the ellipsoid of inertia of Phobos passes through the Mars' mass center (no librations of Phobos taken into account). That is why, we put $\phi_0 = 0$, $\Lambda_0 = 0$ and (1) can be simplified as [1]

$$(2) \quad V_t = \frac{GM}{a}\left(\frac{\rho}{a}\right)^2\left[-\frac{1}{2}P_2^{(o)}(\sin\phi) + \frac{1}{4}P_2^{(2)}(\sin\phi)\cos 2\Lambda\right].$$

2. LONG-TERM VARIATIONS IN THE GRAVITY POTENTIAL

Because of tidal decrease in the semi-major axis of the orbit of Phobos as [2]

$$(3) \quad \frac{da}{dt} = -2.68 \text{ m cy}^{-1} ,$$

gravity potential W of Phobos varies in time:

$$(4) \quad \frac{dW}{dt} = \frac{dV_t}{dt} + \frac{dQ}{dt} ;$$

Q is the potential of centrifugal forces

$$(5) \quad Q = \frac{1}{3}\frac{GM}{a}\left(\frac{\rho}{a}\right)^2\left[1 - P_2^{(o)}(\sin\phi)\right] .$$

Variation (4) at P reads

$$(6) \quad \frac{dW}{dt} = -\frac{GM}{a^2}\left(\frac{\rho}{a}\right)^2\left[1 - \frac{5}{2}P_2^{(o)}(\sin\phi) + \frac{3}{4}P_2^{(2)}(\sin\phi)\cos 2\Lambda\right]\frac{da}{dt} .$$

At critical value $\bar{a}$ gravity $g \doteq -\partial W/\partial\rho$ at P should equal zero, i.e.

$$(7) \quad \frac{GM}{\rho^2}\left\{1 + \sum_{n=2}^{\bar{n}}\sum_{k=0}^{n}\left[(n+1)\left(\frac{a_0}{\rho}\right)^n (J_n^{(k)}\cos k\Lambda + \right.\right.$$

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$$+ S_n^{(k)} \sin k\Lambda) P_n^{(k)}(\sin\phi)\Big]\Big\} = \frac{2}{3}\frac{GM}{\bar{a}^2}\left(\frac{\rho}{\bar{a}}\right)\Big[1 - \frac{5}{2} P_2^{(o)}(\sin\phi) +$$

$$+ \frac{3}{4} P_2^{(2)}(\sin\phi) \cos 2\Lambda\Big] ;$$

$Gm = 8.4 \times 10^5\ m^3\ s^{-2}$ is the phobocentric gravitational constant [3], $a_o = 11\ 905$ m the mean equatorial radius of Phobos [1]. Stokes parameters $J_n^{(k)}$, $S_n^{(k)}$ were computed from the Phobos topography [4] up to $\bar{n} = 8$ [1] assuming constant density; numerical values are given in ([1], Table 1).

3. CRITICAL VALUE OF THE SEMI-MAJOR AXIS OF THE ORBIT OF PHOBOS

Condition (7) can be specified for any $P(\rho, \phi, \Lambda)$; we put $\rho = \tilde{a}$, $\phi = 0$, $\Lambda = 0$; $\tilde{a} = 13\ 218$ m [1] is the largest semi-axis of Phobos:

(8) $$\bar{a}^3 = 3\tilde{a}^3 \frac{GM}{Gm}\Big\{1 + 3\left(\frac{a_o}{\tilde{a}}\right)^2\Big[-\frac{1}{2} J_2^{(o)} + 3 J_2^{(2)}\Big] +$$

$$+ 4\left(\frac{a_o}{\tilde{a}}\right)^3\Big[-\frac{3}{2} J_3^{(1)} + 15 J_3^{(3)}\Big] + 5\left(\frac{a_o}{\tilde{a}}\right)^4\Big[\frac{3}{8} J_4^{(o)} - \frac{15}{2} J_4^{(2)} +$$

$$+ 105 J_4^{(4)}\Big] + 6\left(\frac{a_o}{\tilde{a}}\right)^5\Big[\frac{15}{8} J_5^{(1)} - \frac{105}{2} J_5^{(3)} + 945 J_5^{(5)}\Big] +$$

$$+ 7\left(\frac{a_o}{\tilde{a}}\right)^6\Big[-\frac{5}{16} J_6^{(o)} + \frac{105}{8} J_6^{(2)} - \frac{945}{2} J_6^{(4)} + 10\ 395 J_6^{(6)}\Big] +$$

$$+ 8\left(\frac{a_o}{\tilde{a}}\right)^7\Big[-\frac{35}{16} J_7^{(1)} + \frac{945}{8} J_7^{(3)} - \frac{10\ 395}{2} J_7^{(5)} + 135\ 135 J_7^{(7)}\Big] +$$

$$+ 9\left(\frac{a_o}{\tilde{a}}\right)^8\Big[\frac{35}{128} J_8^{(o)} - \frac{315}{16} J_8^{(2)} + \frac{10\ 395}{8} J_8^{(4)}\Big] -$$

$$- \frac{135\ 135}{2} J_8^{(6)} + 2\ 027\ 025 J_8^{(8)}\Big]\Big\}^{-1} .$$

With numerical values above and in ([1], Table 1) we get

(9) $\bar{a} = 6\ 552.2$ km .

However, the process of desintegration of the body of Phobos will be not instantaneous. It will start at the equatorial zone where the zero-gravity will

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come first, and later on it will continue in the direction to the poles. It follows from (7), that at the latitudes satisfying the condition

$$(10)\quad 1 - \frac{5}{2} P_2^{(o)}(\sin\phi) + \frac{3}{4} P_2^{(2)}(\sin\phi) \lesseqgtr 0 \quad ,$$

i.e. at $-60^o > \phi > 60^o$, the zero-gravity state will never occur for any $a \neq 0$. It means, the process of the desintegration of the body of Phobos because of zero-gravity will be stopped in the polar zones $|\phi| > 60^o$. But after reaching critical value (9) the rate of the decrease in a will be much greater than current value (3), say, 20 m cy^{-1}, and after reaching (9) it will be increasing dramatically ([5], Fig. 1).

The tidal decrease in the orbital angular momentum of Phobos due to (3) should be compensated by the increase in the angular momentum of Mars resulting in the increase in its angular velocity of rotation as 3.23×10^{-27} rad s^{-2} [5]. The product of the Love number of Mars k_2 and the phase lag angle ε comes out as [5]

$$k_2 \varepsilon = 6.89 \times 10^{-4}$$

and the specific dissipation factor of Mars $Q = 725\ k_2$; with $k_2 = 0.08$ [6] $Q = 58$.

CONCLUSIONS

1. The Stokes parameters of Phobos computed up to $\bar{n} = 8$ make it possible to refine the solution for the critical value of the orbit of Phobos at which zero-gravity on the surface of Phobos occurs: $\bar{a} = 6\,552.2$ km.
2. The process of the desintegration of the body of Phobos because of the tides due to Mars will start at the equatorial zones and will continue in the direction to the poles, up to latitudes $\pm 60^o$.

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The future of earth tides measurements

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Being unfortunately unable to come to Potsdam this time, I wish to let the participants of this meeting to consider the table and graphs here attached.

1. A five years series of measurements obtained at Bruxelles with a GWR superconducting gravimeter gives a precision of four digits after the decimal point on the δ factor for the waves O_1 and K_1, quite good determinations of 14 other diurnal waves, specially for the resonant Ψ_1 wave.

   On the other hand, in a recent paper, Neuberg, Hinderer and Zürn (Geoph. J.R. astr. Soc. 91, 853-868, 1987) have shown that, amongst gravimeters, only the two superconducting instruments installed at Bruxelles and Frankfurt give a reasonable value for Q:2781 ± 543.
   (The other gravimeters giving negative values).

   In such conditions it appears to us that classical spring gravimeters should serve to another purpose than for long series in permanent observatories.

2. The Data Bank created by the International Center for Earth Tides (ICET) to day comprises 292 tidal gravity stations all over the world.

   110 of these stations have been installed by a cooperation of ICET with the Royal Observatory of Belgium in Asia, Australia , New Zealand, South Pacific, Africa and South America as temporary stations (six months operation).

   The interpretation of the results for the main waves O_1, K_1, P_1, N_2, M_2, S_2 are described by the vectorial graph of figure 1.

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The correlation of the observed residues $\vec{B}$ (B, β) with the oceanic attraction and loading effects $\vec{L}$ (L, λ) calculated on the basis of the Schwiderski maps looks remarkable as shown by figures 2, 3, 4. However the cosine components exhibit a larger dispersion and, consequently a lower correlation coefficient.

As indicated in our previous publications this cosine component appears to be correlated with heat flow anomalies. This is confirmed by the graph of figure 5 involving results at 139 stations where heat flow data were available : a positive value of X cos χ (bigger tidal deformation) corresponds to an anomalously high heat flow.

The heat flow is taken here as a nummerical parameter describing the tectonic situation.

The results show, in our opinion, that classical spring gravimeters can be very useful to check the validity of oceanic cotidal maps and to look for correlations of tidal deformations with tectonic situations in regions of abnormal heat flow (hot spots or cold spots).

One should recommend to organize series of measurements in such areas.

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Bruxelles Superconducting Gravimeter GWR

Tidal factor Delta = 1 + h - 3/2 k

Theoretical Model

Wave	Frequency degrees/hour	Amplitude Nanogal	YEAR I	II	III	IV	V	Five Years 1983 - 1987	Dehant 1066 A at Ø=51°
2Q1	12.854	894	1.1601	1.1685	1.1769	1.1823	1.1721	1.1727	1.1540
			143	115	119	124	120	57	
σ1	12.927	1.081	1.1604	1.1390	1.1543	1.1637	1.1728	1.1590	1.1540
			125	98	96	95	91	46	
Q1	13.399	6.749	1.1580	1.1540	1.1523	1.1528	1.1510	1.1538	1.1540
			19	15	15	15	15	7	
RO1	13.472	1.255	1.1331	1.1575	1.1388	1.1579	1.1659	1.1530	1.1540
			102	84	79	74	71	37	
O1	13.943	35.149	1.1546	1.1553	1.1553	1.1551	1.1550	1.15504	1.1540
			4	3	3	3	3	13	
τ1	14.025	458	1.1492	1.1663	1.1531	1.1556	1.1930	1.1639	1.1540
			284	232	250	287	290	123	
NO1	14.497	2.791	1.1661	1.1615	1.1544	1.1600	1.1646	1.1595	1.1537
			70	29	26	34	35	16	
CHi1	14.570	536	1.1730	1.1510	1.1361	1.1527	1.1339	1.1494	1.1536
			236	182	181	180	171	87	
π1	14.918	969	1.1693	1.1495	1.1538	1.1710	1.1800	1.1603	1.1505
			135	111	112	115	113	54	
P1	14.959	16.358	1.1546	1.1546	1.1564	1.1546	1.1558	1.15543	1.1489
			8	6	7	7	7	32	
K1	15.041	48.870	1.1414	1.1421	1.1421	1.1417	1.1417	1.14187	1.1334
			3	2	2	2	2	10	
PSI 1	15.082	428	1.2584	1.2250	1.2667	1.2128	1.2570	1.2288	1.2393
			325	264	266	270	270	127	
PHI 1	15.123	725	1.1909	1.2003	1.1973	1.1788	1.1905	1.1871	1.1695
			184	147	154	169	169	75	
θ1	15.513	515	1.1213	1.1518	1.1414	1.1379	1.1970	1.1561	1.1571
			249	191	179	180	177	89	
J1	15.585	2.788	1.1648	1.1668	1.1620	1.1495	1.1647	1.1611	1.1567
			42	34	37	39	38	17	
OO1	16.139	1.518	1.1574	1.1570	1.1620	1.1653	1.1647	1.1611	1.1561
			91	51	44	45	43	24	

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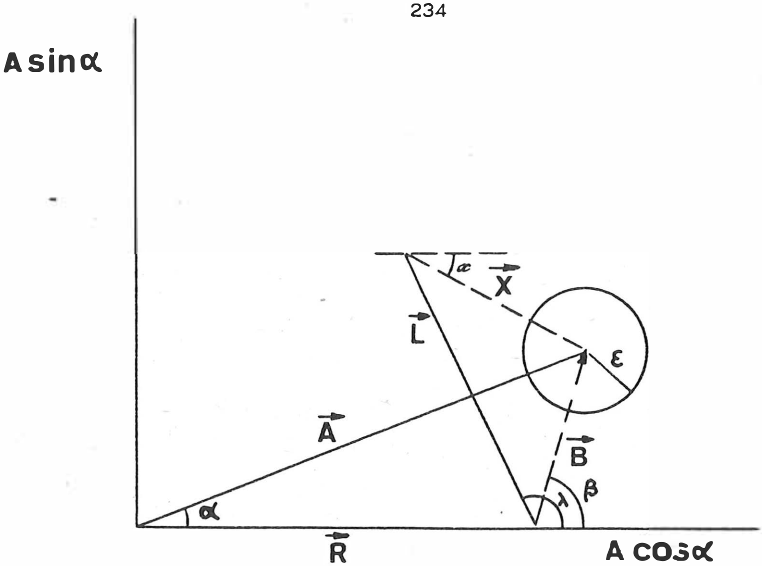

Figure 1 : $\vec{A}$ observed vector (A : amplitude, α : phase)

$\vec{R}$ tidal vector for an elastic non-viscous earth with liquid core but oceanless (R : amplitude, zero phase)

$\vec{L}$ ocean attraction and loading vector (L : amplitude, λ : phase)

$\vec{B} = \vec{A} - \vec{R}$ (B : amplitude, β : phase)

$\vec{X} = \vec{B} - \vec{L}$ (X : amplitude, χ : phase)

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ICET TIDAL GRAVITY DATA BANK

Correlation between vectors $\vec{B}$ and $\vec{L}$

292 stations
(including TWP/ICET)

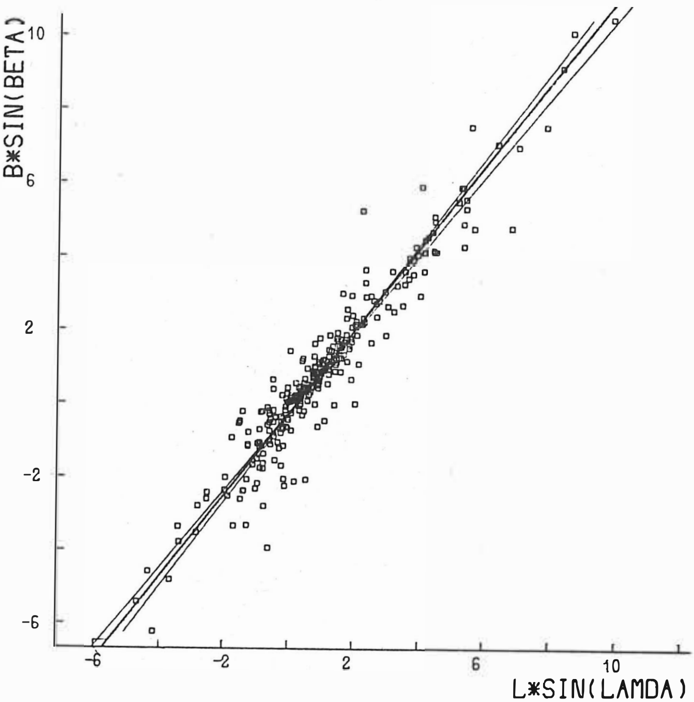

Figure 2.

$B \sin \beta = -0.341 + 1.125 \, L \sin \lambda$ (μgal)

correlation coefficient $k = 0.956$

standard deviation $\sigma = 0.68 \, \mu gal$

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ICET TIDAL GRAVITY DATA BANK

Correlation between vectors $\vec{B}$ and $\vec{L}$

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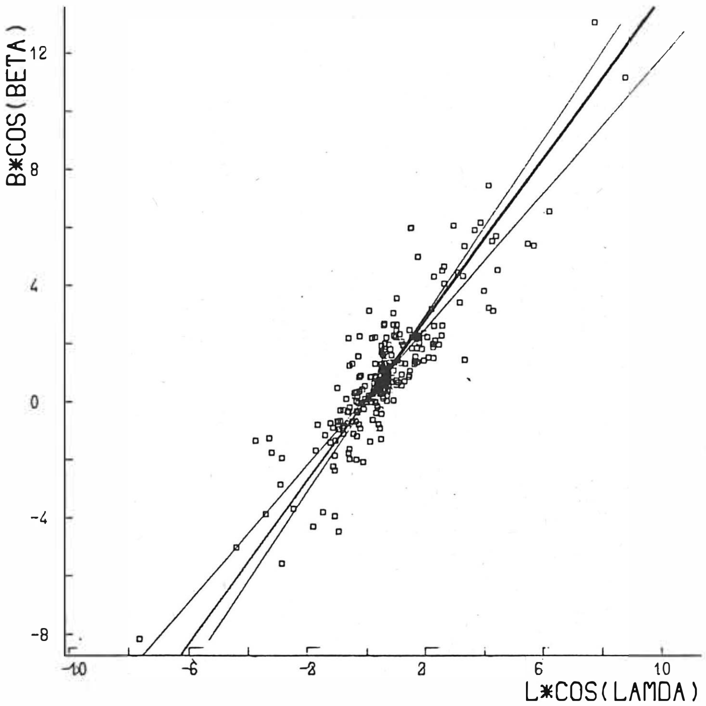

Figure 3.

$B \cos \beta = -0.160 + 1.400\ L \cos \lambda$ (µgal)

correlation coefficient $k = 0.878$

standard deviation $\sigma = 1.04$ µgal

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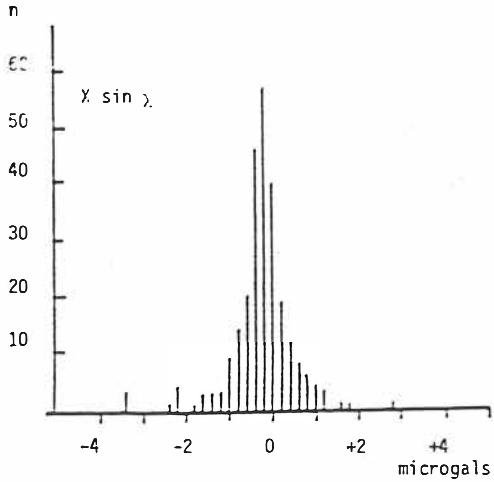

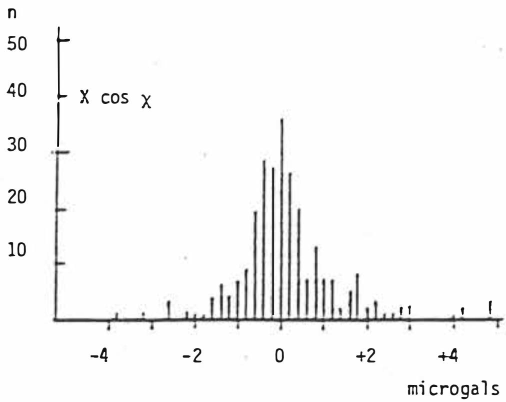

Fig.4. Histograms of the tidal residues for the semi diurnal tide M_2
220 tidal gravity stations
X sin χ: quadrature
X cos χ: in phase
n : number of stations

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ICET TIDAL GRAVITY DATA BANK

Correlation between the residue X cos and heat flow

(139 stations)

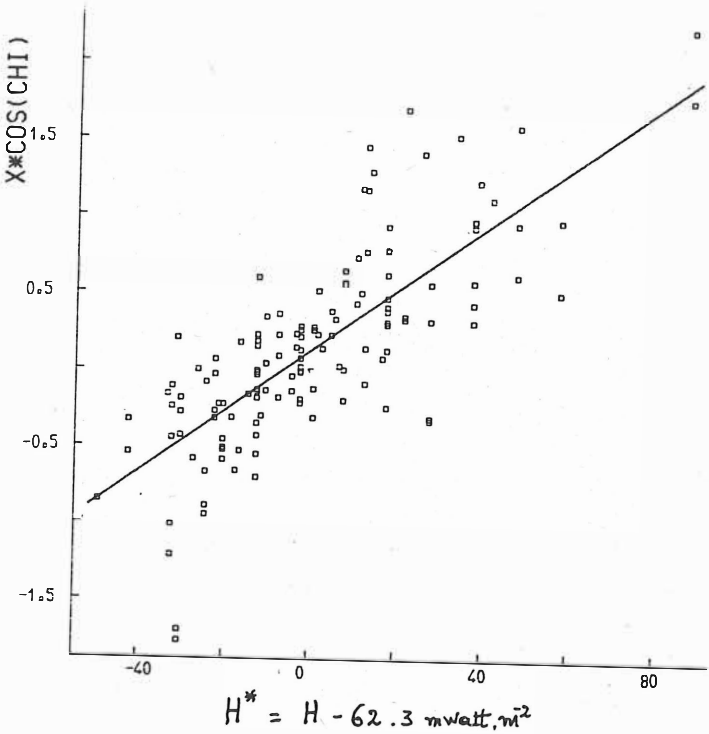

Figure 5.

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THE RESULTS OF THE EXTENSOMETRIC OBSERVATIONS IN VYHNE

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1. Introduction

In the Carpatho-panonian region a network of the extensometric stations was built which consists of the stations Vyhne /Slovakia/, Budapest and Beregovo /Carpatho-Ukraine/. Carpatho-panonian region belongs to the most active tectonic parts of the Europe which is characterized by recent movements of the Earth´s crust, high activity of the tectonic movements, anomalously hight heath flow and high seismicity. For these reasons the research of this region is interesting not only from the point of view of solving the scientific tasks but also for the aplied geophysics.

The purpose of the extensometric measurements in the Carpatho-panonian region is the study of the regional tectonic processes. In the measurements on each of this stations are included the influences of the local effects /cavity, topographic and geological effects/. To obtain the informations on regional level it is necessary to gain a complex analysis of all the data from the network of the extensometric stations as well as the data of the geological tectonic research. This paper is only the first stage in the investigation of the regional characteristics. This study is dedicated to the analysis of the measurements on the tidal station in Vyhne and to the variations of the slow deformations derived from the extensometric measurements in connection with regional tectonic. Extensometric measurements provide the informations about the global processes as liquid core resonance effects.

The quartz extensometer on the tidal station Vyhne was built in cooperation of the O. Yu. Schmidt Institute of the Physic of the Earth of the Soviet Academy of Sciences and the

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Geophysical Institute of the Slovak Academy of Sciences according to the working plan of KAPG /Cooperation of Academies of Socialist Countries on the Field of Planetary Geophysics/. Tidal station Vyhne is located in the region of West Carpathians in "Štiavnické vrchy" mountains some 10 km from Banská Štiavnica. The geographic coordinates of the tidal station are: geographic latitude $\varphi = 48^{O}29'52''$ N, geographic longtitude $\lambda = 18^{O}49''48''$ E, height above sea level h= 420 m.

The underground gallery at which the measurements are performed is breaked in granit massif cutted by local cracks of vulcanic origin in the north - east direction and belong to a system of regional faults.

Extensometer was installed at the distance of 120 m from the entrance of the gallery. The relative depth of the instrument under the earth surface is 50 m. The extensometer is cutting across the line of one of local faults. The azimuth of the quartz rod is $55^{O}27''57''$ and it´s basis is 20,5 m long.The relative humidity in the observations areas is 80 % and the mean annual temperature is $6{,}5^{O}$C with seasonal changes between summer and winter about $0{,}2^{O}$C. The displacement at the free end of the measuring system is indicated by optical /sensitivity 5.10^{-9} of the lenght per millimetre/ and photoelectric /5.10^{-10}/ recording systems with analogue recorder.

2. The analysis of the slow deformations

Fig. 2 shows the curve of the variation of slow deformations derived from the extensometric measurements on tidal station in Vyhne for the period between November 1, 1984 and December 31, 1987. By comparing the curve of the slow deformations and the curve of the thermoelastic deformations [1] we can deduce that the annual variation of this deformations /about 7.10^{-7}/ is of the thermoelastic origin. Except of this deformations there was registred also the irreversible deformation which corresponds with the dilatation of the rock. Total irreversible deformation during considered period was about 14.10^{-7}, i.e. the rate of the slow irreversible deformation was 5.10^{-7} per year.

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We shall study the problem of the relation between the deformation processes registred on the tidal station Vyhne and the regional tectonic. Tectonic map of the Carpatho-panonian region is given on the Fig.1 [2] . This region was formed in Neogene; in the younger tectonic epoch, i.e. in the last 10 million years the activisation of the tectonic processes in the region of the Panonian basin was observed. The mountains surrounding this region were developed in the conditions of the tangential compression. Panonian basin was shaped in the conditions of dilatation or warp. The character of the Earth´s crust in Pannonian basin is similar to the ocean type of the crust.

At present there exist still various hypotheses on the character of the processes which determine the development of the Carpatho-panonian region. The hungarian geologist Z. Balla expressed a hypothesis which is based on the theory of the litospheric plates [3]. In accordance with this hypothesis the existence of the regular circular structure of this region requires the activity of the axialsymetric tectonic sources. Such source can be the convective flow comming out from the Panonian basin whose horizontàl compensating branches are spreading and are reducing the earth´s crust in the Panonian region [4-6]. The hypothesis of taphrogenesis /remake of the continental type of the crust to ocean type in the upper mantle/ also requires expansion of the tectonic process from the centre of the Carpatho-panonian region to its borders. Conforming with this hypothesis Panonian basin was formed in conditions of the warp [7,8].

Provided that the irreversible monotone increasing deformation of the rocks on the tidal station Vyhne has tectonic origin, the result of the extensometric measurements are in agreement with the ideas about the dilatation of the earth´s crust in the Panonian basin. The rate of the dilatation 4-5. $.10^{-7}$ per year is not large. We can explain this fact by the position of this station which is on the border of the Panonian basin. The dilatation in the central parts of this region should be more intensive. Preliminary results of the extensometric measurements on the station MATYASHEGY /Budapest/ showed that the dilatation registred on this station is much

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higher as on the tidal station Vyhne [9]. It is in accordance with Balla´s hypothesis.

3. The analysis of the tidal deformations

In [10] was shown that there exists the correlation in the distribution of the zone of the anomalously gravimetric tides and great tectonic structures of the different level of the mobility. The positive anomalies dominate in the regions of the "burning" astenosphere which are characterized by the high heath flows and young basalt vulcanism. The Panonian basin and West Carpathians belong to such regions.

On the tidal station Vyhne tidal waves of linear deformations are registred. This type of tides contain more intensive influence of the inhomogenities of the Earth´s crust as the gravimetric tides. For that reason we can assume that in the regions of West Carpatians and Panonian basin the amplitudes of the tidal waves will be greater as their mean values for the Earth.

The analysis of the tidal deformations was made using Venedikov´s methods M65 and M74. The measurements registred by optical recording system in the period between July 6, 1984 and December 31, 1986 were analysed using M65 method and the observations registred by photoelectric recording system in the period between September 21, 1984 and January 19, 1987 were analysed using M74 method. The results obtained by both methods of the analysis and the theoretical amplitudes and phases of the main tidal waves calculated for $h = 0{,}611$ and $\ell = 0{,}083$ are given in Table 1. In the Institute of the physics of the Earth of the Soviet Academy of Sciences the extensometric measurements from the tidal station Vyhne were analysed also using Percev´s method. This results are given in [11].

The amplitudes of the tidal waves computed from the data of various periods, using different methods of the analysis and obtained from different recording systems differ by 10 %. This differences are caused by the systematic errors in the determination of the scale coefficient of the optical and photoelectric recording systems. The differences between the observed tidal parameters and their theoretical values could

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be caused by the influence of the indirect effects of the ocean tides, regional inhomogenities, local structure, topographic or cavity effects. In the first line of the Table 2 the theoretical amplitudes and the phase differences of the waves M_2 and O_1 for the elastic sphericsymetrical Earth are given. B.P.Percev and M.V.Ivanova computed the tensor of the surface deformations on the tidal station Vyhne caused by the ocean tides. In the second line of the Table 2 are given corrected values of the tidal parameters considering the indirect effects of the ocean tides. In the third line of the Table 2 are given the amplitudes and the phases of the tidal waves M_2 and O_1 corrected by topographic effect. Preliminary estimation of the influence of the topographic effect was made by Harrison´s model for a V-shaped valley with tides sloping at 24° [12].

Increasing of the tidal deformations could be caused also by the deflection of the instrument´s axis from the axis of the gallery. The angle of this deflection is difficult to determine because the gallery has a curved axis. We estimated this angle within limits $2,9^{\circ}$ and $5,7^{\circ}$. The deformation $e_{x'x'}$ in the direction of the axis x'(x' is the axis of the extensometer) is given by :

$$e_{x'x'} = e_{xx} \cos^2\alpha + e_{xy}\cos\alpha \sin\alpha + e_{yy} \sin^2\alpha \qquad (1)$$

where e_{xx}, e_{yy}, e_{xy} are the components of the tensor of deformation, the x-axis is directed along the gallery and y transversaly of the gallery, α is angle between the axes x and x'. The component of the deformation e_{yy} perpendicular to the axis of the gallery is 2-3 time greater as its value in undivided rock [12]. Considering this fact and using the theoretical values of the tidal deformations we can compute $e_{x'x'}$ for the angle $\alpha = 2,9^{\circ}$ and $\alpha = 5,7^{\circ}$. For the angle $\alpha = 2,9^{\circ}$ the amplitudes of the waves M_2 (O_1) are increasing by 0,1 % respectively 0,4 % and the phases by $0,5^{\circ}$ respectively $0,1^{\circ}$. For the angle $\alpha = 5,7^{\circ}$ the amplitudes of the waves M_2 (O_1)were increased by 0,4 % respectively 1,5 % and the phases by $1,6^{\circ}$ respectively $0,5^{\circ}$.

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The theoretical values of the amplitudes and phase differences are given in the lower line of the Table 2. These values were obtained after eliminating all considered indirect effects. By comparing theoretical and observed values it can be concluded that the observed mean amplitude of the wave M_2 is by 18 % greater as its theoretical value and the observed and theoretical amplitude of the wave O_1 are identical within limits of r.m.s.

4. Liquid core resonance effect

The informations about interaction between core and mantle of the Earth which are presented in the liquid core resonance effects in the Earth´s tides are contained. In the past the tidal deformations were not used for the study of this resonance effects because they were influenced by inhomogenities of the Earth´s crust.

In [13] was shown that in the specific combination of the Love´s number h and Shida´s number ℓ of the waves O_1 and K_1 the influence of the inhomogenities is not contained and it is possible to use it for the study of the resonance effects. This combination is ration $\eta(O_1)/\ \eta(K_1)$ which we mark R, where

$$\eta(O_1) = h_1 - 2\ell_1\ (1 + \cos^2\alpha)\ ,$$
$$\eta(K_1) = h_2 - 2\ell_2\ (1 + \cos^2\alpha)\ . \qquad (2)$$

Here α is the azimuth of the extensometer and h_1, ℓ_1, h_2, ℓ_2 are the parameters of the waves O_1 and K_1. If this effect is not observed the parameters h and ℓ for both waves are equal and R = 1. If the resonance effect is discovered in the wave K_1, the ratio R increases by 20-40 %.

The theoretic values h and ℓ for the waves K_1 and O_1 for the Molodensky´s and Wahr´s models of the Earth, the combination $\eta(O_1)$ and $\eta(K_1)$ for $\alpha = 0^o$ (NS), $\alpha = 90^o$ (EW) and the azimuth of the extensometer on the tidal station in Vyhne α = $= 55^o27'57''$ are given in the Table 3. The observed wave O_1 can be written as follows :

$$A(O_1)\cos(\ \omega_1 t + \varphi_1) = A(O_1)[\cos\varphi_1\ \cos\omega_1 t - \sin\varphi_1\ \sin\omega_1 t] \quad (3)$$

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where $A(O_1)$ is observed amplitude of the wave O_1, φ_1 is the phase difference of the wave O_1, ω_1 is the frequency of this wave. Eq. (3) can be expressed as :

$$A(O_1)\cos(\omega_1 t + \varphi_1) = E\ \{[h_1 - 2\ell_1(1 + \cos^2\alpha)]\ \sin 2\Theta\ \cos\ \omega_1 t - \\ - 2\ \ell_1 \sin 2\alpha\ \sin\Theta\ \sin\omega_1 t\} \qquad (4)$$

where Θ is colatitude, E is the combination of the astronomic elements of the wave O_1 which is $E = 15{,}863.10^{-9}$ [14]. Comparing (3) and (4) we obtain :

$$A(O_1)\cos\varphi_1 = E\ [h_1 - 2\ell_1\ (1 + \cos^2\alpha)]\sin 2\Theta \qquad (5)$$

and analogical for the wave K_1 :

$$A(K_1)\cos\ \varphi_2 = 1{,}407\ E\ [h_2 - 2\ell_2\ (1 + \cos^2\alpha)]\ \sin 2\Theta \qquad (6)$$

where $A(K_1)$, φ_2 are observed amplitude and phase difference of the wave K_1.

Using the observed amplitudes and phases (see Table 1) we can determine the values $\eta(O_1)$, $\eta(K_1)$ and the ratio R which are given in the two last lines of the Table 3. It was shown that the ratio R is by 15-20 % higher than 1, namely the measurements of the tidal deformations on the station Vyhne confirm the existence of the liquid core resonance effects. The ratio R is lower as the predicted value for the Molodensky´s and Wahr´s models of the Earth. The estimation of the ratio R from the world network of stations [13] was lower by 12 % as the theoretical values.

5. Conclusion

From the analysis of the extensometric measurements on the tidal station in Vyhne resulted that the irreversible deformations can be interpreted in the frame of recent dilatation of the Earth´s crust in Panonian region. The tidal deformations are characterized by a small positive anomalies which

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can be explained by a high mobility of this region. From the parameters of the tidal waves K_1 and O_1 the liquid core resonance effects were confirmed.

Fig. 1 Tectonic scheme of the intra - Carpathian basins and the associated folded arc : 1 – platforms, 2 – Outer Carpathian flysh belt, 3 – molasse of foredeep, 4 – – elevations with pre - Tertiary complexes, 5 – volcanites.

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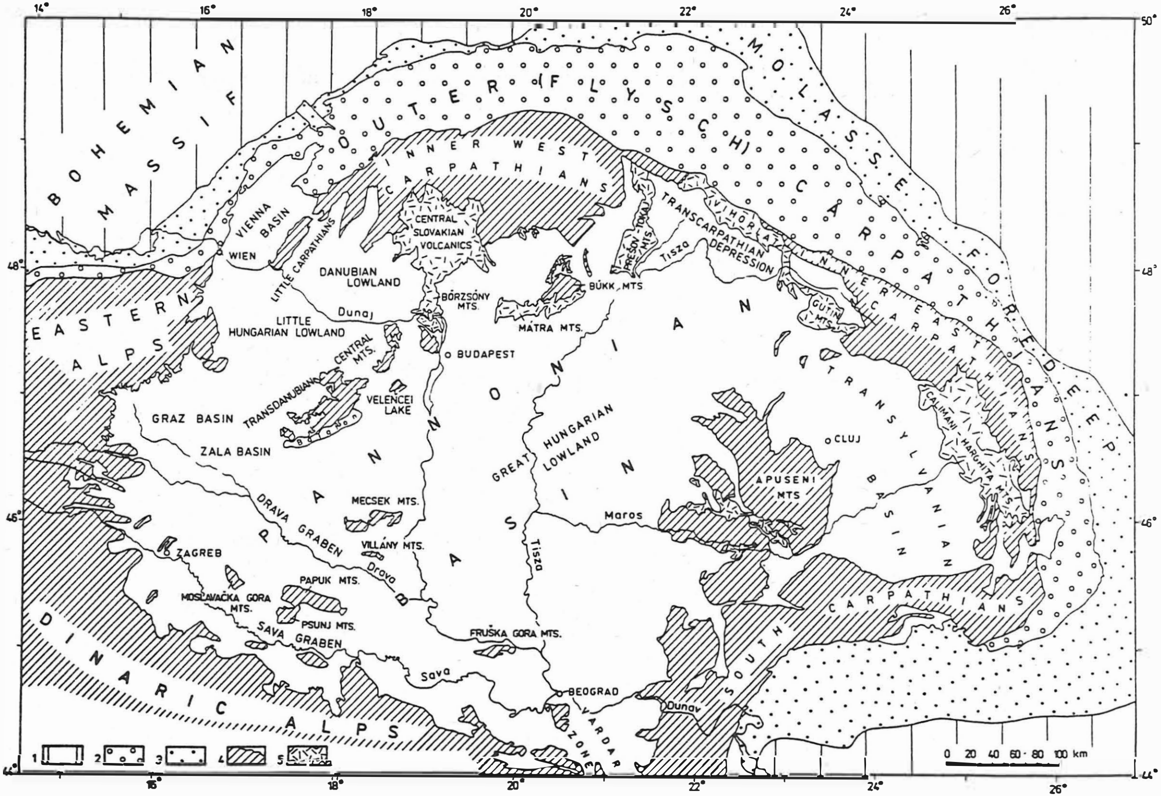
Fig. 1



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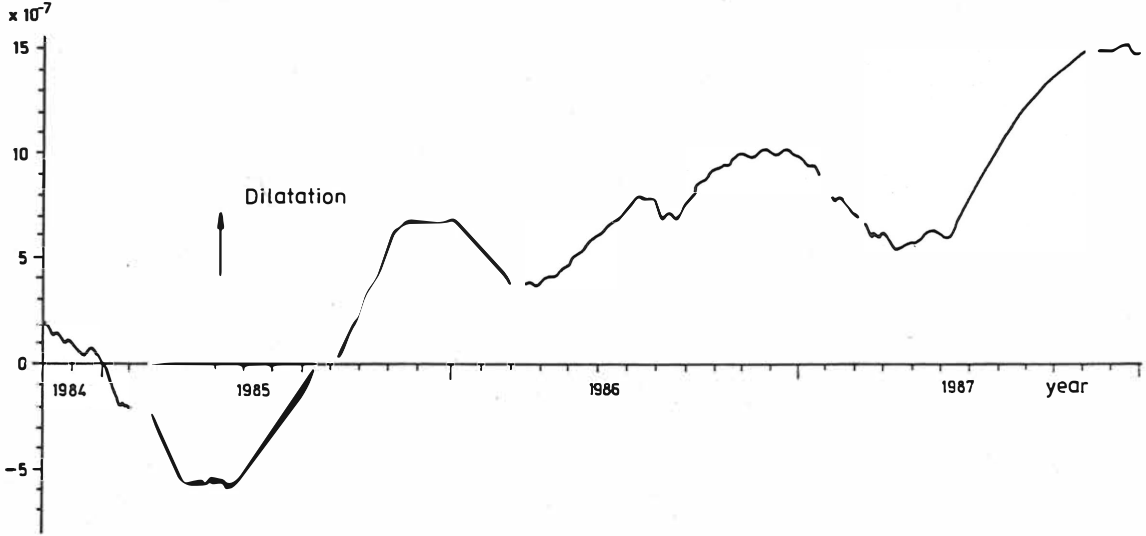

Fig. 2. Time variations of the slow deformations at the tidal station Vyhne

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Table 1 Results of the analysis of the extensometric measurements at the tidal station Vyhne.

Wave group	Number of waves	Venedikov´s M74 method Photoelectric registration		Number of waves	Venedikov´s M65 method Optical registration		Theoretical values	
		Amplitude.10^9	Phase		Amplitude.10^9	Phase	Amplitude.10^9	Phase
Q_1	65	1,293 ± 31	23,6° 6,4°	30	1,453 ± 31	19,4° ± 8,5°	1,22	
O_1	26	7,326 ± 18	18,0° 1,2°	26	6,487 ± 18	19,3° ± 1,1°	6,38	14,8°
K_1	33	9,173 ± 17	22,1° 1,0°	33	7,759 ± 21	22,2° ± 1,0°	7,14	19,2°
N_2	24	1,762 ± 14	-38,6° 2,6°	24	1,494 ± 11	-37,9° ± 2,3°	1,20	-46,0°
M_2	26	7,630 ± 8	-44,1° 0,5°	26	7,072 ± 9	-44,8° ± 0,5°	6,22	-46,0°
S_2	47	4,053 ± 11	-38,2° 1,0°	21	3,806 ± 12	-40,1° ± 0,8°	2,89	-46,0°
M_3	17	0,055 ± 48	-52,2° 43,8°	16	0,062 ± 42	-61,2° ±40,3°		

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Table 2 Theoretical amplitudes and phases of the waves M_2 and O_1 on the tidal station Vyhne.

	M_2		O_1	
	Amplitude	Phase	Amplitude	Phase
Theoretical value	$6{,}22.10^{-9}$	$-45{,}5^{o}$	$6{,}38.10^{-9}$	$19{,}2^{o}$
Theoretical value corrected for indirect effects of the ocean tides	$6{,}10.10^{-9}$	$-48{,}2^{o}$	$6{,}36.10^{-9}$	$21{,}1^{o}$
Theoretical value corrected for topographic effect	$6{,}41.10^{-9}$	$-48{,}2^{o}$	$6{,}68.10^{-9}$	$21{,}1^{o}$
Theoretical value corrected for cavity effect	$6{,}44.10^{-9}$	$-46{,}6^{o}$	$6{,}78.10^{-9}$	$21{,}6^{o}$

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Table 3 Dynamic effects of the liquid core

Model	Wave	Azimuth	h	ℓ	$\eta(O_1)$	$\eta(K_1)$	$\eta(O_1)/\eta(K_1)$
Molodensky´s model	O_1		0,614	0,0809			
	K_1		0,535	0,0837			
		0°			0,2904	0,2002	1,45
		90°			0,4522	0,3676	1,23
		$55,5^{\circ}$			0,4003	0,3139	1,275
Wahr´s model	O_1		0,603	0,0841			
	K_1		0,520	0,0868			
		0°			0,2666	0,1728	1,54
		90°			0,4348	0,3764	1,25
		$55,5^{\circ}$			0,3820	0,2919	1,31
Observed values Optical registration		$55,5^{\circ}$			0,3422	0,2844	1,20
Photoelectric registration		$55,5^{\circ}$			0,4431	0,3837	1,15

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TEMPORAL TRENDS in the VARIATIONS of TIDAL PARAMETERS

by Hans-Jürgen Dittfeld

Abstract
Time series of different gravimeters at several sites are analysed by uniform methods. Evident long-term trends of the amplitudes and phases of the resulting tidal parameters are discribed.
Especially for the waves M1,N2 and L2 very similar trends are observed, independently of the measuring conditions and of the analysis methods.
Object of the investigations are the measurements of two ASKANIA-GS15 and two GWR - superconducting gravimeters.
The considered variations are not confirmed by the Earth models and their reality is frequently called in doubt. Therefore the significance of the variations is critically discussed.

Zusammenfassung
Gravimetrische Gezeitenmessungen an vier Stationen wurden mit einheitlichen Methoden analysiert, wobei sich augenfällige Langzeitvariationen einiger Ergebnisparameter zeigten, die für verschiedene Stationen und Meßsysteme erhebliche Ähnlichkeiten aufweisen.
Unabhängig von Analysenmethoden und Beobachtungsbedingungen gilt dies besonders für die Wellengruppen M1,L2 und N2.
Derlei Variationen ergeben sich nicht aus den gültigen Erdmodellen und werden oft in Zweifel gezogen. Deshalb wurde die Signifikanz dieser Variationen besonders kritisch untersucht.
Der Arbeit liegen die Langzeitreihen von zwei ASKANIA-GS15 - und zwei Supraleitgravimetern zugrunde.

Already eight years ago we published first remarks concerning the temporal variations of tidal parameters within the Potsdam gravimetric results, giving a first impression of our intentions /1/. Temporal variations are also observed by RICHTER /3/ and VOLKOV et.al. /4/ for the stations Bad Homburg/FRG and Sofia/Bulgary respectively.

Of course such kind of variations are not predicted by the Earth models and so these results have been called in doubt in a number of discussions. But there seems to be more information in the results as generally supposed.

So we have been looking for temporal trends of the parameters within corresponding series of other stations and we found remarkable similarities with the trends inside the 12.5 years part of our series evaluated at present.

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In the first picture is represented the amplitude factor of the wave L2. The points are showing results of overlapping analyses by CHOJNICKIs method A15K using the error estimation based on residuals. The analysis period is always about 480 days (16 monthes), the shift is 180 days or six monthes. A resolution of nineteen wave groups was used. There are compared four stations. At Potsdam/GDR and Pecny/CSSR are registrating the Askania GS15 gravimeters No.222 and No.228 but in Brussels/Belgium and Bad Homburg/FRG there are superconducting once (GWR type). The general trend found for these very different measurements is nearly the same.

The slope downward in 1983/84 is good confirmed by both the superconducting gravimeters and the result of the registration at Potsdam. Comparing the L2 DELTA factors resulting from the total series at Bad Homburg (1981/84) and Brussels (1982/86) we found a difference of about 10%. From former publications 3.9 or 5.1% difference may be calculated. These discrepancies can be fully explained by the temporal variations at Fig.1: The Bad Homburg series is measured mostly near to the maximum but the Brussels measurement is passing through the minimum of 1984. So the temporal variations may be the reason for different results of very precise measurements if these are not carried out contemporary.

Naturally the other series are not so long as in Potsdam. But also by parts the general trend is very similar if constant deviations are neglected which are caused by different influences of the indirect effects and the calibration problems of the superconducting gravimeters. So for instance follows from the averaged relations of the amplitude factors of seven main waves that the calibration factor of the gravimeter GWR TT40 at Bad Homburg is about 0.83% smaller than that of the instrument in Brussels. The corresponding relations to the Potsdam series are -0.55%(Bad Homburg) and +0.28%(Brussels) respectively. In the considered frequency bands the inner accuracy of these latter instruments is higher than those of the Potsdam series by a factor of about 1.5.

The Figure 2 represents the phase shift of the same tidal wave. The inner accuracy of the Pecny analyses is practically equal to that of the Potsdam series. But the Pecny series was often interrupted and therefore there seems to be a little bit more noise. Thats because of the seasonal effects. Owing to the missed contributions of not existing parts of the measurement the result is shifted somewhat in the direction towards the result of fulfilled seasons. So we have a scattering in comparison with uninterrupted series. The last point of the Pecny curve connected with a broken line represents the result of a yearly analysis after a break of two years in the registration but it is also situated within the general trend.

Fig.3 is a corresponding representation for the tidal wave N2 which has an amplitude of about six microgal at Potsdam. The variation in amplitude is much more significant and amounts to about two percent corresponding to nearly nine times the error of a single result. It is impossible to explain such variations by imperfections of the Cartwright-Tayler-Edden development of the tidal potential used for the analysis because the contributions of not regarded waves are almost

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very small.

At the picture for the phase lag of the wave N2 very good is to be seen the decrease of the influence of the indirect effect of the ocean from near the coast (Brussels) to Pecny station which is situated near Prague. But without mentioning these differences the long term trends are very similar again.

So our statements concerning the temporal variations are consequently supported by the results of the investigations of the other series.

To be sure that these features are not a effect of the analysis method our series was also analysed by Prof.VENEDIKOV using his VM74 method. At Fig.4 are pictured the results of independent (not overlapping) yearly and biennial parts of the measurement. The other curve is showing the results of the CHOJNICKI method like on the foregoing Figures. The different level in the case of the amplitude factor is originated by the inertial effect which is corrected by the VM74 programme but not during the CHOJNICKI analysis. Both the methods are giving similar trends.Therefore the variations are not a failure of a singular method nor a phenomenon of a singular station.

The significance of the results was already discussed in /2/. (From other comparisons was estimated that for such kind of investigations a particular measuring accuracy is needed as for instance characterised by a mean square error of Mzero smaller than 1.0 microgal in the CHOJNICKI analysis.) Now we have these new results underlining the assertion concerning the temporal variations of the tidal parameters. Naturally these effects are very small and the errors are big in comparison with the variations itself. That holds also for the best series available at present. So a real congruence of the curves of different stations is not to be expected even if the local effects may be excluded. Just therefore the presented features are extremely astonishing.

We have been looking for especially remarkable trends and found these for the constituents M1, N2 and L2 which are connected in the development of the tidal potential with the perigeum of the moon.

A special software system was developed by our colleague Mrs.HARNISCH for the presentation of these variations inside the DELTA-KAPPA plane. So we get pictures showing the variation in amplitude as well as in phase at the same figure.

In the figures 5, 6 and 7 is demonstrated the way of the end of the DELTA-KAPPA vector during the time. Close to the dots is marked the central month of the corresponding analysis.

These figures for L2, N2 and M1 are showing a quasi circular behaviour having a comparable clear period : The vector returns to the vincinity of the starting point after nearly ten years. The total variations are 97; 110 and 252 nanogal respectively. Here we have some new experiences resulting from a fourteen years observation which was seldom interrupted (13 gaps only) and carried out almost without changing the used instruments.

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Until now we don't have a determined explanation for the outlined features but we warrant for the significance of these variations. Corresponding pictures are available for nineteen constituents of the tidal potential.

The ten years period of the mentioned tides is within the error borders near to the eleven years sun freckles cyclus as well as near to the half of the 18.6 years period of the moon. But the explanation may lie also in the interferences of diurnal and semidiurnal features connected with non tidal amplitude variations of M2 or S1 acting on the neighboured bands. References therefore are already visible in the spectrum of the residuals /5/. In the figures 5, 6 and 7 the vector of L2 is turning **counter-clockwise** but for N2 and M1 we see a **clockwise** rotation. As pointed out by SCHWAHN et al /6/ the opposite rotation of the N2 and L2 vectors is a proof therefore that the variations are caused by a modulation of the M2 main wave which is producing satellites in the amplitude spectrum situated (symmetrically to the M2 line) in the N2 and L2 wave group respectively.

For the preparation of the showed pictures was needed a constant and precise measurement of about fourteen years. Of course in shorter series are such kind of long acting phenomena much more difficult to discover.

These variations are open for interpretation. First ideas are mentioned but other ideas for which we are waiting may be more acceptable.

One of the main tides, almost hold for very constant, is O1. It was making a flight between 1979 and 1982 (Fig.8). This variation was amounted to about 0.51% corresponding to 176.6 nanogal. That means that for instance yearly measurements carried out in 1977/78 or in 1981/82 will have a different result also for one of the biggest tidal waves.

In our experience the most stable wave of the tidal spectrum is M2. It shows anomalies of about 0.15 degree of the phase only, registrated in 1982 and practically not connected with an amplitude variation (Fig.9). The total M2 variation is about 95 nanogal or 0.28%.

To avoid misunderstandings - these latter are results of the Potsdam series only not ever underlined by corresponding results of the other stations. To compare several stations on this type of pictures is not yet possible at present.

Furthermore shall be remarked that the existence of other variations can be expected: If they are shorter as the analysis interval of 480 days used for the investigations they will not be clearly detected by the presented methods.

In every case it is shown that the tidal parameters are not so constant as ever believed. Therefore we have to measure and we have to observe the tidal parameters in order to get their real values for every epoch in which accurate tidal prognoses are needed.

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Finally is listed the result of the 12.5 years tidal measurement at Potsdam. The last column gives the deviations against the WAHR model which are between 0.74 and 1.37%.

Gravimetric Observatory Potsdam / GDR
GS15 No.222 1974 - 1986
CHOJNICKI A15K
N = 103 640 hrs. Mzero = 0.603 microgal

WAVE	DELTA	KAPPA	AMPLIT.	DELTA	KAPPA	DT/DT(O1)	MODEL %
	Observation		Indirect	effect	corrected	(SCHWIDERSKI/ICET)	
Q1	1.1503	-0.24	6.6594	1.1560	-0.056	0.99953	0.790
	14	07					
O1	1.1522	0.02	34.7984	1.1565	-0.086	1.00000	0.838
	3	01					
P1	1.1519	0.33	16.1101	1.1504	0.189	0.99474	0.746
	6	03					
K1	1.1398	0.16	48.1394	1.1376	0.041	0.98367	0.951
	2	01					
N2	1.1764	1.93	6.2238	1.1561	0.092	0.99964	0.942
	7	04					
M2	1.1845	1.20	32.5012	1.1559	-0.212	0.99944	0.922
	1	01					
S2	1.1878	0.40	15.1873	1.1609	-0.002	1.00383	1.366
	3	01					
K2	1.1822	0.17	4.1172	1.1564	-0.114	0.99991	0.969
	11	06					

DT(O1) - DT(K1) =			
	0.0124	0.0189	0.0200
DT(O1) - DT(M2) =			
	-0.0323	0.0006	0.0016

Acknowledgement

For the hourly values of the series measured at Pecny, Brussels and Bad Homburg we are very indebted to Dr.Zd.Simon / VUGTK Zdiby - CSSR, Dr.B.Ducarme / ORB - Belgium and to Dr.B.Richter / IfAG, Frankfurt/M - FRG respectively.
Thanks are also du to Mrs.M.Harnisch for programming and preparation of the vector scetches as well as to Mr.W.Altmann who supported the tidal observation at Potsdam with continuity and care.

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Figure captions

Fig 1 Temporal trends of the L2 amplitude factor at different stations

Fig. 2 Corresponding trends of the L2 phase lags

Fig. 3a Temporal trends of the N2 amplitude factor

Fig. 3b Temporal trends of the N2 phase lag

Fig. 4a Trends of the N2 amplitude factor in Potsdam calculated by different methods

Fig. 4b Corresponding trends of the L2 phase lag

Fig. 5 The variation of the L2 vector at Potsdam

Fig. 6 The variation of the N2 vector at Potsdam

Fig. 7 The variation of the M1 vector at Potsdam

Fig. 8 The variation of the O1 vector at Potsdam

Fig. 9 The variation of the M2 vector at Potsdam

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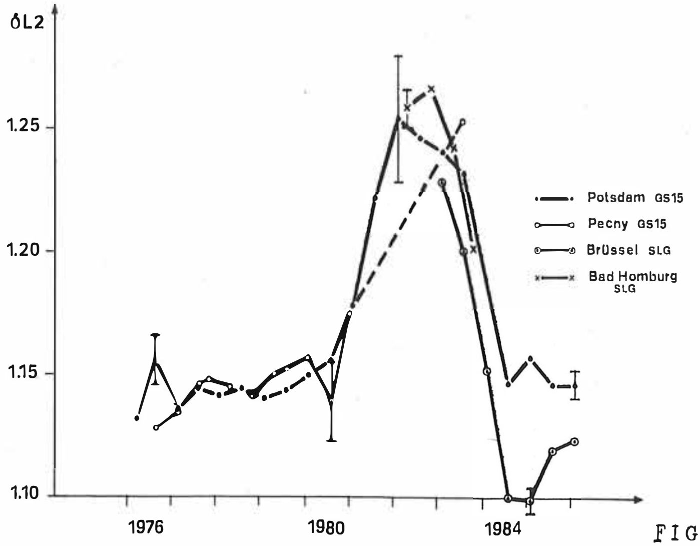

FIG. 1

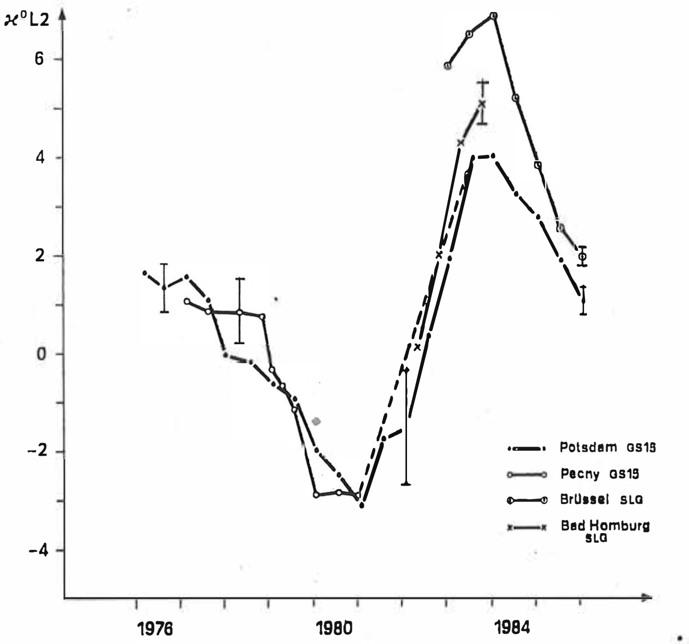

FIG. 2

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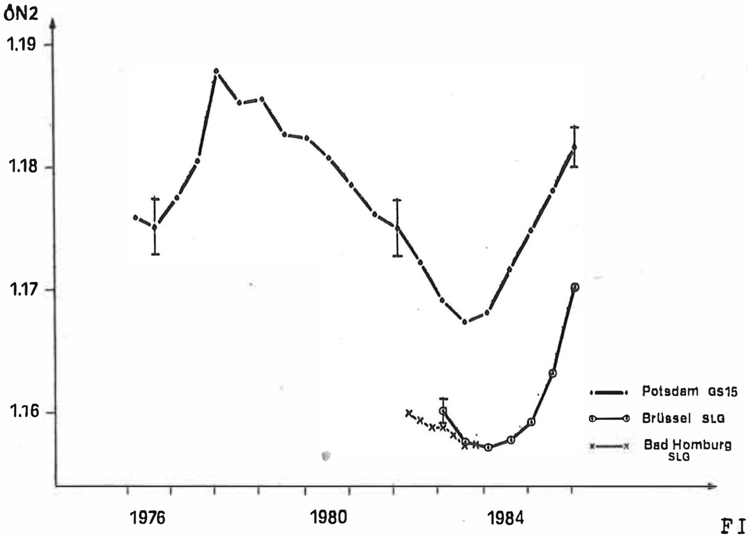

FIG. 3 A

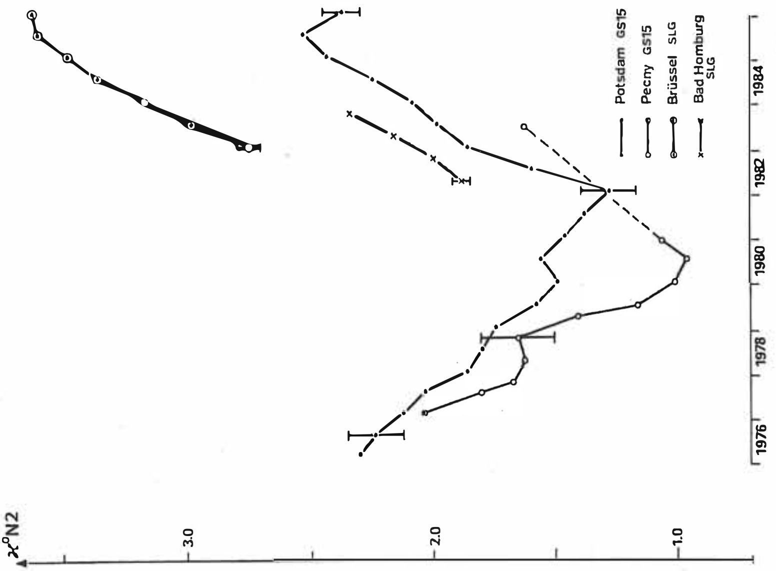

FIG. 3 B

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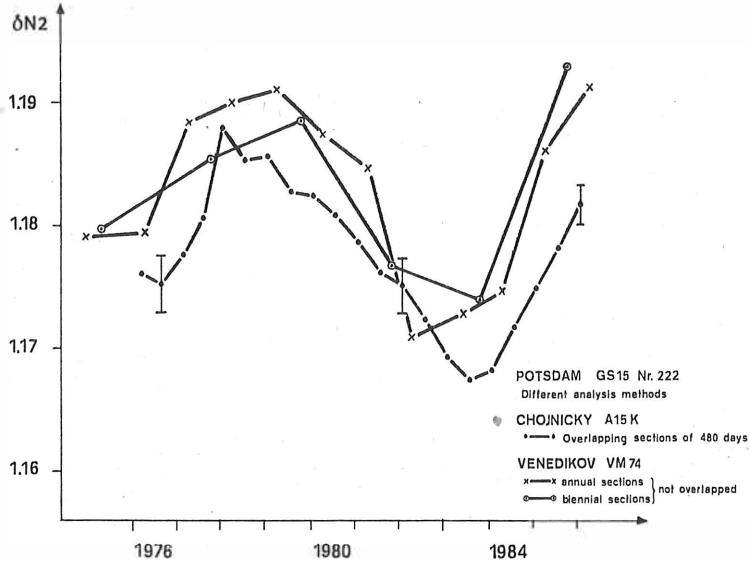

FIG. 4A

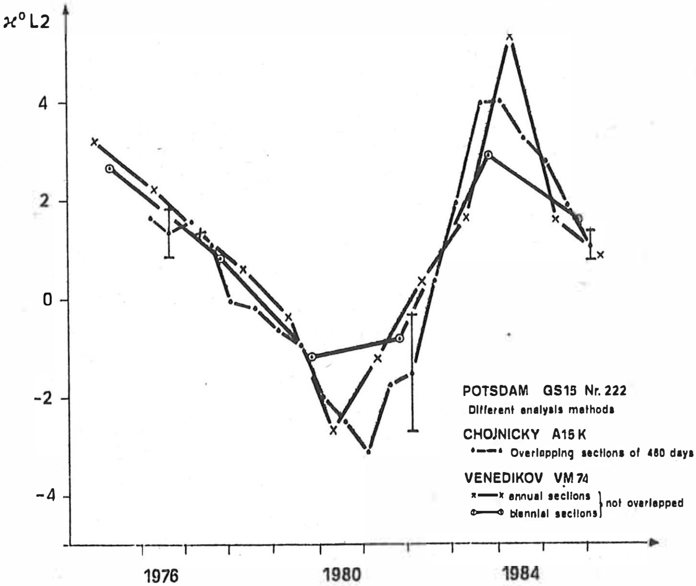

FIG. 4B

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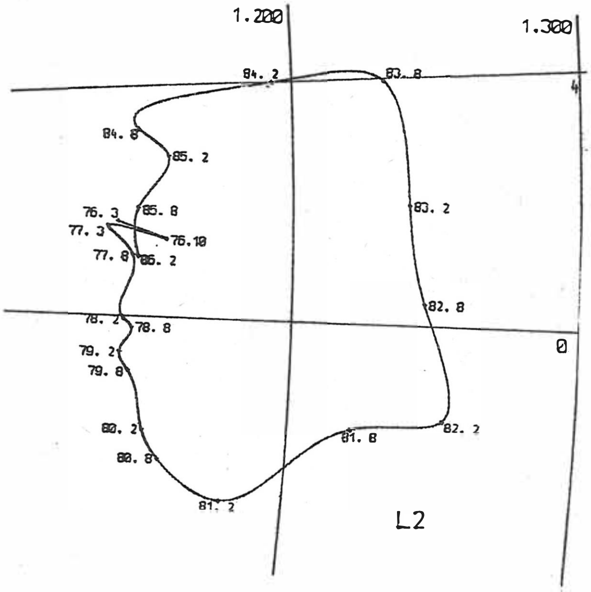

FIG.5

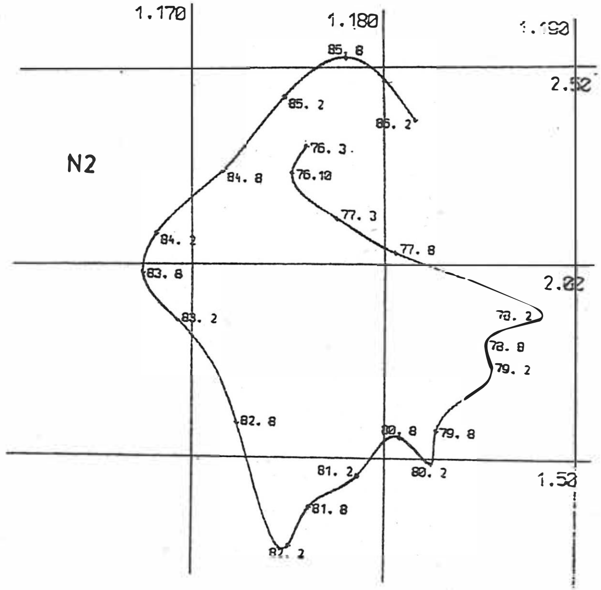

FIG.6

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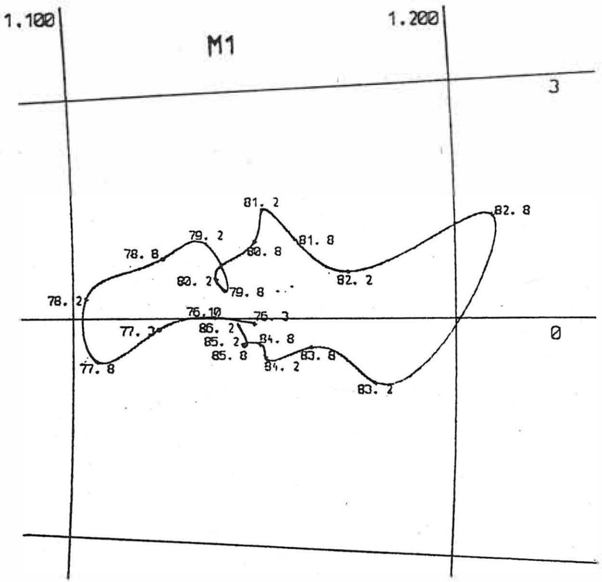

FIG.7

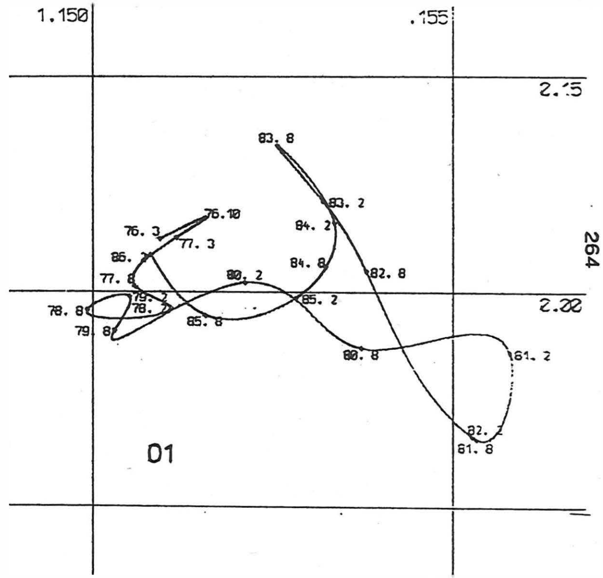

FIG 8

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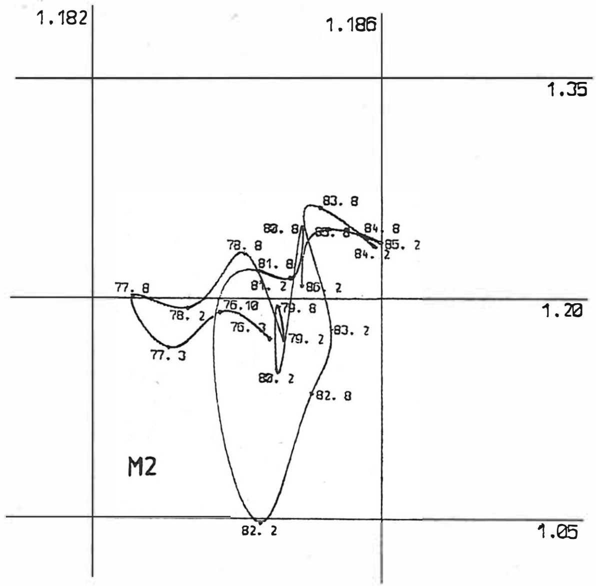

FIG. 9

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First star transit registrations by means of a new Photoelectric Zenith Tube

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Zusammenfassung

In den letzten Jahren wurde am Zentralinstitut für Physik der Erde, Potsdam, ein neues Photoelektrisches Zenitrohr (PEZR) auf der Basis des älteren Photographischen Zenitteleskopes (PZT 1) entwickelt.
In dem neuen Instrument befindet sich an der gleichen Stelle des optischen Systems, an der beim PZT die photographische Platte liegt, ein optisches Präzisionsgitter, so daß das PZT-Prinzip erhalten bleibt. Wenn das Sternlicht das Präzisionsgitter passiert, wird ihm die Gittergeometrie aufmoduliert (Intensitätsvariation). Nachdem es die Objektivlinse ein zweites Mal passiert hat, trifft es auf einen über dem Objektiv positionierten Sekundärelektronenvervielfacher und löst an dessen Katode eine seiner Intensität proportionale Anzahl von elektrischen Impulsen aus, die jeweils für die Dauer eines Abtastintervalls gezählt werden.
Ende 1987 begannen umfangreiche experimentelle Arbeiten zur Einsatzvorbereitung des PEZR. Neue Baugruppen waren zu testen und ihr Zusammenspiel zu überprüfen.
Im Juni dieses Jahres wurden erste Sterndurchgänge registriert. Obwohl der Zeitanschluß und einige Justierungen noch ausstehen, konnten Messungen der Abstände benachbarter Gitterspalte aus Durchgängen verschiedener Sterne zur Genauigkeitsabschätzung von Zeit- und Breitenbestimmungen genutzt werden.

1. Introduction

It is an important task to determine the Earth's Orientation Parameters (EOP) using international collaboration. Several methods of observation can fulfil our purpose. One of them is

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the optical method using the Photographic Zenith Tube (PZT) which can solve both of the aims simultaneously: the determination of longitude and the determination of latitude. The results of the PZT reach the best accuracy in comparison with other optical methods. Though the Satellite Laser Ranging (SLR) and the Very Long Baseline Interferometry (VLBI) reach a higher accuracy in determining the EOP we are not able to give up the optical methods with their large amount of data. Moreover, their results have a direct relation to the plumbline being very important for geophysical investigations.
Among other activities in this field the Central Institute for Physics of the Earth, Potsdam, takes part in the Earth's Rotation Service of the Counsel of Mutual Economic Cooperation with the Photographic Zenith Tube and works in the field of promoting the automation of observations, particularly on photoelectric zenith tube observations.

2. On the development of Photoelectric Zenith Tube (PEZR)

In the last years the Potsdam PEZR has been developed in the Central Institute for Physics of the Earth on the basis of the former PZT [1, 2].
The PZT-principle has been preserved in the new instrument. By means of an optical precision grating situated in the focal plane the star light is transformed into a light density variation. The light passes the lens a second time upward and meets a photomultiplier (PMT) above the objective lens (Fig. 1).

Therefore by this way it is not necessary to compensate the appearent star motion on the firmament. The background effect of the sky has been minimized by means of a slit diaphragm with a distance of 0.4 mm. It can be moved in z-direction for each star by a step-motor. A micro-computer determines the position of slit diaphragm (on-line).
The grating has been built as a fish-bone (Fig. 2). It enables to determine time and latitude by means of one star transit in two positions performed in two steps before meridian transit and in the other position of instrument's head after meridian transit.

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Twice of 65 slits with 5 mm in length form an angle of 90^0 but with the path of star an angle of 45^0. The grating has been positioned on a round glass disk with 50 mm in diameter. It can be adjusted in the optical system.
The precision of grating must be very high. This is most important for the accuracy of star transit measurement. The parallelism of our grating-slits has been measured. It is 1.5 μm/5 mm, that's less than 1 arc minute. The right angle has the same accuracy. The distance between two slits is $(270 \pm 1)\mu m$, its width $(152 \pm 1)\mu m$. We get 10 to 12 time measurements (slit-transits) for each star in each position of instrument's head.

3. Full automatic control and measurement

After passing both the grating in the optimal focal plane and the objective lens a second time the star light will be imaged on the PMT cathode. The modulated star light genetates electrical pulses at the PMT anode proportional to the instantaneous magnitude of the light intensity. During crossing the optical grating by the star image the electrical pulses will be counted in a fixed time interval (0.2 .... 1.0 s). Corresponding with the chosen scan time there are 42....210 measuring time intervals during each grating crossing and each position of telescope's head (direct and inverse).
The preamplification and the level of the discriminator following the PMT have such a value that single photoelectron detection is possible basically. In this way maximum signal - to - nois ratio (SNR) will be attained by optimal choose of the trigger level. For the following processing it is fortunate too that the electrical signal has been already digitized in the first stage of the electronic additional circuit.
Central device of the closed control and data acquisition is the microprocessor system MPS 4944 from Central Institute for Nuclear Research (ZfK) Rossendorf assembled by the U880 family. Real time control and acquisition have been related to a station standard clock.

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In connection with the additional circuits the following functions will be realized by the computer:

- Input of the protocol data by teletype (date, number of cycles and star groups, magnitude of the scan time interval).
- Computation and presetting of the actual slit diaphragm position for each star and each position of teleskope's head by means of the ephemeris for the year 2000.0.
- Presetting of the signal pulse divider corresponding to the star brightness.
- Computation of the entry time of the star image for each actual grating passage (by Universal Time UTC).
- Comparison of the computed entry time with the station clock and start of the scanning by interrupt routine.
- Transfer of the pulse rate from the pulse counter to a 16-bit-memory and read-out by the computer for each scan time interval.
- Computation of the mean values for each grating slit and storage in the computer RAM.
- Turning of the telescope's head.
- Cessation of the automatic observation after passage of the last star of the last chosen star group.
- Read-out of all computed mean slit values.

Fig. 3 shows the scheme of the computer-aided control and measurement equipments of the Photoelectric Zenith Tube. In Fig. 4 you can see the closed simplified programme flow chart.

4. Star transit time registrations and estimation of its accuracy

At the end of 1987 the new instrument had been installed in PZT-pavilion Potsdam-Babelsberg and we had the opportunity to experimentalize for the first time. The mercury mirror, the tube and the objective of PZT 1 has not been changed. Some of the system groups had been newly developed and tested in their

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function with each-other and had finally been adjusted. Such new system groups are as following: the device of turning the instrument's head, the photoelectric monotoring device above the objective, the control of slit diaphragm and the micro-computer. It was necessary to calibrate the position of slit diaphragm into zenith distance direction by means of photographic plates. In that manner we could find the near focus too. A very difficult problem was to find the most appropriate position of photomultiplier. Using a laser results in a convenient solution. A lot of trouble was caused by stray light which reached the photomultiplier and produced additional pulses. We succeed in reducing this rate.

In June 1988 we recorded first star transit times (Fig. 5). You can see star transit time registrations of 3 stars of different magnitude. Although up till now the azimuth adjustment is not yet performed and the ralation to the time scale ist not yet installed an accuracy estimation by means of time measurements between neighbouring slits on the basis of several star transits was made.

The accuracy estimation showed the following results in time:

1 slit - transit .... 50 - 70 ms
1 star - transit (~20 slits) ...... 11 - 17 ms
1 star - programme (~12 stars)..... 3 - 5 ms.

Simultaneously we can compute latitude values with equivalent accuracy. In the near future we hope to complete our new PEZR in order to receive time and latitude determinations.

The Photoelectric Zenith Tube is an instrument which combines some of modern aspects in a sense of rationalization and automation of zenith observations and it aims for an automatic station. We expect an increase of its accuracy because of larger amount of star transits which can be included.

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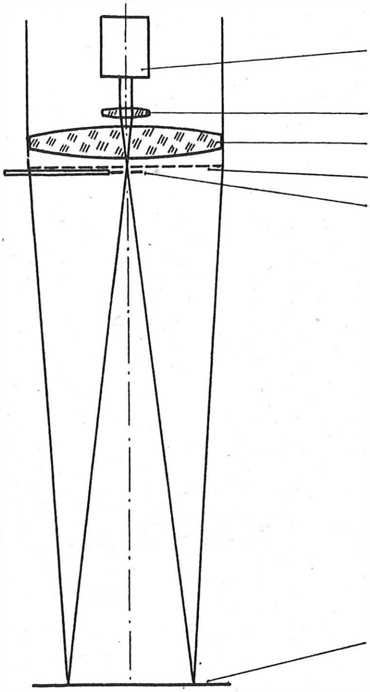

Fig. 1: Optical system of PEZR

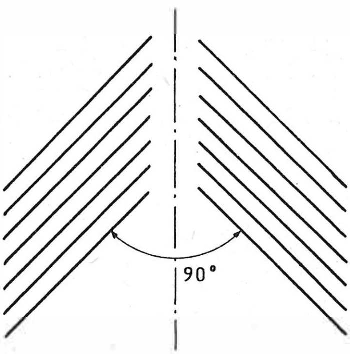

Fig. 2: Grating

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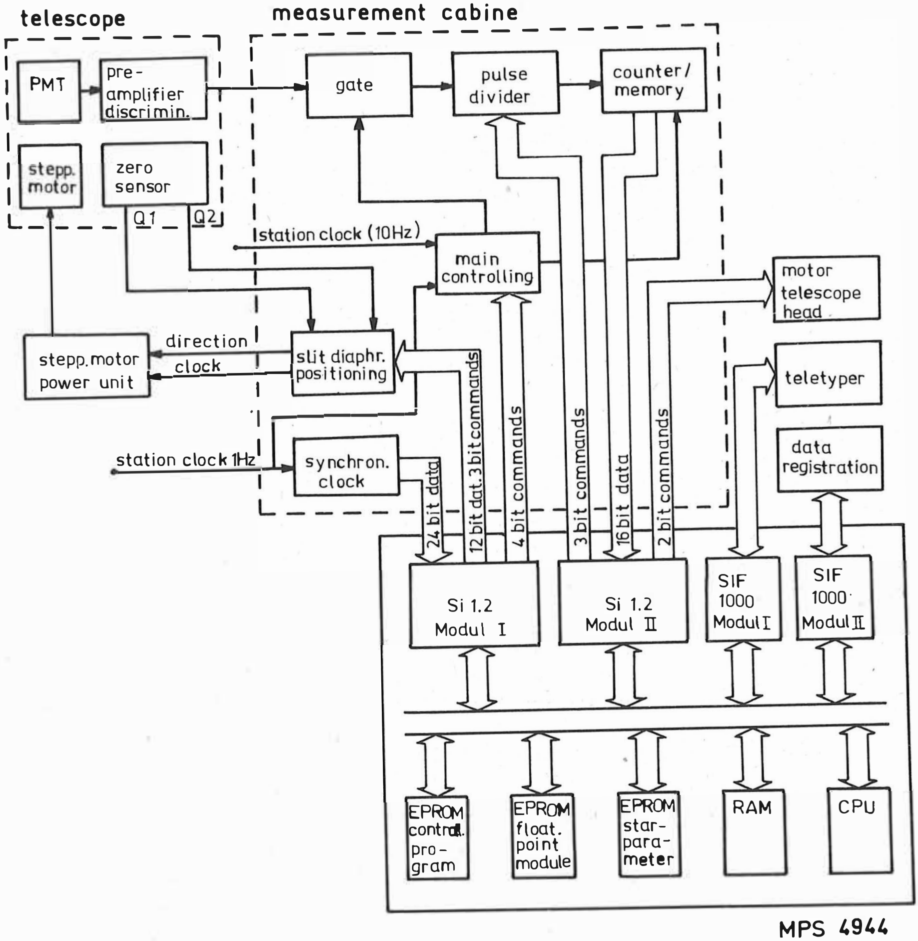

Fig.3: Scheme of the computer aided control and measurement for the Photoelectric Zenith Tube

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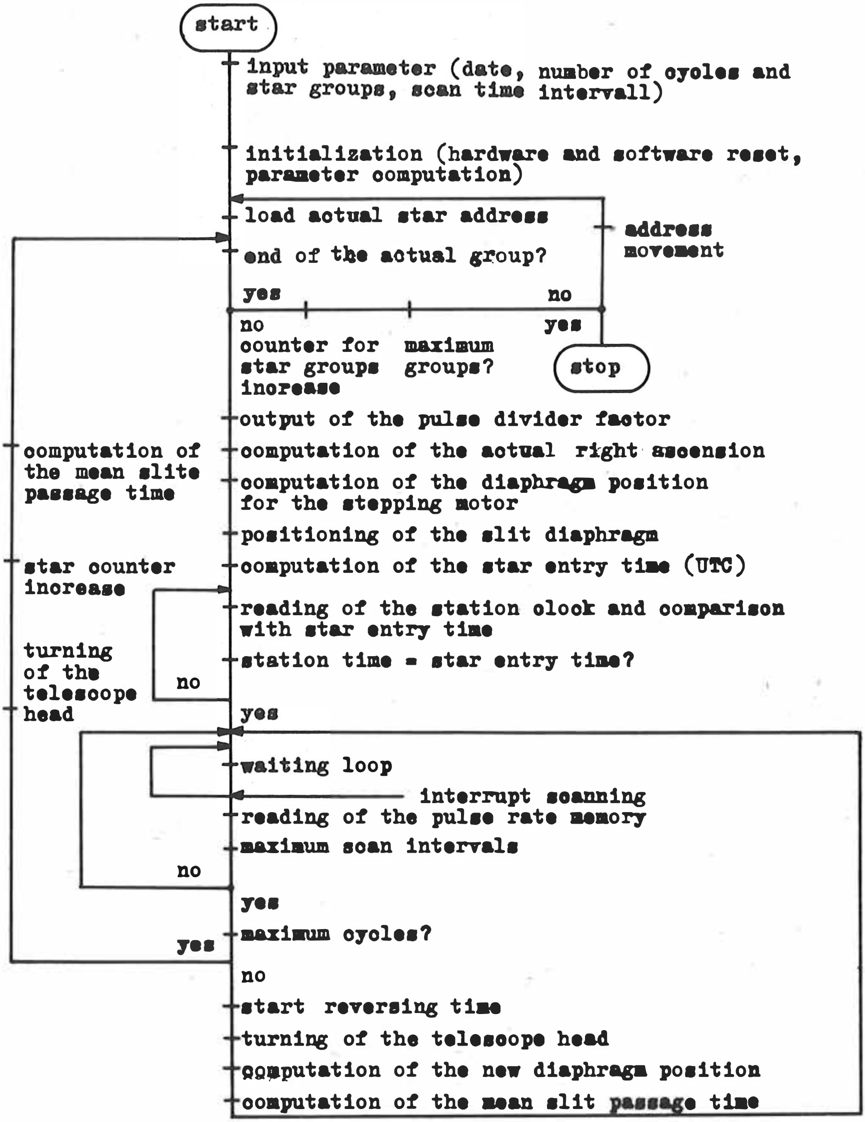

Fig. 4: Simplified programme flow chart

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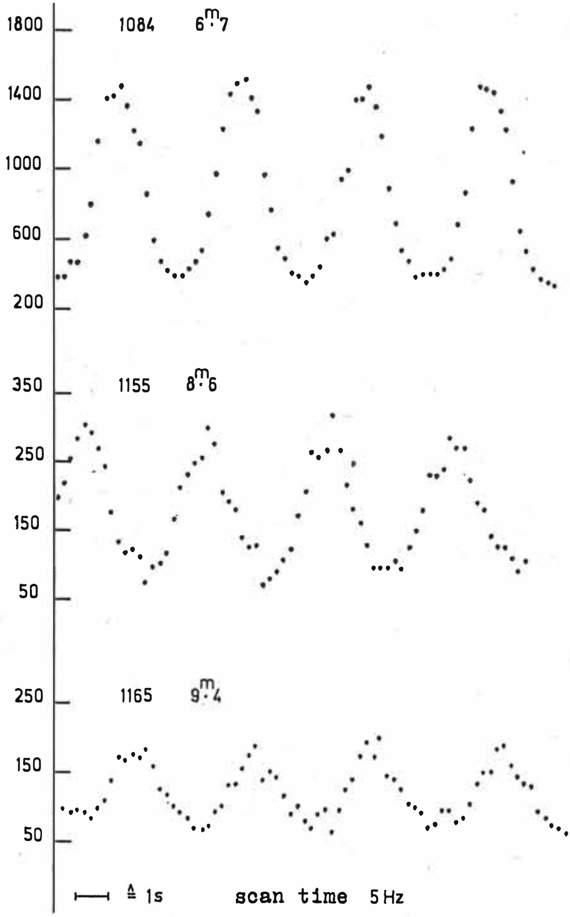

Fig. 5: Graph of pulses measurements for 3 seperate stars and 4 slit-passages in each case

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ON THE DETERMINATION OF TIDAL PARAMETERS USING LAGEOS LASER RANGING DATA

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ABSTRACT: Further development of the orbital program POTSDAM-5 allows to determine solid earth and ocean tidal parameters. LAGEOS data of 21 months starting at September 1983 were analysed. They gave local determinations of LOVE numbers for different stations and global means of $h_2 = 0.605 \pm 0.004$, $l_2 = 0.097 \pm 0.002$. Frequency-dependent tidal parameters were included into the model by time variable geopotential harmonics. An adjustment of these parameters gives the summarized effect of earth and ocean tidal constituents with the same frequency. When fixing one component the other can be extracted. By this way corrections to the frequency-dependent LOVE number k_2 and the ocean tidal constituents could be adjusted. The selected constituents were limited by the relatively small data interval.

1. Introduction

The tidal forces of moon and sun cause a deformation of the solid earth and the ocean surface ("geometrical effects") and, resulting from this, a change in the geopotential ("gravimetric effects"). Modern cosmic methods are able to determine these effects independently of each other. The VLBI technique is able to yield the LOVE numbers h_2, l_2; altimetry can determine sea-surface heights and from these ocean tidal maps and parameters. The satellite laser ranging (SLR) technique can contribute to the determination of both h_2, l_2 and gravitational tidal parameters (k_2, ocean tides). In the case of ocean tides the analysis of SLR data cannot result in a detailed tidal map but in the first coefficients of a spherical harmonic development for each of the tidal constituents. There are two different ways to extract tidal information from satellite data. The older method consists in a long-term harmonic analysis of mean orbital elements. The new method (WILLIAMSON and MARSH, 1985) uses variational equations to get partial derivatives for the tidal parameters and can therefore adjust for these parameters simultaneously with other ones.

2. Data, software and technology

For this investigation, LAGEOS laser ranging data from September 1983 to May 1985 are used. They comprise about 6000 satellite passes with approximately 62000 normal points (3-minutes bin width).
The computations were made by the orbital program system POTSDAM-5 (GENDT 1984). Its implementation is in accordance with the MERIT Standards (MELBOURNE et al. 1983), especially the following tidal components are included:

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- solid earth tides — $k_2 = 0.30$, $\varphi = 0^o$ (excluding permanent tide) WAHR corrections for M_2, S_2, O_1, P_1, K_1, Ψ_1
- ocean tides — SCHWIDERSKI model (11 constituents; harmonics 2nd to 6th degree)
- solid earth tides effects on the station coordinates — $h_2 = 0.609$, $l_2 = 0.085$ $\Delta h^2_{K1} = -0.0887^2$ (including permanent deformation)
- tidal variation of UT1
- ocean loading site displacement

The geopotential model GEM-L2 with GM = 398600.440 km^3/s^2 was used.
To get all necessary information for an adjustment two separate parts of POTSDAM-5 have to run. The first part, which integrates the satellite orbit, yields the residuals O-C and the partial derivatives for all non-dynamical parameters like station coordinates, polar motion, h_2, l_2. The second part must be used to compute partial derivatives of all dynamical parameters (geopotential coefficients, GM, tidal parameters) by integrating variational equations. The obtained two files of derivatives can be mixed to get then the normal equations containing all parameters of interest. The adjustment of the tidal parameters is performed simultaneously with that of geopotential parameters up to degree 4 and order 2, station coordinates, pole coordinates (5-days-intervals) and orbital parameters for different interval lengths (7.5-, 15-, 30-days-arcs). For the computations the UT1-data of the IRIS-Earth Orientation Bulletin are used and fixed.

3. Results

The LAGEOS laser ranging data were used to adjust for the LOVE numbers h_2, l_2 and for the amplitudes and phases of ocean tidal constituents resp. corrections to frequency-dependent LOVE numbers k_2 of solid earth tides. As the have the same frequency, ocean and solid earth tides cannot be separated by satellite techniques. Fixing one model component (e.g. WAHR model for solid earth tides) the parameter of the other (e.g. ocean tides) can be determined and vice versa.
For the investigation the 11 tidal constituents contained in the ocean tidal model of SCHWIDERSKI were selected. In Table 1 the influence of solid earth and ocean tides on the orbits of LAGEOS and STARLETTE is given. Here the models of WAHR resp. SCHWIDERSKI were used.
The tides and the constant geopotential may be correlated, especially if there is a poor distribution of data. This effect could have influenced the geopotential model in its determination process. Therefore it is recommendable to adjust these geopotential coefficients simultaneously with the tidal parameters. However, it turned out that the correlations were small and that their corrections mount only up to $8*10^{-9}$. The tidal solutions were practically not influenced by such simultaneous estimation of geopotential coefficients.
First investigations showed a formal standard deviation (cf. Tab. 2) in the range of ± 0.1 cm to ± 0.3 cm for the long-periodic

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tides (C^+_{20}, S^+_{20}) and generally for all fourth-degree tidal coefficients from ± 0.06 cm to ± 1.2 cm. Additionally, there are strong correlations between second and fourth degree coefficients. On the base of these facts, we decided to determine only the diurnal and semi-diurnal tides of second and third degree. The K_1-tide was excluded because of the relatively small data interval, so finally the tidal constituents M_2, N_2, S_2, K_2, O_1, Q_1, P_1 remained. The phases are defined according to SCHWIDERSKI. After these general considerations the results shell be discussed.

The LOVE numbers h_2 and l_2

The authors have already presented some contributions to the problem of determination of LOVE numbers h_2 and l_2. The first attempt to compute h_2 using the LAGEOS laser ranging data was made with the data of the MERIT Short Campaign 1980 with mostly second generation laser devices. The result was h_2 = 0.56 ± 0.06 (DIETRICH and GENDT, 1984). A simulation study was carried out which was to give an estimation for the reachable accuracy using better laser data. This investigation showed that a global determination of the LOVE number h_2 can be done with an accuracy of ±0.01. The greatest part of the error budget results from errors in the geopotential, followed by calibration uncertainties (GENDT and DIETRICH, 1987). The obtained results were confirmed by analysing real LAGEOS data (see Table 3). This was done by two different ways. First, a direct global adjustment was carried out. Here the formal standard deviations are too optimistic. Second, local values of LOVE numbers for each station were computed and from these the global means. By this way a more realistic error estimation was possible. It can be seen that both values (mean or direct adjustment) do not differ much and that the formal error is too optimistic by a factor of 4. Considering this factor, the values of h_2 and l_2 have no significant difference to the standard values from classical earth tides. The simultaneous adjustment of ocean tidal parameters (resp. frequency-dependent LOVE number k_2) has only a small influence on the result. The accuracies of h_2 and l_2 correspond to relative accuracies of 2% resp. 10%. Compared to the results of the MERIT Short Campaign one can state a progress by a factor of 5. The results are comparable with those determined by VLBI.

Ocean tides resp. frequency-dependent k_2

Fixing the solid earth tidal response by using the theory of WAHR the ocean tidal parameters were adjusted. For these computations 15-days arcs were used. To value the stability of the solutions also arc lengths of 7.5 and 30 days were analysed. The results are given in Table 4 together with the model of SCHWIDERSKI and the satellite-derived solutions of other authors. The formal errors (Table 2) are again too optimistic as the investigation with different arc lengths and data selections had shown. More realistic is an error with a factor of 2 to 5. The amplitudes and phases in Table 4 are corrected by their side-band effects. The dominant side-band frequency is caused by the lunar node the period of which (18.6 yr) is much larger than the data interval. Therefore, its influence cannot be isolated. Our results can be corrected using the mean value of the lunar node for this interval (Ω=64^o) and the amplitudes of the term in the harmonic expansion of tidal potential by CARTWRIGHT and EDDEN (1973). The corrections are the following values for phase shift and amplitude factor: M_2, N_2 with +2^o and factor 1.02; K_2 with -13^o and

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factor 0.86; O_1, Q_1 with 08.9° and factor 0.91; K_1 with -6.5° and factor 0.94 and P_1 with +0.6°.
The solutions for the semi-diurnal tides show a better stability within the POTSDAM-5 variants than the diurnal tides. Such a picture can also be seen in the comparisons with the other satellite solutions. The accuracies of the phase determinations are satisfactory except for the third-degree phases of N_2, P_1, O_1 where one has to consider, of course, that small amplitudes cause large phase instabilities. Systematic phase shifts in the satellite solutions can be registered for M_2, S_2, K_2, Q_1. Compared with the model of SCHWIDERSKI the differences are in the same range as the differences between the various hydrodynamical-numerical models (e.g. PARKE) and the difference to the solution by CHRISTODOULIDIS (1985). The STARLETTE solutions differ by larger values.
For nearly all tides a bigger amplitude can be stated. Taking the effective k_2 from these amplitudes (Fig. 1), an accuracy can be deduced which is equivalent to about ± 0.01 in k_2.
The bigger errors for the diurnal tides may have their origin in orientation errors of the earth spin axis relative to the satellite orbit. Such orientation errors yield a tilt of C_{20} which gives changes in C_{21}, S_{21}. Error sources may be the nutation, polar motion, node and inclination of the satellite orbit. They can reach some 0.001" and give changes in the amplitudes of about 0.1 cm (1" corresponds to about 43.21 cm in the amplitude of ocean tide). This corresponds to the errors of Table 2. Some systematic differences may have their origin in the errors of the orbital modelling (first of all the geopotential). By this way the larger deviations of the STARLETTE solutions may be explained. There is also a difference between terrestrial and satellite methods which differently take into account the atmospheric influence.

Fixing the ocean tidal model (here SCHWIDERSKI), corrections to the frequency-dependent LOVE number k_2 can be computed. These results are shown in Fig.2. Here the above-mentioned fact can be seen, i.e. that errors of ± 0.01 are expected. On the one hand, these are errors of the method and the data and on the other hand errors in the fixed ocean tidal model. In these solutions also the semi-diurnal tides are more stable.

4. Conclusions

SLR to LAGEOS can contribute to tidal research , and here mainly in the field of ocean tidal models. The advantage of the analysis of satellite perturbations consists in the quasi low-pass-filter effect on the tidal forces because of the integral effect of tidal gravity disturbances on the satellite orbit. Therefore, the long wave-length characteristics of the ocean tidal constituents (lower spherical harmonics) can be determined accurately. Satellite-derived results may be important for the calibration of long wave-lengths of tidal models.

The accuracy of the results will be increased in future by improved geopotential models and improved calibration of data. For modelling of STARLETTE orbits one can expect a greater improvement than for LAGEOS (STARLETTE can now be modelled only with an accuracy of about 0.5 meter), and because of the sensitivity of STARLETTE with respect to the tidal parameters one can expect for this satellite improved results in the future.

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Table 1: Theoretical amplitudes of tidal perturbations on LAGEOS and STARLETTE (solid earth tides according to WAHR and ocean tides in second and fourth degree according to SCHWIDERSKI, amplitudes in 0.001" and periods in days)

Tide		LAGEOS solid earth tides E, ocean tides 2,4				STARLETTE solid earth tides E, ocean tides 2,4			
		period	Δi	$\Delta\Omega$	$\Delta(\omega+M)$	period	Δi	$\Delta\Omega$	$\Delta(\omega+M)$
	E		54	18	152		200	197	208
M_2	2	14.03	5	1.6	14	10.51	19	18	19
	4		.1	1.3	0		12	10	45
	E		7	2	18		28	26	34
N_2	2	9.30	.7	.3	1	7.61	19	18	19
	4		0	.2	0		12	10	45
	E		507	192	2397		323	426	225
S_2	2	280.72	32	12	150	36.43	20	27	14
	4		.8	10	2		15	7	30
	E		256	446	272		109	157	143
K_2	2	522.80	17	28	18	45.50	7	10	9
	4		.5	6	1		5	2	7
	E		8	19	52		78	14	314
O_1	2	13.84	.7	2	5	11.88	7	1	29
	4		.1	0	1		0	10	5
	E		1	2	7		11	2	45
Q_1	2	9.21	.1	.3	.7	8.30	1	0	5
	4		0	0	.1		0	1	1
	E		720	269	787		740	626	967
K_1	2	1045.20	65	24	69	91.00	65	55	84
	4		11	28	23		1	102	63
	E		57	171	461		181	82	130
P_1	2	221.29	4	13	36	60.74	14	6	10
	4		.8	.8	9		.3	22	13
	E		-	5	8		-	57	59
M_f	2	13.66	-	.5	.8	13.66	-	6	6
	4		-	0	0		-	0	2
	E		-	5	8		-	61	63
M_m	2	27.55	-	0	.1	27.55	-	7	8
	4		-	0	0		-	1	1
	E		-	31	49		-	353	365
S_{sa}	2	182.62	-	5	8	182.62	-	57	59
	4		-	.3	.1		-	0	13

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Table 2: Formal standard deviations of tidal parameters derived from LAGEOS laser ranging data

Tide	second degree			third degree		
	C^+_{2m}, S^+_{2m}	ampl. [cm]	phase [deg]	C^+_{3m}, S^+_{3m}	ampl. [cm]	phase [deg]
M_2	.01	.02	.4	.02	.03	4.4
N_2	.02	.03	2.4	.03	.05	21.8
S_2	.02	.03	1.7	.01	.02	3.7
K_2	.02	.03	6.2	.01	.02	10.8
O_1	.04	.05	1.2	.06	.08	3.7
Q_1	.05	.07	7.3	.09	.12	22.5
P_1	.06	.08	5.0	.03	.05	8.8

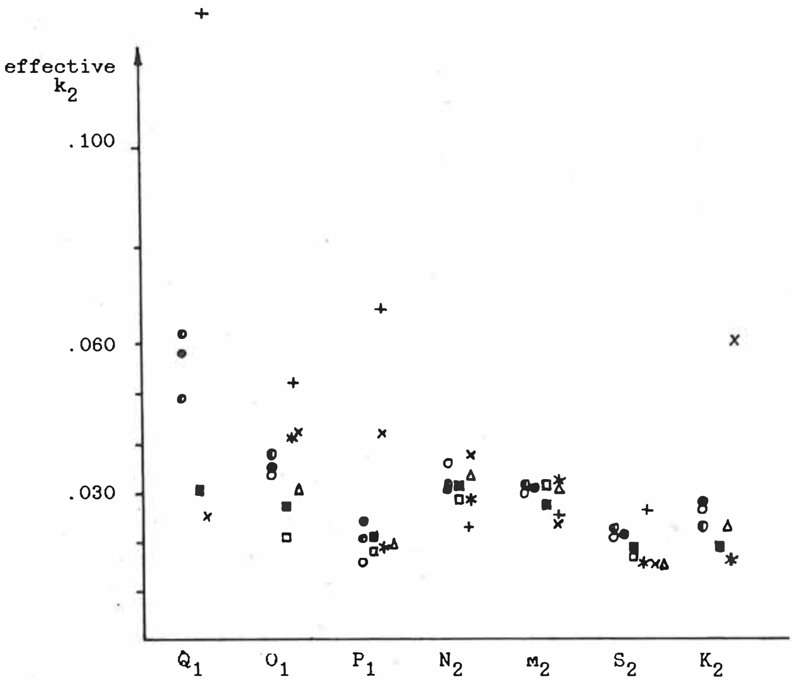

Figure 1: Effective k_2 computed from ocean tidal amplitudes

● ◐ o POTSDAM-5 results for 15-,7.5- and 30-days-arcs
■ □ SCHWIDERSKI, PARKE
* LAGEOS 1980-83, CHRISTODOULIDIS et al. 1985
x STARLETTE 1980, WILLIAMSON and MARSH 1985
\+ STARLETTE 1983/84, MOORE 1987
Δ VARIOUS SATELLITES, MARSH et al. 1988

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Table 3: Different variants of global determination of LOVE numbers h_2 and l_2 from laser ranging data of LAGEOS (Sept.1983 to May 1985)
(standard deviation of mean resp. formal standard deviation)

h_2	l_2	characteristics of determination
0.605 ±0.004	0.097 ±0.002	direct global adjustment
0.610 ±0.004	0.098 ±0.002	direct global adjustment (ocean tides simultaneausly adj.)
0.598 ±0.012	0.092 ±0.009	mean of local determinations
0.6135±0.0054	0.0768±0.0191	VLBI,1980-84,CARTER et al.(1985)
0.608 ±0.003	0.0934±0.002	LAGEOS, 1980-83, CHRITODOULIDIS et al. (1985)

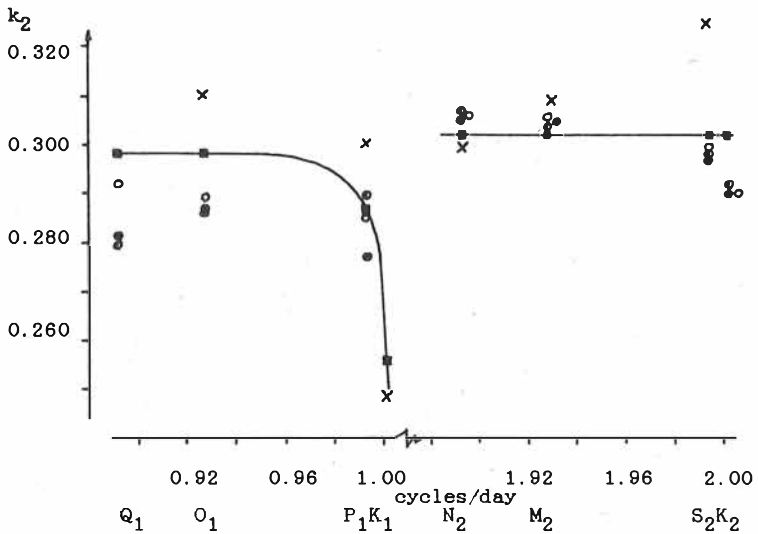

Figure 2: POTSDAM-5 results for frequency dependent LOVE number k_2 using LAGEOS
(▪ WAHR earth model, other symbols see Figure 1)

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Table 4: POTSDAM-5 results for amplitudes und phases of ocean tidal constituents using LAGEOS laser ranging data from September 1983 to May 1985 (results from other authors for comparisions)

Tide	deg	POTSDAM-5 results with arc-length of 15-days		for comparison 7.5-days		for comparison 30-days		Model of SCHWIDERSKI (1980)		Results of other authors using LAGEOS 1980-83 (a)		STARLETTE 1980 (b)		STARLETTE 1983/84 (c)		VARIOUS SATELLITES (d)	
		ampl [cm]	phase [deg]	ampl [cm]	phase [deg]	ampl [cm]	phase [deg]	ampl [cm]	phase [deg]	ampl [cm]	phase [deg]	ampl [cm]	phase [deg]	ampl [cm]	phase [deg]	ampl [cm]	phase [deg]
M_2	2	3.26	320.1	3.22	320.9	3.30	317.6	2.96	310.6	3.46	318.7	2.57	319.2	2.70	342.4	3.26	320.9
	3	.39	171.5	.26	182.3	.47	166.6	.36	168.6	.22	172.5	–		–		.20	152.4
N_2	2	.62	321.0	.73	327.8	.63	323.9	.65	321.8	.59	346.4	.76	322.9	.46	8.5	.70	334.0
	3	.06	130.1	.06	56.0	.12	73.5	.11	171.9	.13	202.6	–		–		.10	84.9
S_2	2	1.07	308.1	1.04	309.5	1.10	308.9	.93	314.0	.78	302.7	.78	32.4	1.37	304.7	.80	301.9
	3	.35	261.0	.30	265.5	.34	259.5	.26	202.0	.28	228.7	–		–		.38	237.4
K_2	2	.36	296.9	.36	300.6	.31	297.2	.26	315.1	.21	348.5	.83	23.4	–		.31	302.1
	3	.24	200.1	.22	198.9	.24	200.0	.09	195.0	.48	200.7	–		–		.51	206.3
O_1	2	3.06	312.1	2.93	314.8	3.32	317.0	2.42	313.7	2.84	326.6	2.85	344.3	3.61	18.7	2.69	318.5
	3	1.40	81.0	1.69	87.6	1.47	75.8	1.32	83.6	1.61	104.4	–		–		1.73	77.6
Q_1	2	0.98	310.0	.83	323.8	1.05	311.3	.54	313.7	–		2.14	12.2	.41	62.0	–	
	3	.41	123.3	.42	137.4	.66	167.2	.31	107.3	–		–		–		–	
P_1	2	1.03	330.4	.71	321.3	.90	337.9	.90	313.9	.79	266.2	1.77	188.3	2.77	289.2	.81	296.8
	3	.43	34.7	.43	47.6	.46	44.5	.30	40.0	.60	321.3	–		–		.33	2.1

a CHRISTODOULIDIS et al. 1985
b WILLIAMSON and MARSH, 1985
c MOORE 1987
d MARSH et al. 1988

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Models for the tidal tilt wave M_2(EW) in the zone of the diminished cavity effects

by JENTZSCH, G.[1]; KACZOROWSKI, M.[2]; SIMON, D.[3]

Abstract

Eight different models were calculated to interprete the M_2(EW) tilt waves measured along a transcontinental profile near the latitude circle 50° N. Former modellings at BAKER (1978) applying the ocean tidal map of HENDERSHOTT revealed deviations to the measured values at the Belgian stations of 12 % for γ and 20° for $\varkappa$. This indicated that tilt measurements were not suitable for more global interpretations. Yet, applying the map of SCHWIDERSKI, the discrepancies are reduced to 2 % for γ and 2 to 3° for $\varkappa$. Thus, these tilt measurements contain informations not only of local but also of regional scale.

It was shown, that the influences of the parcelling of the ocean areas and the application of different algorithms for the calculations are negligibly small. The introduction of the viscoelastic Earth model instead of the purely elastic model only caused changes of 0,1 % for and 0,2° for . On the other hand, the neglect of the conservation of mass of the ocean tide enlarged the maximum deviations between the observed and calculated M_2(EW) parameters by 1 % for and 1° for . The explanation of most of the remaining deviations by an additional wave of an uniform amplitude of 0,26 x 10^{-3}" and inphase with the ocean loading tilt requires lateral inhomogenities not included in the spherical shell models applied up to now.

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1. Introduction

Compared with the world-wide network of the tidal gravimeter profiles installed for the investigation of the ocean tide effects the corresponding activities in the field of tidal tilt measurements are rather small. The cavity effect has discredited the results of the tidal tilt measurements.

But there are two possibilities to diminish the influences of the cavity effects on tidal tilt data so drastically, that informations of regional representation are obtainable. That are

- a suitable choice of the measuring place inside the stations in accordance with certain rules resulting from the modellings of HARRISON (1976) (small coupling factors)
- a suitable choice of the geographical latitude of the station since it was experimentally proved by SIMON, et al. (1985) that the cavity effects of the semidiurnal tilt waves (EW components) are diminished within a zone located between latitudes 49° N and 53° N. This diminution is induced by an amplitude zero of the corresponding body strain waves (EW direction) located in the mentioned zone.

The latter phenomenon enables the application of the results of many old tiltmeter measurements for the investigation of ocean tide effects though a lot of those tiltmeter were installed - before the publication of HARRISON's rules - at unfavourable places.

2. The observed M_2(EW) tilt waves

In Europe there are a lot of tiltmeter stations situated near the latitude 50° N. The tables 1 and 2 contain the results of 23 of these stations taken from the literature. For stations where more than one tiltmeter have recorded in the EW azimuth the arithmetical mean was used for the following comparisons (table 3).

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3. The calculated M_2(EW) tilt waves

Eight different models were calculated to interprete the M_2(EW) tilt waves measured at the stations along the transcontinental profile inside the mentioned zone. That are the variants:

m 1: basing on the models of WAHR (body tilt amplitude with the usual statement of ZSCHAU concerning the phase of the latter: $\varkappa_0 \approx 0^0$), SCHWIDERSKI (global map of ocean tides transformed to the form fulfilling the law of conservation of mass) and ZSCHAU (ocean tide loading on a viscoelastic Earth)

m 2: like m 1 but with the Earth model of GUTENBERG-BULLEN instead of that one of ZSCHAU

m 3: like m 1 but including the tides of the Baltic Sea according to the map of MAGAARD-KRAUSS (1966)

m 4: like m 2 + the mentioned tides of the Baltic Sea

m 5: like m 3 but the tides in the shelf areas North Sea, Irish Sea and La Manche Channel drastically changed in consideration of the empirical map of HANSEN (1942)

m 6: like m 5 but with the Earth model of GUTENBERG-BULLEN instead of that one of ZSCHAU

m 7: like m 2 but with the original SCHWIDERSKI map

m 8: like m 7 but with SCHWIDERSKI's map adapted to the shelf tides of the Norwegian coast (JENTZSCH (1986)).

Table 4 shows the results of the modellings for 30 stations since we completed the EW profile by 7 fictive stations, F 1 - F 7, located at the latitude 50^0 N between the longitudes 18^0 E and 30^0 E.

A comparison of the results of independent modellings carried

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out by JENTZSCH (m 8) and KACZOROWSKI (m 7) on the basis of the original SCHWIDERSKI map shows that the parameter deviations induced by differences in the parcelling of the ocean areas or by different algorithms are negligibly small. The shelf tides along the Norwegian coast considered in model 8 have obviously a very small influence on the M_2(EW) tilt parameters at the profile stations. To enable further comparisons with the results of other authors we present additionally the corresponding parameters of the EW tilt waves induced by the ocean tides with M_2 period in table 5.

4. Comparison of the calculated and observed tilt waves

The calculated γ and $\varkappa$ values are compared with the measured ones in the diagrams 1 and 2.

Obviously the models m 1 and m 2 yield the best-fitting parameters (table 4). The change from the Earth model of GUTENBERG-BULLEN (m 2) to the viscoelstic model of ZSCHAU (m 1) led only to discrepancies of 0,1 % for γ and 0,2^{o} for $\varkappa$. On the other hand the neglect of the fullfilling of the law of conservation of mass enlarged the maximal deviations between the measured and calculated M_2(EW) parameters from 2 % for γ , 3^{o} for $\varkappa$ (m 2) to 3 % for γ , 4^{o} for $\varkappa$ (m 7, m 8). In the comparison were included the results of BAKER (1978) used by SIMON (1981) for a first interpretation of the observational data along the profile.

The application of SCHWIDERSKI's global map of ocean tides instead of that of HENDERSHOTT reduced the maximal deviations between the observed and calculated M_2(EW) parameters from $\Delta\gamma$ = 12 %, $\Delta\varkappa$ = 20^{o} (BAKER) to $\Delta\gamma$ = 2 %, $\Delta\varkappa$ = 2-3^{o} (model m 2). In coherence with the observational data the new modelings yield some detailed informations concerning the M_2(EW) parameters along the profile, as for instance

- the phase lead by 4-6^{o} at the Belgian stations Dourbes and Sclaigneaux

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- the change from phase lead to phase lag between Sclaigneaux and Kanne
- the relative maximum of phase lag at the longitude $\lambda = 10^o$ E (stations Tiefenort, Bad Grund, Clausthal-Zellerfeld)
- a phase lag between 4^o and 2^o in the Ukrainian region (fig. 2).

Further informations obtained from the modellings concern the influence of the shelf tides.
Starting from the longitude $\lambda = 18{,}0^o$ E (F 1 station) along the profile into the East direction the model pairs m 1 and m 6, m 2 and m 5, m 7 and m 8 (table 4), respectively, yield practically the same results in spite of the fact that these models are basing on very different maps of the ocean tides in the European shelf areas.

As a consequence, the influence zone of the shelf tides seems to be restricted along the profile only to the range between the stations Dourbes ($\lambda = 4{,}6^o$) and Ksiaz ($\lambda = 16{,}3^o$), respectively.

5. The remaining discrepancies

A look at the diagrams 1 and 2 shows that outside of the influence zone of the shelf tides, that means inside the innercontinental part of the profile between the stations F 1 and Chewcenkovo, the observed amplitudes and phase lags of the M_2(EW) tilt waves are larger than the calculated ones. As may be shown for the best-fitting model m 2 the discrepance wave

$$(1) \quad \vec{i}_\Delta = (|\vec{i}_\Delta| \; ; \varphi^G_\Delta)$$

between the observed and the model M_2(EW) tilts

$$\vec{i}_{obs} = (|\vec{i}_{obs}| \, ; \varkappa^G_{obs}); \qquad \vec{i}_{mod} = (|\vec{i}_{mod}| \; ; \varkappa^G_{mod})$$

has approximately the same parameters at any station of the mentioned innercontinental part of the profile

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(2) $\vec{i}_{\Delta} = \vec{i}_{obs}(n) - \vec{i}_{mod}(n) = (0{,}26 \times 10^{-3"}; 357^{o})$.

Here are for the station No n with the geographical coordinates λ_n, φ_n

$$|\vec{i}_{obs}(n)| = \gamma_{obs}(n) \cdot I_{theor}(\varphi_n) \quad (3)$$

$$|\vec{i}_{mod}(n)| = \gamma_{mod}(n) \cdot I_{theor}(\varphi_n)$$

the absolute amounts of the observed and calculated tilts expressed in the unit $10^{-3"}$

$\gamma_{obs}(n)$, $\gamma_{mod}(n)$ diminishing factors taken from the tables 2-4

$I_{theor}(\varphi_n)$ tilt amplitudes calculated for the model of a rigid Earth

$$\varkappa^{G}_{obs}(n) = \varkappa^{L}_{obs}(n) + 2|\lambda_n| \quad (4)$$

$$\varkappa^{G}_{mod}(n) = \varkappa^{L}_{mod}(n) + 2|\lambda_n|$$

The corresponding phase lags are related to the phase of the body tilt wave M_2(EW) at Greenwich.

This empirical result of tidal tilt measurements carried out by different authors, and our modellings lead to the following conclusions:

The reasons of the remaining discrepancies between the observed and calculated M_2(EW) tilt waves cannot be given by

- unconsidered contributions of the shelf tides, since the relation (2) is valid for stations located at the innercontinental part of the profile where the influence of the shelf tides can be neglected;
- unconsidered components of the direct tidal effect, since at the mentioned profile stations the phases $\varkappa^{G}_{o}$ of the body tilt waves differ widely from the constant phase of the dis-

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crepance wave $\varphi_\Delta^G = 357^o$ and vary along the profile like

(5) $\kappa_o^G (n) = 2 \, |\lambda_n|$.

For instance at the F 1 station ($\lambda = 18{,}0^o$) we obtain from (5) the phase value $\kappa_o^G = 36{,}0^o$, but at the Chewcenkovo station ($\lambda = 35{,}6^o$) the corresponding phase is $\kappa_o^G = 71{,}2^o$.

- errors of the ocean tide model of SCHWIDERSKI (1979) since the amplitude of the discrepance wave

$$|\vec{i}_\Delta| = 0{,}26 \times 10^{-3"}$$

reaches for instance in the Ukrainian region (see table 5, models m 1 - m 8) about 65 - 84 % of the amount of the total ocean tide effect (attraction + elastic loading). But it is impossible to explain an additional effect of such an order of magnitude by a drastical change of SCHWIDERSKI's global map of ocean tides.

On the other hand the conclusion seems to be justified that the reasons of the significant discrepancies between the observed and calculated M_2(EW) tilt waves must be effects of large-regional or even global relevance, since these discrepancies appear along the innercontinental part of the profile.

6. Results of an attempt to interprete the residuals

The starting point of the following investigations was the idea, that a consideration of the lateral anomalies of the elastic parameters especially within the global tectonic zones of weakness could help to solve the mentioned problems of model adaptation.

Model experiments carried out at the Tiefenort station in 1982/83 gave a first impression of the effects of a lateral inhomogenity of elastic parameters on the surface tilt movements induced by loading variations.

Fig. 3 shows in its upper part the surface tilt amplitudes

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induced by the load of a circle-cylindrical weight of 900 kp loading the salt ground.

The tilts were measured by means of OSTROVSKIJ pendulums with a sensitivity 2 x 10^{-4}"/mm at maximum along a profile situated in the axis of symmetry of an adit with the geometrical dimensions: length 180 m, width 22 m, height 2,5 m. After the first loading experiments a vertical slit was drilled into the ground perpendicularly to the profile with the dimensions: length 6 m, depth 1m, width 0,15 m. The slit crossed the profile in its centre. Now the loading experiments were repeated. Fig. 3 contains the corresponding tilt values in its middle part.

A second slit was drilled at the other side of the load symmetrically to the first one. In the lower part of fig. 3 the tilt values are shown resulting from the last step of the experiment.

Fig. 4 presents the alterations of the tilt amplitudes produced by the first slit. It is visible that the slit simulating a vertical cleft or tectonical weakness zone has induced several effects:

- In the environs of the cleft "behind" the latter in relation to the loading area an amplitude diminuation of the loading tilt is observed.
  The effect is connected with an amplitude diminuation of the components of the loading surface strain.
- The amplitude of the surface tilt is enlarged in greater distances to the cleft (tectonical weakness zone). The reason of this phenomenon is may be that existence of the weakness zone enabled the loaded surface layer to sink deepper into the ground than before.
- All the additional tilts appeared with the same phase like the elastic loading tilts or with a phase difference of 180^{o}. But the latter can be considered in the modellings by an amplitude factor of (-1), too. These results of local experiments have encouraged to draw analogical conclusions concerning the regional loading effect along the profile:

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At any profile station the additional wave AW was first applied with the local phase φ^L_{AO} of the corresponding elastic loading tilt wave induced by the tides of all oceans (table 6, column 3):

(6) $\varphi^L_{AW}(n) = \varphi^L_{AO}(n)$.

After that the amplitude characterization of the additional wave along the profile was changed step by step till an optimal adaptation of the corresponding M_2(EW) parameters to the measured ones was reached.

These calculations led to an AW wave with an uniform amplitude of

(7) $|\overrightarrow{AW}(n)| = 0{,}26 \times 10^{-3}$"; $1 \leq n \leq 30$

at all profile stations, and to the parameters of the model tilt wave M_2(EW) written in table 7.

But we made a further attempt to improve the adaptation of the M_2(EW) model parameters to the observed ones. For this purpose the statement

(8) $\varphi^L_{AW}(n) = \varphi^L_{NA}(n)$

was made, where $\varphi^L_{NA}(n)$ means the local phase of the elastic loading tilt wave induced only by the ocean tides of the North Atlantic area (table 6, column 4) at the station number n.

The results of the second calculations was an AW wave with the same amplitude distribution along the profile as before, but the fitting of the obtained model M_2(EW) waves to the observed ones is improved (table 8, diagrams 5-6).

In this connection the composition of the elastic loading tilt waves was checked. Table 6 shows that at any profile station the North Atlantic component of this effect predominates widely the corresponding contributions of all the other ocean areas.

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It shares by 80-90 % in the total elastic loading effect.

Furthermore it is shown in table 6, that the phase $\varphi^G_{NA}(n)$ of the latter wave, related to the phase of the body tilt wave at Greenwich, is practically constant within the innercontinental part of the profile ranging between $\lambda = 18{,}0^o$ E (F 1 station) and $\lambda = 35{,}6^o$ E (Chewcenkovo station).

The amount of this phase is

$$(9) \quad \varphi^G_{NA}(n) \approx 357^o \; ; \quad 13 \leq n \leq 30$$

and was calculated analogically to the relation (4) from the local phases $\varphi^L_{NA}(n)$ by

$$(10) \quad \varphi^G_{NA}(n) = \varphi^L_{NA}(n) + 2|\lambda_n|$$

where λ_n means the geographical longitude of the station n. At the end of this chapter we can state that the conception applied here for the interpretation of the remaining discrepancies led to plausible results. Since the strong relation of the additional wave to the elastic loading effect of the tides in the North Atlantic can may be explained

- by the upper-mentioned predominance of the North Atlantic component of elastic loading effect calculated for the profile stations between Dourbes and Chewcenkovo;
- by the different large distances of the measuring area to the next tectonical weakness zones of global relevance crossing perpendicularly the profile direction: the Middle Atlantic rift system (distance: 3600 km) and the Circum-Pacific one (distance 10 000-11000 km). The latter fact simplifies the situation in Europe and relieved its interpretation.

  The orientation of the North Atlantic rift system perpendicular to the profile is comparable with the orientation of the vertical slit in our model experiment. Therefore we can assume that the weakness zone amplifies the vertical (and tilt) movements of the loaded surface layers inside the

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Atlantic ocean and at the neighbouring continents.

7. An experimental control possibility

Table 9 shows that in the case of a lengthening of the profile by about 860 km to East there is a good opportunity for a further confirmation of the existence of the additional (tectonical) wave AW.

Here it is visible that in the new part of the profile the local phase of the elastic loading wave (North Atlantic) differs from the phase $\varkappa_0^L \approx 0^{\circ}$ of the body tilt wave in an average by -91°. That means the elastic wave produces in the first line a phase lag of the observed wave.

In the new profile part the mean phase lag of the observed M_2(EW) wave must be about -1.89° in accordance with the model m 8 and about -3.97° in accordance with the model (m 8 + AW). The modern recording technics allow a phase measurement of the largest tidal tilt wave, M_2(EW), with an error $\pm$ 0,5°.

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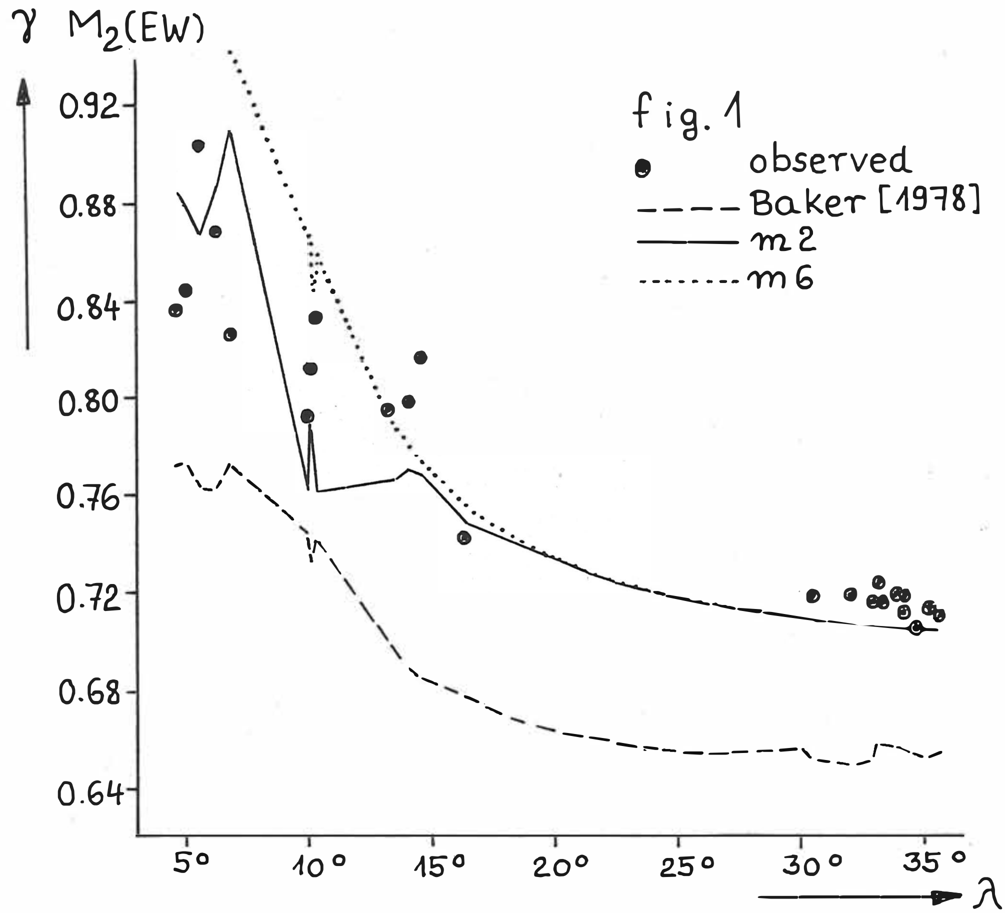

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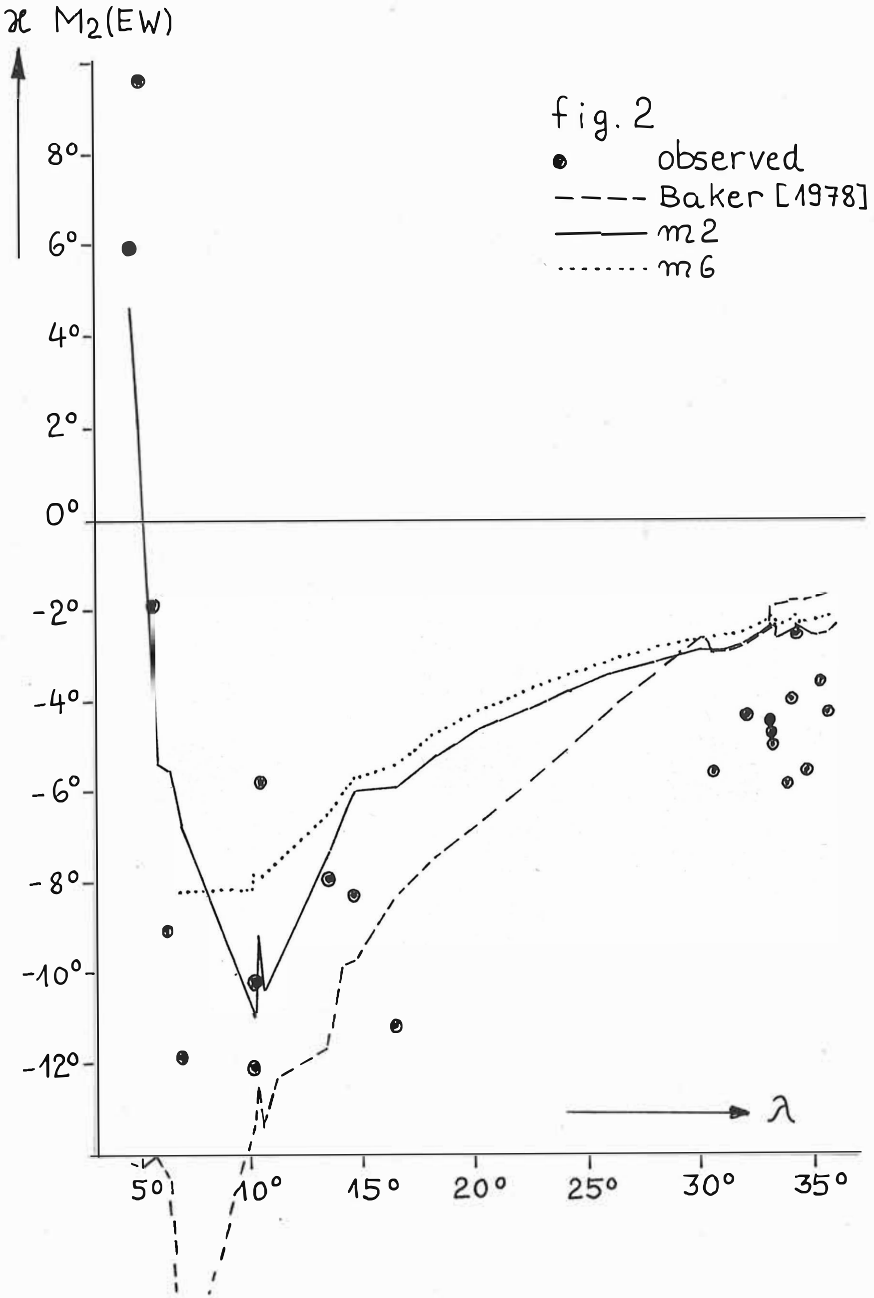

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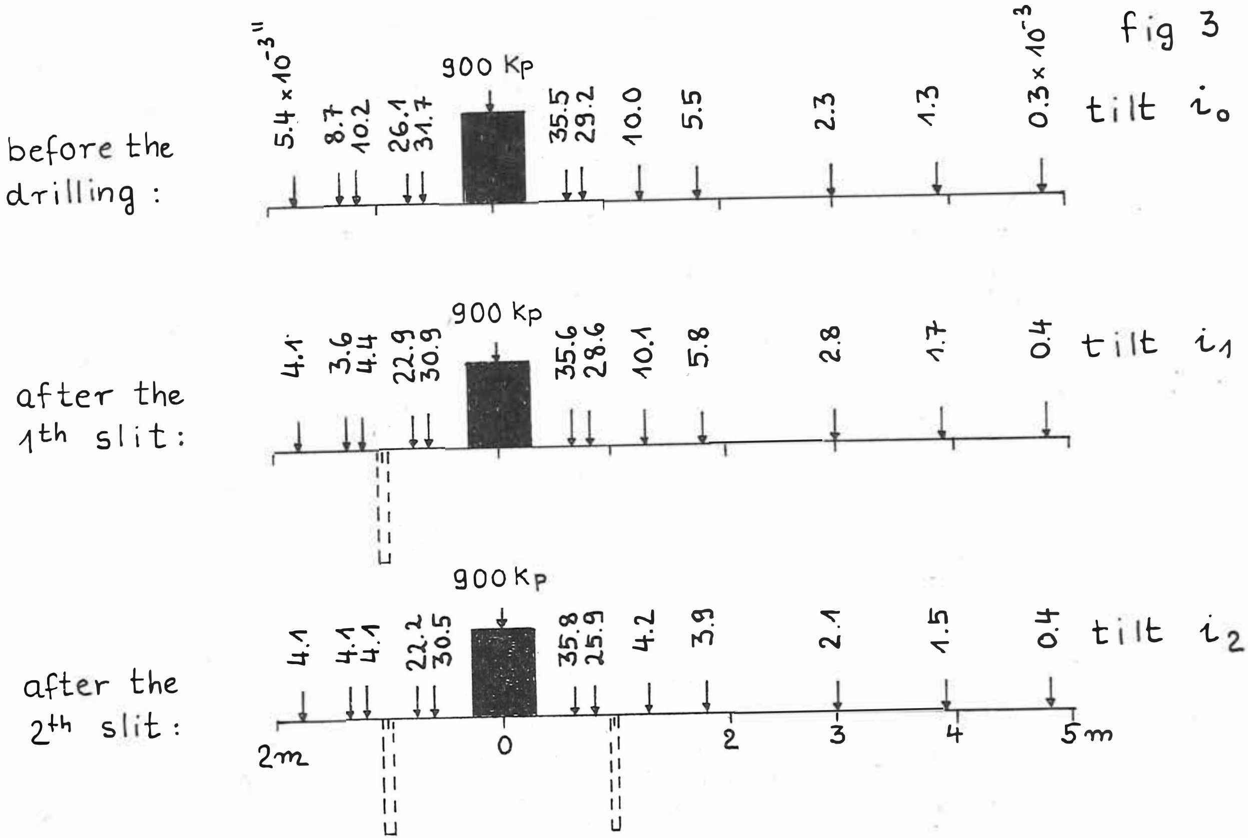

fig 3

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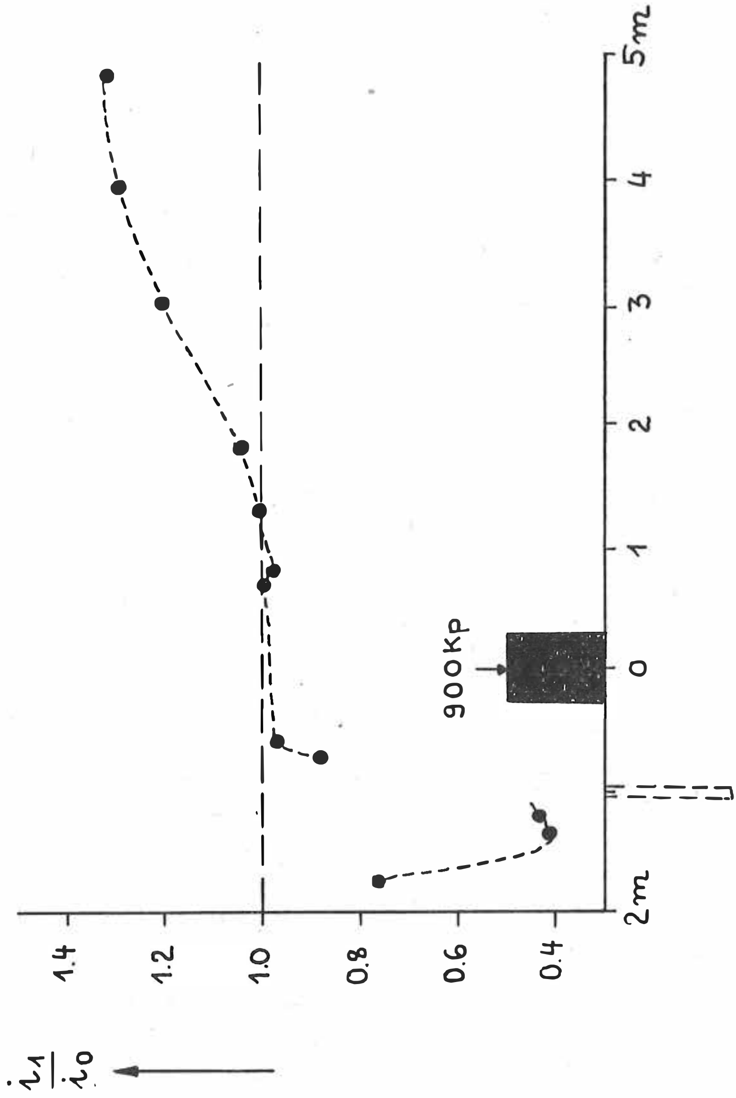
fig. 4 : ratio of tilt amplitudes



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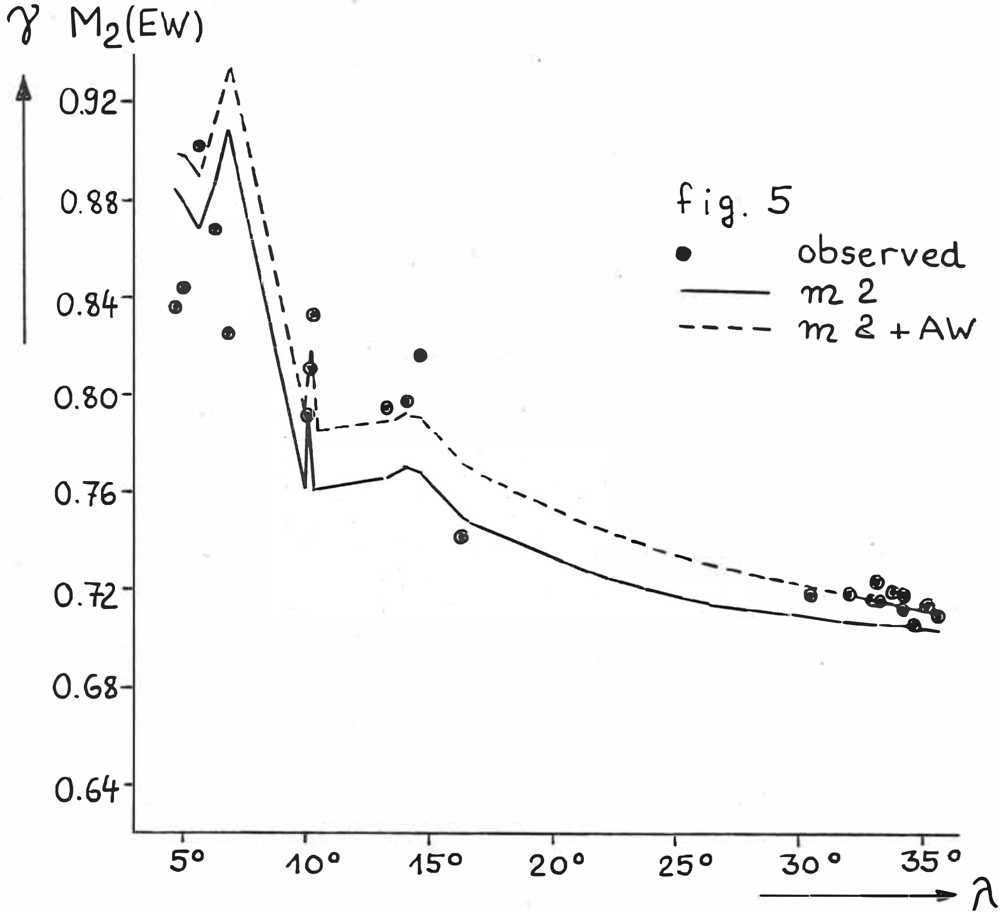

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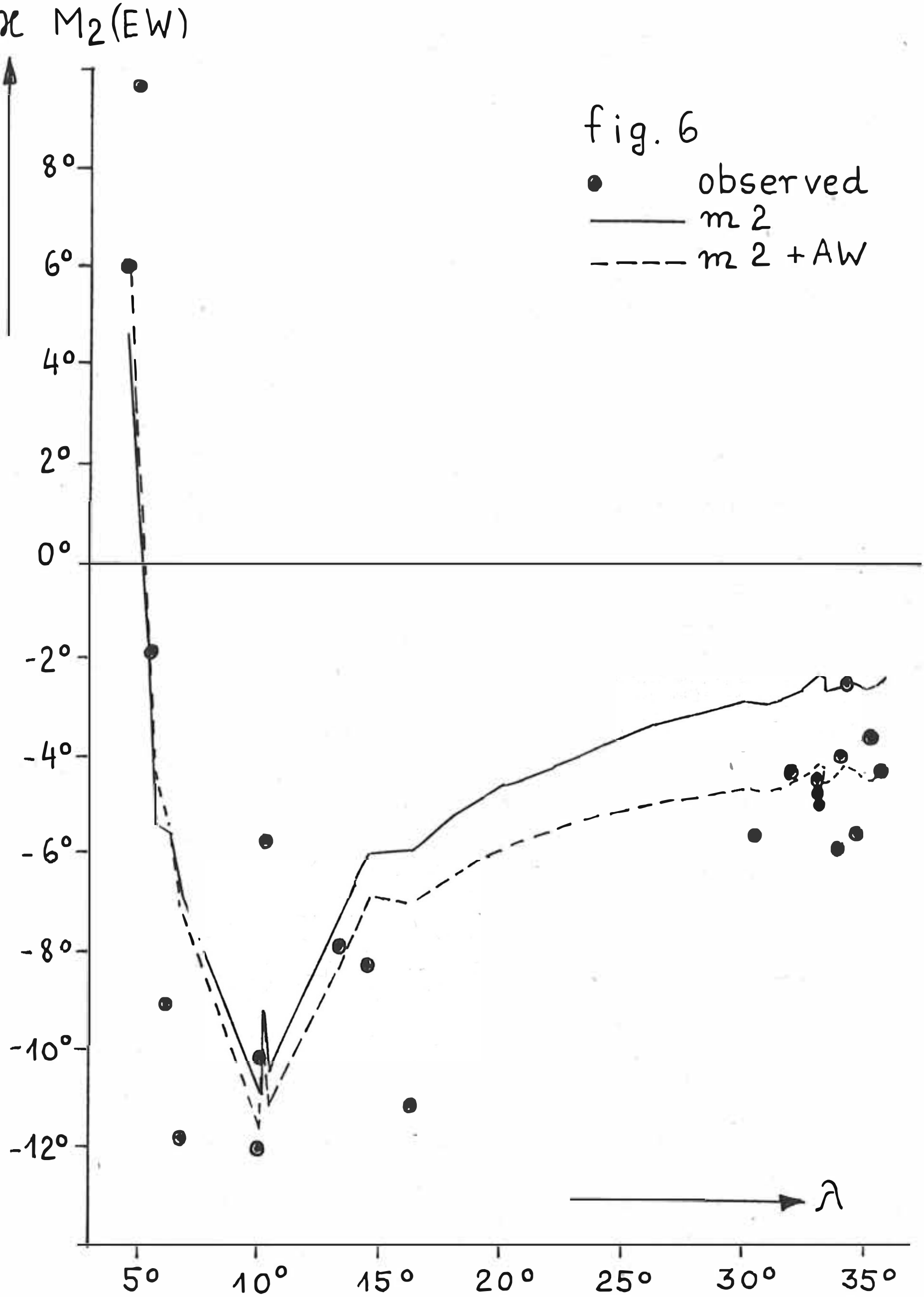

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table 1 : The observed parameter of the tidal tilt waves M_2 (EW)

station	long. $\lambda[°]$	lat. $\varphi[°]$	symbol	record. days	M_2(EW) γ	$\varkappa[°]$	references
Dourbes	4.6	50.1	DOU 1	3062	0.856	6.9	DUCARME [1973]
"			DOU 2	2924	0.817	5.0	"
Sclaigneaux	5.0	50.5	SCL 1	2512	0.894	9.2	DUCARME [1973]
"			SCL 2	906	0.837	10.4	"
"			SCL 3	1718	0.802	9.4	"
Kanne	5.7	50.8	KAN 1	1678	0.910	0.4	MELCHIOR [1973]
"			KAN 2	730	0.893	-2.9	"
Walferdange	6.2	49.6	WLF 1	1174	0.878	-8.5	DUCARME [1973]
"			WLF 2	836	0.921	-9.6	"
"			WLF 3	320	0.805	-8.9	"
Bussange	6.8	47.8	BUS 1	82	0.825	-11.8	LECOLAZET, STEINMETZ, ... [1969]
Bad Grund	10.0	51.8	BGR 1	312	0.792	-12.0	MELCHIOR [1973]
Tiefenort	10.1	50.8	TIE 1	448	0.818	-9.5	SCHNEIDER, HARWARDT, SIMON [1977]
"			TIE 2	406	0.810	-11.1	"
"			TIE 3	312	0.814	-11.3	"
"			TIE 4	492	0.806	-9.2	"
"			TIE 5	322	0.816	-9.3	SIMON, SKALSKY, JERABEK [1985]
Clausthal	10.3	51.8	CLS 1	712	0.817	-6.2	FLACH, GROSSE-BRAUCKMANN, ... [1975
"			CLS 2	712	0.849	-5.2	"
Freiberg	13.3	50.9	FRG 1	388	0.803	-8.6	SCHNEIDER [1966]
Příbram	14.0	49.7	PRM 1	316	0.780	-16.1	SKALSKY [1976]
"			PRM 2	62	0.809	-12.6	"
"			PRM 3	98	0.766	-15.6	"
"			PRM 4	210	0.785	-14.7	"
"			PRM 5	804	0.852	-10.3	"
Řimov	14.5	49.0	RIM 1	222	0.812	-8.0	SKALSKY [1976]
"			RIM 2	222	0.818	-8.0	"
"			RIM 3	222	0.815	-8.0	"
"			RIM 4	222	0.820	-8.8	"
Ksiaz	16.3	50.7	KSZ 1	3652	0.742	-11.1	CHOJNICKI, KACZOROWSKI [1985]

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table 2: The observed parameter of the tidal tilt waves M_2 (EW)

station	long. λ[°]	lat. φ[°]	symbol	record. days	M_2 (EW) γ	$\varkappa$[°]	references
Kiew	30.5	50.4	KIEW	210	0.718	-5.5	DYČKO, PANČENKO [1976]
B. Rudka	32.0	50.0	RDK	652	0.718	-4.2	BALENKO, KUTNI, ... [1978]
Murachovka	33.0	47.2	MUR	650	0.717	-4.4	MATVEEV, GOLUBITZKI, ... [1977]
P. Bagatchka	33.1	50.0	BAG	390	0.717	-4.9	DYČKO, PANČENKO [1976]
Christoforovka	33.1	48.0	CHR	300	0.724	-4.6	DUBIK, GOLUBITZKI [1978]
Lichovka	33.9	48.7	LICH	319	0.719	-5.8	MATVEEV, GOLUBITZKI, ... [1977]
Sudijevka	34.0	48.0	SUD	989	0.719	-3.9	" "
Peregonovka	34.2	49.0	PRG	165	0.713	-2.5	BOGDAN, GOLUBITZKI, ... [1977]
V. Budysha	34.6	49.9	BUD	381	0.705	-5.5	DYČKO, PANČENKO [1976]
Samotojevka	35.2	50.8	SAM	487	0.713	-3.5	MATVEEV, GOLUBITZKI, ... [1977]
Chewčenkovo	35.6	49.5	CHEW	450	0.710	-4.2	DYČKO, PANČENKO [1976]

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table 3: Observed M_2(EW) tilt parameter with arithmetical means for stations with more than one EW instrument

number n	station	symbol	longitude λ_n [°]	latitude φ_n [°]	M_2(EW) γ	$\varkappa$ [°]
1	Dourbes	DOU	4.6	50.1	0.837	6.0
2	Sclaigneaux	SCL	5.0	50.5	0.844	9.7
3	Kanne	KAN	5.7	50.8	0.902	-1.3
4	Walferdange	WLF	6.2	49.6	0.868	-9.0
5	Bussange	BUS	6.8	47.8	0.825	-11.8
6	Bad Grund	BGR	10.0	51.8	0.792	-12.0
7	Tiefenort	TIE	10.1	50.8	0.813	-10.1
8	Clausthal	CLS	10.3	51.8	0.833	-5.7
9	Freiberg	FRG	13.3	50.9	0.795	-7.8
10	Příbram	PRM	14.0	49.7	0.798	-13.9
11	Řimov	RIM	14.5	49.0	0.816	-8.2
12	Ksiaz	KSZ	16.3	50.7	0.742	-11.1
13	F1	F1	18.0	50.0		–
14	F2	F2	20.0	50.0		–
15	F3	F3	22.0	50.0		–
16	F4	F4	24.0	50.0		–
17	F5	F5	26.0	50.0		–
18	F6	F6	28.0	50.0		–
19	F7	F7	30.0	50.0		–
20	Kiew	KIEW	30.5	50.4	0.718	-5.5
21	Rudka	RDK	32.0	50.0	0.718	-4.2
22	Murachovka	MUR	33.0	47.2	0.717	-4.4
23	P. Bagatchka	BAG	33.1	50.0	0.717	-4.9
24	Christoforovka	CHR	33.1	48.0	0.724	-4.6
27	Lichovka	LICH	33.9	48.7	0.719	-5.8
26	Sudijevka	SUD	34.0	48.0	0.719	-3.9
27	Peregonovka	PRG	34.2	49.0	0.713	-2.5
28	V. Budysha	BUD	34.6	49.9	0.705	-5.5
29	Samotojevka	SAM	35.2	50.8	0.713	-3.5
30	Chewčenkovo	CHEW	35.6	49.5	0.710	-4.2

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table 4 : Parameter of the model tilt waves $M_2(EW)$

model>	m1		m2		m3		m4		m5		m6		m7		m8		BAKER	
station symbol	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]	γ $[10^{-4}]$	$\varkappa$ [°]
DOU	8832	4.89	8840	4.71									8776	6.36	8768	6.32	7710	-14.1
SCL	8784	1.75	8796	1.61									8729	3.20	8721	3.13	7725	-14.2
KAN	8656	-5.24	8661	-5.35									8590	-3.94	8590	-3.42	7609	-14.0
WLF	8823	-5.48	8839	-5.57									8776	-4.52	8780	-4.43	7609	-14.4
BUS	9057	-6.79	9081	-6.90							9428	-8.18	9033	-6.14	9014	-6.12	7714	-19.1
BGR	7619	-10.68	7602	-10.96							8649	-8.10	7565	-9.84	7581	-9.75	7430	-13.3
TIE	7928	-9.00	7930	-9.20	7938	-9.01	7941	-9.19	8436	-7.65	8451	-7.79	7894	-8.30	7879	-8.20	7317	-12.5
CLS	7610	-10.17	7605	-10.38							8588	-7.83	7565	-9.37	7571	-9.23	7414	-13.3
FRG	7661	-7.12	7659	-7.24	7641	-7.12	7640	-7.26	7901	-6.30	7911	-6.44	7641	-6.52	7607	-6.24	6998	-11.6
PRM	7697	-6.31	7695	-6.43							7806	-6.00			7681	-5.77	6889	-9.84
RIM	7680	-5.83	7679	-5.95							7748	-5.65			7669	-5.35	6848	-9.72
KSZ	7493	-5.76	7490	-5.89	7469	-5.76	7465	-5.90	7573	-5.22	7572	-5.35	7478	-5.33	7474	-5.26	6774	-8.40
F 1	7428	-5.05	7425	-5.17							7455	-4.72			7424	-4.64	6692	-7.55
F 2	7340	-4.53	7332	-4.59							7346	-4.16			7336	-4.13	6632	-6.76
F 3	7271	-4.08	7260	-4.14							7272	-3.75			7273	-3.75	6587	-5.94
F 4	7210	-3.66	7203	-3.71	7201	-3.61	7195	-3.68	7215	-3.27	7211	-3.35	7218	-3.40	7219	-3.40	6559	-5.10
F 5	7168	-3.33	7160	-3.37							7165	-3.04			7175	-3.08	6539	-4.2
F 6	7133	-3.04	7125	-3.09							7129	-2.76			7138	-2.81	6544	-3.40
F 7	7100	-2.74	7097	-2.85							7100	-2.54			7109	-2.59	6564	-2.64
KIEW	7092	-2.72	7089	-2.83	7089	-2.70	7083	-2.78	7100	-2.44	7094	-2.51	7107	-2.63	7108	-2.62	6513	-2.99
RDK	7078	-2.57	7070	-2.62							7078	-2.37			7086	-2.42	6493	-2.75
MUR	7059	-2.31	7067	-2.27							7069	-2.06			7084	-2.16	6501	-2.42
BAG	7063	-2.43	7062	-2.56							7064	-2.26			7078	-2.38	6553	-2.02
CHR	7070	-2.30	7063	-2.34							7067	-2.12			7081	-2.23	6568	-1.94
LICH	7060	-2.30	7054	-2.34							7059	-2.11			7072	-2.23	6557	-1.89
SUD	7062	-2.25	7055	-2.29	7058	-2.21	7054	-2.27	7065	-2.02	7060	-2.07	7068	-2.12	7068	-2.12	6561	-1.86
PRG	7059	-2.33	7052	-2.36							7058	-2.14			7065	-2.19	6548	-1.8
BUD	7050	-2.33	7048	-2.44							7056	-2.20			7063	-2.26	6538	-1.82
SAM	7048	-2.40	7040	-2.44											7055	-2.26	6522	-1.75
CHEW	7042	-2.25	7038	-2.29	7041	-2.23	7036	-2.29	7050	-2.03	7043	-2.05	7055	-2.18	7055	-2.18	6530	-1.66

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table 5: Ocean tide induced tilt waves with M_2 period in EW direction

model >		m 1		m 2		m 7		m 8		BAKER [1978]	
station	n	10^{-3} "	φ^L_{OT} [°]	10^{-3} "	φ^L_{OT} [°]	10^{-3} "	φ^L_{OT} [°]	10^{-3} "	φ^L_{OT} [°]	10^{-3} "	φ^L_{OT} [°]
DOU	1	2.09	381.3	2.09	380.5	2.11	387.7	2.10	387.6	2.0	287.8
SCL	2	1.93	368.0	1.94	367.3	1.91	374.8	1.90	374.5	2.0	288.0
KAN	3	1.91	335.7	1.92	335.3	1.78	340.8	1.77	343.3	1.9	285.6
WLF	4	2.13	336.2	2.15	336.0	2.04	339.8	2.04	340.2	2.0	284.6
BUS	5	2.51	333.2	2.54	333.0	2.45	335.4	2.43	335.3	2.7	279.4
BGR	6	1.50	293.7	1.52	292.4	1.38	294.4	1.38	295.2	1.7	282.0
TIE	7	1.56	307.8	1.58	307.1	1.47	309.6	1.45	309.6	1.6	279.8
CLS	8	1.44	294.9	1.46	294.1	1.33	295.8	1.32	296.5	1.7	281.4
FRG	9	1.19	307.7	1.20	307.1	1.12	309.8	1.07	310.0	1.4	269.4
PRM	10	1.17	312.7	1.18	312.0			1.11	315.0	1.2	266.0
RIM	11	1.13	314.6	1.14	313.9			1.08	316.9	1.2	264.0
KS7	12	0.95	307.9	0.96	307.1	0.90	309.7	0.89	309.9	1.0	260.0
F1	13	0.85	309.0	0.86	308.1			0.81	311.4	0.92	255.0
F2	14	0.74	307.7	0.74	306.8			0.70	310.2	0.84	250.0
F3	15	0.65	306.5	0.65	305.5			0.62	309.2	0.76	245.0
F4	16	0.57	305.3	0.57	304.3	0.55	308.1	0.55	308.2	0.68	240.0
F5	17	0.51	304.5	0.51	303.4			0.49	307.4	0.60	234.0
F6	18	0.46	303.8	0.46	302.5			0.44	306.6	0.52	229.0
F7	19	0.41	303.1	0.42	301.7			0.40	305.8	0.44	224.0
KIEW	20	0.40	302.5	0.41	301.0	0.40	305.3	0.40	305.4	0.5	223.0
RDK	21	0.38	302.3	0.38	300.8			0.37	305.0	0.5	219.0
MUR	22	0.36	305.2	0.36	303.8			0.36	307.5	0.4	216.0
BAG	23	0.36	301.9	0.37	300.4			0.36	304.5	0.4	215.0
CHR	24	0.36	304.1	0.36	302.7			0.36	306.4	0.4	215.8
LICH	25	0.35	302.9	0.35	301.5			0.35	305.3	0.4	214.2
SUD	26	0.35	303.6	0.35	302.2	0.34	306.1	0.34	306.1	0.4	214.0
PRG	27	0.35	302.4	0.35	301.0			0.34	304.9	0.4	212.6
BUD	28	0.34	301.3	0.35	299.8			0.34	303.9	0.4	211.8
SAM	29	0.34	300.3	0.34	298.8			0.33	302.9	0.4	209.6
CHEW	30	0.33	301.0	0.33	300.0	0.33	303.7	0.33	303.7	0.4	208.8

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tab. 6 : Elastic loading components of the M_2(EW) tilt waves, model m 8, selected ocean areas

1		2	3		4			5		6		7	
ocean area >			all oceans		North Atlantic			Norw./Greenl.		Jndian Oc.		North Sea	
station	n	long. λ_n [°]	10^{-3}"	φ^L_{AO} [°]	10^{-3}"	φ^L_{NA} [°]	φ^G_{NA} [°]	10^{-3}"	$\varphi^L_{N/G}$ [°]	10^{-3}"	φ^L_{JO} [°]	10^{-3}"	φ^L_{NS} [°]
DOU	1	4.6	1.30	426.6	1.04	424.2	433.4	0.10	244.1	0.02	128.2		
SCL	2	5.0	1.02	416.3	0.82	413.6	423.0	0.10	242.1	0.02	126.8		
KAN	3	5.7	0.55	375.4	0.61	394.2	395.6	0.11	239.4	0.02	125.3		
WLF	4	6.2	0.67	356.1	0.71	360.0	372.4	0.09	239.3	0.02	126.4		
BUS	5	6.8	0.92	337.6	0.94	341.6	355.2	0.07	238.8	0.02	128.4		
BGR	6	10.0	0.48	278.3	0.55	327.8	347.8	0.10	222.5	0.02	116.1		
TIE	7	10.1	0.49	304.0	0.56	330.6	350.8	0.09	224.2	0.03	117.0		
CLS	8	10.3	0.45	280.9	0.54	327.0	347.6	0.10	221.4	0.03	115.4		
FRG	9	13.3	0.37	309.2	0.45	323.2	349.8	0.08	213.3	0.03	109.2	0.05	198.9
PRM	10	14.0	0.40	315.1	0.45	325.2	353.2	0.07	215.2	0.03	110.1	0.03	216.0
RIM	11	14.5	0.39	317.3	0.44	325.6	354.6	0.06	214.8	0.03	109.7	0.02	226.7
KSZ	12	16.3	0.32	310.5	0.38	319.7	352.3	0.07	207.0	0.03	103.9	0.02	204.0
F1	13	18.0	0.30	312.1	0.35	318.4	354.4	0.06	204.1	0.03	100.6	0.01	232.3
F2	14	20.0	0.26	310.8	0.31	315.2	355.2	0.05	199.1	0.03	95.8	0.01	260.1
F3	15	22.0	0.23	309.4	0.28	311.9	355.9	0.05	194.2	0.04	90.9	0.01	284.0
F4	16	24.0	0.21	307.9	0.26	308.4	356.4	0.04	189.5	0.04	86.0	0.01	296.4
F5	17	26.0	0.19	306.3	0.24	304.7	356.7	0.04	184.9	0.04	81.2	0.01	301.0
F6	18	28.0	0.17	304.5	0.22	300.9	356.9	0.04	180.3	0.04	76.3	> 0.01	301.8
F7	19	30.0	0.16	302.6	0.20	296.9	356.9	0.04	175.8	0.04	71.5	> 0.01	301.2
KIEW	20	30.5	0.15	301.8	0.20	295.7	356.7	0.04	174.2	0.04	70.4	> 0.01	301.9
RDK	21	32.0	0.14	300.5	0.19	292.7	356.7	0.03	171.3	0.04	66.8	> 0.01	300.1
MUR	22	33.0	0.14	301.8	0.18	292.1	358.1	0.03	171.5	0.05	63.0	> 0.01	295.0
BAG	23	33.1	0.14	299.2	0.18	290.6	356.8	0.03	168.9	0.05	64.2	> 0.01	299.0
CHR	24	33.1	0.14	300.9	0.18	291.6	357.8	0.03	170.7	0.05	63.1	> 0.01	295.9
LICH	25	33.9	0.13	299.3	0.17	289.5	359.4	0.03	168.3	0.05	61.6	> 0.01	296.0
SUD	26	34.0	0.13	299.9	0.17	289.6	357.6	0.03	168.6	0.05	60.9	> 0.01	295.0
PRG	27	34.2	0.13	298.7	0.17	288.7	357.1	0.03	167.4	0.05	61.0	> 0.01	296.1
BUD	28	34.6	0.13	297.5	0.17	287.5	356.7	0.03	165.7	0.05	60.7	> 0.01	296.9
SAM	29	35.2	0.13	296.2	0.17	285.8	356.2	0.03	163.5	0.05	59.9	> 0.01	297.6
CHEW	30	35.6	0.12	296.6	0.17	285.5	356.7	0.03	163.8	0.05	58.1	> 0.01	295.0

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table 7: Parameter of the model tilt waves M_2 (EW) with consideration of the additional waves $\vec{AW} = (0.26 \times 10^{-3''}$; $\varphi^L_{AW} = \varphi^L_{AO})$; φ^L_{AO} s. table 6, column 3

model >		m2		AW		m2 + AW		m8		m8 + AW	
station	n	γ	$\varkappa$ [°]	$\Delta\gamma_{AW}$	φ^L_{AW} [°]	γ	$\varkappa$ [°]	γ	$\varkappa$ [°]	γ	$\varkappa$ [°]
DOU	1	0.8840	4.71	0.02577	426.6	0.8964	6.16	0.8768	6.32	0.8899	7.76
SCL	2	0.8796	1.61	0.02599	416.3	0.8949	2.97	0.8721	3.13	0.8879	4.47
KAN	3	0.8661	-5.35	0.02616	375.4	0.8906	-4.75	0.8590	-3.42	0.8838	-2.87
WLF	4	0.8839	-5.57	0.02551	356.1	0.9094	-5.52	0.8780	-4.43	0.9035	-4.42
BUS	5	0.9081	-6.90	0.02461	337.6	0.9318	-7.30	0.9014	-6.12	0.9250	-6.55
BGR	6	0.7602	-10.96	0.02673	278.3	0.7694	-12.84	0.7581	-9.75	0.7668	-11.65
TIE	7	0.7930	-9.20	0.02616	304.0	0.8111	-10.54	0.7879	-8.20	0.8057	-9.58
CLS	8	0.7605	-10.38	0.02673	280.9	0.7706	-12.23	0.7571	-9.23	0.7667	-11.11
FRG	9	0.7659	-7.24	0.02621	309.2	0.7851	-8.56	0.7607	-6.24	0.7796	-7.59
PRM	10	0.7695	-6.43	0.02556	315.1	0.7897	-7.58	0.7681	-5.77	0.7881	-6.94
RIM	11	0.7679	-5.95	0.02520	317.3	0.7882	-7.05	0.7669	-5.35	0.7871	-6.46
KSZ	12	0.7490	-5.89	0.02610	310.5	0.7681	-7.23	0.7474	-5.26	0.7663	-6.62
F1	13	0.7425	-5.17	0.02572	312.1	0.7616	-6.48	0.7424	-4.64	0.7613	-5.97
F2	14	0.7332	-4.59	0.02572	310.8	0.7517	-5.97	0.7336	-4.13	0.7520	-5.52
F3	15	0.7260	-4.14	0.02572	309.4	0.7440	-5.58	0.7273	-3.75	0.7451	-5.19
F4	16	0.7203	-3.71	0.02572	307.9	0.7376	-5.20	0.7219	-3.40	0.7391	-4.90
F5	17	0.7160	-3.37	0.02572	306.3	0.7327	-4.92	0.7175	-3.08	0.7341	-4.63
F6	18	0.7125	-3.09	0.02572	304.5	0.7285	-4.69	0.7138	-2.81	0.7297	-4.42
F7	19	0.7097	-2.85	0.02572	302.6	0.7249	-4.51	0.7109	-2.59	0.7260	-4.25
KIEW	20	0.7089	-2.83	0.02594	301.8	0.7240	-4.52	0.7108	-2.62	0.7258	-4.31
RDK	21	0.7070	-2.62	0.02572	300.5	0.7214	-4.33	0.7086	-2.42	0.7229	-4.13
MUR	22	0.7067	-2.27	0.02433	301.8	0.7206	-3.87	0.7084	-2.16	0.7223	-3.76
BAG	23	0.7062	-2.56	0.02572	299.2	0.7201	-4.30	0.7078	-2.38	0.7216	-4.12
CHR	24	0.7063	-2.34	0.02471	300.9	0.7201	-3.98	0.7081	-2.23	0.7219	-3.87
LICH	25	0.7054	-2.34	0.02505	299.3	0.7189	-4.04	0.7072	-2.23	0.7206	-3.93
SUD	26	0.7055	-2.29	0.02471	299.9	0.7190	-3.96	0.7068	-2.12	0.7202	-3.79
PRG	27	0.7052	-2.36	0.02520	298.7	0.7185	-4.08	0.7065	-2.19	0.7198	-3.91
BUD	28	0.7048	-2.44	0.02567	297.5	0.7180	-4.22	0.7063	-2.26	0.7194	-4.04
SAM	29	0.7040	-2.44	0.02616	296.2	0.7169	-4.28	0.7055	-2.26	0.7183	-4.09
CHEW	30	0.7038	-2.29	0.02446	296.6	0.7159	-4.00	0.7055	-2.18	0.7176	-3.89

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table 8: Parameter of the model tilt waves M_2(EW) with consideration of the additional waves $\vec{AW} = (0.26 \times 10^{-3}$"; $\varphi^L_{AW} = \varphi^L_{NA}$); φ^L_{NA} s. table 6, column 4

model >		m2		AW		m2+AW		m8		m8+AW	
station	n	γ	$\varkappa$[°]	$\Delta\gamma_{AW}$	φ^L_{AW}[°]	γ	$\varkappa$[°]	γ	$\varkappa$[°]	γ	$\varkappa$[°]
DOU	1	0.8840	4.71	0.02577	424.2	0.8974	6.13	0.8768	6.32	0.8908	7.72
SCL	2	0.8796	1.61	0.02599	413.0	0.8960	2.91	0.8721	3.13	0.8891	4.41
KAN	3	0.8661	-5.35	0.02616	384.2	0.8890	-4.52	0.8590	-3.42	0.8823	-2.63
WLF	4	0.8839	-5.57	0.02551	360.0	0.9093	-5.41	0.8780	-4.43	0.9034	-4.31
BUS	5	0.9081	-6.90	0.02461	341.6	0.9322	-7.20	0.9014	-6.12	0.9255	-6.44
BGR	6	0.7602	-10.96	0.02673	327.8	0.7851	-11.69	0.7581	-9.75	0.7828	-10.52
TIE	7	0.7930	-9.20	0.02616	330.6	0.8176	-9.83	0.7879	-8.20	0.8123	-8.87
CLS	8	0.7605	-10.38	0.02673	327.0	0.7852	-11.13	0.7571	-9.23	0.7816	-10.02
FRG	9	0.7659	-7.24	0.02621	323.2	0.7888	-8.18	0.7607	-6.24	0.7834	-7.21
PRM	10	0.7695	-6.43	0.02556	325.2	0.7921	-7.31	0.7681	-5.77	0.7905	-6.67
RIM	11	0.7679	-5.95	0.02520	325.6	0.7901	-6.82	0.7669	-5.35	0.7890	-6.24
KSZ	12	0.7490	-5.89	0.02610	319.7	0.7707	-6.99	0.7474	-5.26	0.7689	-6.38
F1	13	0.7425	-5.17	0.02572	318.4	0.7633	-6.32	0.7424	-4.64	0.7631	-5.80
F2	14	0.7332	-4.59	0.02572	315.2	0.7530	-5.85	0.7336	-4.13	0.7533	-5.41
F3	15	0.7260	-4.14	0.02572	311.9	0.7447	-5.51	0.7273	-3.75	0.7459	-5.13
F4	16	0.7203	-3.71	0.02572	308.4	0.7378	-5.19	0.7219	-3.40	0.7392	-4.89
F5	17	0.7160	-3.37	0.02572	304.7	0.7321	-4.95	0.7175	-3.08	0.7335	-4.67
F6	18	0.7125	-3.09	0.02572	300.9	0.7272	-4.77	0.7138	-2.81	0.7284	-4.49
F7	19	0.7097	-2.85	0.02572	296.9	0.7228	-4.62	0.7109	-2.59	0.7239	-4.36
KIEW	20	0.7089	-2.83	0.02594	295.7	0.7216	-4.64	0.7108	-2.62	0.7235	-4.43
RDK	21	0.7070	-2.62	0.02572	292.7	0.7184	-4.47	0.7086	-2.42	0.7199	-4.27
MUR	22	0.7067	-2.27	0.02433	292.1	0.7171	-4.04	0.7084	-2.16	0.7187	-3.93
BAG	23	0.7062	-2.56	0.02572	290.6	0.7167	-4.45	0.7078	-2.38	0.7182	-4.27
CHR	24	0.7063	-2.34	0.02471	291.6	0.7167	-4.15	0.7081	-2.23	0.7184	-4.03
LICH	25	0.7054	-2.34	0.02505	289.5	0.7151	-4.20	0.7072	-2.23	0.7169	-4.09
SUD	26	0.7055	-2.29	0.02471	289.6	0.7151	-4.13	0.7068	-2.12	0.7163	-3.96
PRG	27	0.7052	-2.36	0.02520	288.7	0.7146	-4.25	0.7065	-2.19	0.7159	-4.07
BUD	28	0.7048	-2.44	0.02567	287.5	0.7140	-4.38	0.7063	-2.26	0.7154	-4.20
SAM	29	0.7040	-2.44	0.02616	285.8	0.7126	-4.44	0.7055	-2.26	0.7140	-4.26
CHEW	30	0.7038	-2.29	0.02446	285.5	0.7117	-4.17	0.7055	-2.18	0.7133	-4.05

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table 9 : Model parameter for 7 additional fictive stations located at the East continuation of the profile

station	long.	lat	ocean tide induc. tilt		m 8		ocean tide induc. tilt elast. comb.		AW		m 8 + AW	
			all oceans				North Atlant.					
	λ [°]	φ [°]	$10^{-3''}$	φ^L_{AO} [°]	γ	$\varkappa$ [°]	$10^{-3''}$	φ^L_{NA} [°]	$\Delta\gamma_{AW}$	φ^L_{NA} [°]	γ	$\varkappa$ [°]
F8	38.0	50.0	0.30	301.7	0.7030	- 2.06	0.16	280.1	0.02572	280.1	0.7089	- 4.09
F9	40.0	50.0	0.29	300.1	0.7078	- 2.03	0.15	275.7	0.02572	275.7	0.7057	- 4.10
F10	42.0	50.0	0.27	298.2	0.7000	- 1.93	0.14	271.2	0.02572	271.2	0.7019	- 4.03
F11	44.0	50.0	0.26	295.9	0.6986	- 1.90	0.13	266.7	0.02572	266.7	0.6984	- 4.07
F12	46.0	50.0	0.24	293.2	0.6967	- 1.79	0.12	262.1	0.02572	262.1	0.6944	- 3.90
F13	48.0	50.0	0.23	290.0	0.6951	- 1.76	0.11	257.5	0.02572	257.5	0.6908	- 3.86
F14	50.0	50.0	0.22	286.2	0.6934	- 1.73	0.11	252.9	0.02572	252.9	0.6870	- 3.80
				mean		- 1.89°						- 3.97°

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Tidal Pendulum Signal in Tectonically Active Periods

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Summary

Usually the Analogue Recording Speed (ARS) of the tidal pendulum is ~cm/h in case of photo recording method. The capacitive horizontal pendulum offers a chance to increase ARS till ~cm/min. Therefore more frequent data acquisition can be performed and higher frequencies than the tidal ones can be investigated. During the period 1983-88 ARS was increased in the tidal station Sopron at the tectonically active intervals ; parts of such records were digitized (data/min) and their power spectra were computed. Some periods which can be regarded as tectonically calm ones were similarly processed as reference.
The active and calm intervals were compared by means of correlation analysis to point out the effect of tectonical disturbance on the tidal signal.

Introduction

The free oscillation was recorded at first after the Chilean quake (1960). It was reported by different observatories in several papers [Bolt & Marussi,1962;Alsop at al.,1961;Benioff at al.,1961]. Moreover Benioff was able to show the characteristic frequencies in an earlier record (Kamchatkaian quake ,1952). Both mentioned quakes had a magnitude bigger than 8 . Since then several papers dealt with this topic . In the 70's the characteristic frequencies have been found in records of quakes of smaller magnitude [Dratler & Block ,1971;Agnew at al.,1976]. Benioff tried to find these frequencies in the records of quake-free periods [Benioff at al.,1959]. This attempt was not successful due to the low sensitivity of the instruments - as he

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wrote - but the development of the instrumentation would bring success .
The instrumentation for the detection of the free oscillation was : tiltmeters , gravymeters and extensometers i.e. the instrumental technics of the tidal research . The Geod. Geoph. Res. Inst. has been inspired to take part in this investigation by the improved observational technics (high sensitiv horizontal pendulum , digital recording) .In the period 83-88 the speed of the analogue recorder of a capacitive tidal pendulum was increased after some quakes . The first results of the evaluation of these recorders were reported [Bartha,1983;Bartha & Czompo , 1984] .
In these papers the theoretical background of the free oscillation and the operation of the pendulum in tiltmeter and accelerometer mode were described . In the present paper the data processing methods and some new results are given .

Data & Data Processing

The data were produced from the digitizing of the mentioned accelerated analogue signal of the capacitive pendulum . The sampling period was 57.9 sec. The data set "TEST" was produced at similar conditions, but in an inactive period.The parameters of the quakes are summarized in the Table I.
In the observational period the sensitivity of the pendulum and the condition of the analog recording were different .
The data processing of the free oscillation records has a long historical background . The majority of the methods was the high pass filtering process and after that Fourier spectra (amplitude,phase,power) were computed . Someones used low pass or band pass filters ,respectively . Alsop applied a correction method to eliminate the frequency-shift [Alsop at al.,1961]. Several scientists investigated the relation between the Q value of the peaks and the Rayleigh waves [Sailor at al.,1977].The main goal of ours processing was to find the correct frequencies and amplitudes of the free oscillation from a unique big quake . We have choosen different ways for the investigation. The possibility of detection has been investigated on several records , run after

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smaller quakes .For this purpose the correlation analysis was applied to find the frequencies of the free oscillation. The autocorrelation and cross correlation functions contain the characteristic frequencies - this feature is used in our processing .

If the signal is: $x(t)=x_1(t)+x_2(t)$

where the stochastic component : $x_1(t)$

and the periodic component:

$$x_2(t)=\frac{a_\emptyset^2}{2}+\sum_{n=-\infty}^{\infty}(a_n\cos(n\omega t)+b_n\sin(n\omega t))$$

then the autocorrelation function : $R_{xx}=R_{11}+R_{22}+R_{12}+R_{21}$

where $R_{12}\approx\emptyset$; $R_{21}\approx\emptyset$

R_{11}-->const. or $\emptyset$

thus

$$R_{xx} \to R_{22}(\tau)=\frac{a_\emptyset^2}{2}+\frac{1}{2}\sum_{n=-\infty}^{\infty}(a_n^2+b_n^2)\cos(n\omega\tau)$$

i.e. the autocorrelation function has the similar angular frequency ω than the periodic component .The cross correlation function contains the common frequencies of periodic components of the signals .

The band pass filtering has been solved by corelation computation, too . A so called "CHIRP" signal was at first produced .This signal contains a band of linearly increasing frequencies (2ØØ-333Ø sec)[Fig.1.].The cross correlation function of the data set and CHIRP is - filtered signal ,due to the shape of the CHIRP signal in the frequency domain [Fig.2.].

The consequencies were drawn partly from the cross correlation function of TEST and the data set and from the cross correlation function of CHIRP and the data set and partly from their spectra [Fig. 3.].

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Results & Consequencies

The detected frequencies are shown in Table II. The frequencies detected in the cross correlation of TEST and CHIRP are not included in the Table II. , because they can not be the frequencies of the free oscillation . The frequencies present in the crosscorrelation functions of the data set and TEST are denoted with an asterix . Therefore they have lower reliability . The sign plus (+) denotes the lower sensitivity of the pendulum .
All this shows that this technics (tidal instrumentation + data processing) can be used for the detection of the free oscillation of the Earth , but the instruments should operate with high sensitivity - risking the possibility of continuous recording .
There is planned to instal a digital recording system to record automatically the signal of the last 2 days with dense sampling. By mens of this system the post-quake period would always be recorded and saved for processing .

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EARTHQUAKE	DATE	ORIGIN TIME (GMT)	EPICENTER		DEPTH (km)	MAGNITUDE
			LAT.	LONG.		
El Salvador	29.Ø4.83	Ø1h-Ø2m-2Øs	13.43N	89.22W	92	4.8
California	Ø2.Ø5.83	23h-42m-38s	36.24N	12Ø.3ØW	12	6.5
Japan	26.Ø5.83	Ø3h-ØØm-Ø1s	4Ø.37N	139.15E	33	7.6
Ryukyu Islands	Ø4.Ø9.84	13h-Ø8m-16s	24.65N	124.58E	72	4.7
Taiwan	14.11.86	22h-34m-23s	24.Ø4N	121.96E	33	6.2
Tonga Islands	Ø6.1Ø.87	Ø4h-19m-Ø6s	17.94S	172.23W	16	7.3
Alaska	3Ø.11.87	19h-23m-2Øs	58.68N	142.79W	1Ø	7.6
Komandorsky Island	29.Ø2.88	Ø5h-31m-41s	55.Ø1N	167.45E	33	6.8

Table I.
The registered Earthquakes

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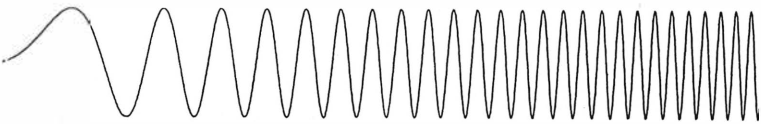

Figure 1.
The CHIRP signal in the time domain

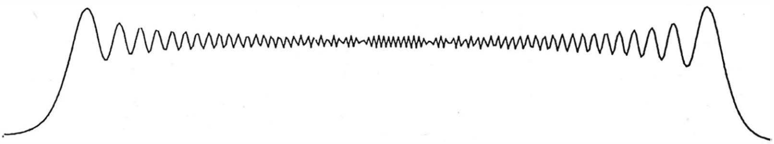

Figure 2.
The CHIRP signal in the frequency domain

a.

b.

c.

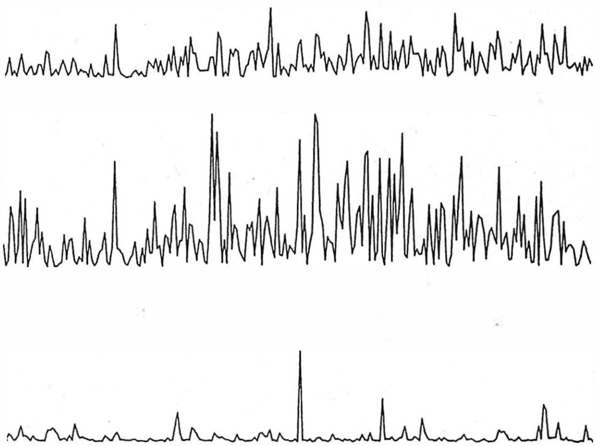

Figure 3.

a. Power spectrum of the data set (26.Ø2.88)
b. Power spectrum of the crosscorrelation function of the data set and the CHIRP signal
c. Power spectrum of the crosscorrelation function of the data set and the TEST record

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MODE	PERIOD from Mendiguren, 1973 (sec)	29.04.83 +		02.05.83		26.05.83		04.09.84 +		14.11.86 +		06.10.87 +		30.11.87 +		29.02.88 +	
		period	ampl.	period	ampl.	period	ampl.	period	ampl.	period	ampl.	period	ampl.	period	ampl.	period	ampl.
T 5	1059					1058	69	1021*	19	1040	10						
S 7	812	823	36			823*	191	801*	45								
S 8	707			714	101	706	103			714	11	689	19	689	13		
S 9	635	631	12			630	470	631	19	637	9			651	21	651	15
S 10	581					584	82	581	34							575	18
S 11	537			534	136	529	221					539	13	529	15		
S 12	504	510	28	515	85	515	351			498	13					510	31
S 13	473			482	88	474	307	478	29			481*	13	478	14		
S 14	448			442	103	449	417			445	16			449*	17	445	16
S 15	426	420	34	426	102	426	53									432	54
S 17	389			382	111	385	560	389	55			390	11	385	22	382	35
S 18	374	370	42	370	335	375	441	375	90	370	11						
S 19	360			365	224	359	211	359*	39	359	15	366	12			361	19
S 20	347	348	643	345	107	345	69					341	18	346	16	352	24
S 21	336					331	132							331	16	337*	26
S 22	325	327	18	320	218	327	59							320	11	327*	25
S 23	315	311	109	309	191											311	30
S 26	290	291	13	291	58			289*	13							291*	13
S 28	275													278	10	276	25
S 29	268	269	13	267	43			274*	12							268	12
S 33	245	248	10													248	12
S 35	235															234	13
S 36	229					227	195										
S 37	224			224*	120	225*	60										
S 38	220							221*	14							221	17
S 40	212					211*	56									212*	13

Table II.
The identified periods of the spectra

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TEST OF A PORTABLE SHORT-BASE QUARTZ TUBE STRAINMETER WITH CAPACITIVE TRANSDUCER

by NEUMEYER, J.; SIMON, D.; HARWARDT, H.; KARMALEEVA, R.M., GDR/USSR

1. Application of the portable strainmeter

The portable strainmeter was constructed for temporary measurements of the tidal strain variations along profiles or within local arrays. Measurements of this kind are required for different geophysical problems. Samples for such measuring problems are shown by the figures 1 and 2.

Fig. 1 shows the calculated variations of the tidal waves $e_{\lambda\lambda}$(M2) and $e^{oc}_{\lambda\lambda}$(M2) along

- a NS profile at the meridian λ = 10.1° E
- an EW profile at the latitude φ = 51° N in a part of Europe

The body strain waves were calculated for the reference Earth models which were used for the interpretation of Earth tide measurements before 1983 (MOLODENSKI /1961/) and after 1985 (WAHR/1981/). Depending on the applicated Earth model there is a large difference concerning the locality of the amplitude zero of $e^{o}_{\lambda\lambda}$(Me). We found a distance of 235 km between the corresponding latitudes. Considering the spherical structure of the field of the semidiurmal body strain waves $e^{o}_{\lambda\lambda}$ within the zone between the latitudes 49 N and 53 N, SIMON & KACZOROWSKI 1981 presented an empirical method for the determination of the second order Love numbers by strain measurements along a NS profile. At the latitude φo, where the amplitudes of the body strain waves $e^{o}_{\lambda\lambda}$ disappear, direct measurements of the corresponding ocean tide induced strain waves e are possible. The latter enables a control of the modellings concerning the ocean loading effect.

Fig. 1 shows the large variations of the ocean loading strain waves $e^{oc}_{\lambda\lambda}$ (M2) along such an EW profile situated here along the latitude circle 51 N. The parameters of the $e^{oc}_{\lambda\lambda}$ (M2) waves are tabulated in SIMON & KACZOROWSKI /1988/.

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The portable strainmeter may be applicated usefully too in local arrays to estimate and minimize the falsifications induced by the cavity effect. Using the results of HARRISON's /1976/ modellings the rough drawing in fig. 2 shows the deformation of a long tunnel or adit of square cross-section (lower part) by horizontal tension. The undeformed corners are represented by solid lines and the deformed ones by dashed lines. The falsifications induced by the cavity effect can be minimized if the following rules for the installation of strainmeters would be considered:

1. the measuring places must be near the axis of symmetry of the tunnel, and distant to the ends of it;
2. the strainmeters must measure approximately in the direction of the tunnel axis;
3. normally the length of the measuring (for instance quartz tube) must be small with respect to the length of the tunnel, but large compared with the depths of local cracks induced by shooting and blasting in the making of the tunnel.

In order to check and to minimize the falsifications induced by the cavity effect we propose array measurements of that kind as shown in fig. 2. Here by the symbols S1, S2, S3 three parallel strainmeters are marked measuring approximately in the direction of the tunnel axis but installed in different perpendicular distances to the latter one.

2. Special requirements concerning the construction of the portable strainmeter

Resulting from the destinations of the instrument the following requirements concerning the construction of the portable strain-meter have been considered:

- short time for the dismounting, the transport and the rein-stallation of the instrument at another place
- short length of the measuring base and consequently a high sensitivity of the transducer
- a simple calibration method notwithstanding the possibility of an additional (control) calibration by means of a Laser interferometrical method.

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3. Technical realization

The mechanical construction of the portable short-base strainmeter is shown in principle in fig. 3.
Here are

1 - Invar anchor, 0.8 m long
2 - horizontal Invar bar, 0.3 m long
3 - system of two Invar clamping devices which enable the translation of the horizontal bars 2 at both ends of the strainmeter in three orthogonal directions
4 - magnetic circuit with coils for the generation of the magnetostrictive calibration signal
5 - quartz tube, 3.0 m long
6 - support with a mirror on both sides of the quartz tube 5 destinated for Laser interferometrical calibrations
7 - support holding the quartz tube by two wires
8 - cylindrical roll corpus moving due to the strain movement between the quartz tube 5 and a quartz plate 9 located upon a base plate 10 which can be adjusted by three screws 11. The rolling corpus is equipped with a mirror which enables a direct foto-optical record of the strain movements. The beam-length is about 10 m. This simple method used for the calibration of the strainmeter was more extensively described in LATYNINA, KARMALEEVA, HARWARDT & SIMON /1980/.
12 - capacitive transducer

Structure and mode of action of the transducer 12 and of the corresponding amplifier are explained by means of figure 4. Figure 4 shows the functional block diagram of the electronics. The capacitive transducer is part of a carrier frequency bridge used in form of a differential bridge. The measuring signal results from a detuning of this bridge, characterized by amplitude and phase. The signal passes an impedance converter and a preamplifier and later on a phase-sensitive rectifier which was developed especially.

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A differential plate capacitor (fig. 5) was chosen, because of the linear transfer function of this kind of transducer. A suitable value for the distance of the standing plates is 0.6 mm. The transducer consists of two capacitors, the first one works like a differential capacitor, the second one as a mutual capacitance connected directly with the impedance converter. Reasons for the accuracy are: The amplitude stability of the oscillator supplying the bridge, careful screening of the sensor, capacitive release of the signal from the middle plate and the phase-sensitive rectification. The solution of the transducer is better than 1 nm.

4. Results of checking the portable strainmeter

The test instrument has recorded 1986-1987 during a period of about 1 year inside the Tiefenort station at a place marked by the symbol "N3" in fig. 7, lefthand. As shown in the figure, the measuring direction, NS, differs by 17° from the azimuth of the tunnel axis. In october 1987, the instrument was dismounted and transported away during 1 day. After drilling a cleft (length 10 m, depht 1 m, width 0,15 m) crossing the measuring place N3 perpendicularly, the instrument was reinstalled and was set into operation during 2 days. A recording sample is given by fig. 6. Here the recording sensitivity was 1,467 x 10^{-9} m/mm. The maximal sensitivity of the sensor applicated here is about 5 x 10^{-10} m/mm. Table 1 gives an impression of the reproducibility of the tidal parameters observed by means of the test instrument. In the table are shown the results of monthly analysis of the records calculated by application of VENEDIKOV's method. The table contains the parameters of the lunar main waves M2 and O1 which are not disturbed so drastically by meteorological effects as for instance the solar main waves S2 and K1.

In table 2 the measuring results of the test instrument are compared with those of two other NS strainmeters installed at the measuring places N1 and N2 within the Tiefenort station (see fig. 7, lefthand).

Furthermore the $e_{\theta\theta}$ (M2) waves measured by all the 3 strainmeters are drawn in vectorial form at the right side of fig. 7.

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The measured waves are compared with the corresponding model waves calculated on the base of the WAHR model or SCHWIDERSKI's map of ocean tides and the Earth model of GUTENBERG-BULLEN, respectively, by SIMON & KACZOROWSKI /1981/.
Fig. 7 shows that the largest parameter deviations from the calculated ones were measured at the measuring place N2. This result corresponds with the results of the modellings of HARRISON /1976/ where strainmeter measurements performed perpendicularly to the tunnel axis must contain the relatively largest falsifications by the cavity effect (see fig. 2).
The best-fitting parameters were received by means of the new instrument at the place N3. Concerning the comparability of the results of quartz tube and wire strainmeters we hint to the comparison of the records of both the strainmeters E1 and E2 (s. LATYNINA, KARMALEEVA, HARWARDT & SIMON /1980/). Here no significant discrepancies were found between the corresponding parameters.

5. Conclusions

As a test result we can state that the new instrument seems to be suitable for profile measurements or for an application in local arrays.
In this connection it must be considered that the test was made in the salt mine of Tiefenort where the humidity of the air amounts only 40 %. At the other hand, it is a well known fact, that variations of the air humidity have a falsificating influence on the measuring results of capacitive transducers.
In underground cavities with strong variations of the air humidity it seems therefore better to install the capacitive sensor within a container filled with a fluid, oil or a flourcarbone (see ZUERN, JENSCH et al. /1985/)

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table 1
Tiefenort station
ambulatory strainmeter N3

recording	recording	$e_{\theta\theta}$ (M2)		$e_{\theta\theta}$ (01)	
periods	days	$A \times 10^{-10}$	κ	$A \times 10^{-10}$	κ
13.9.-22.10.86	40	124.48	1.58°	48.75	0.57°
		1.53	.70	3.14	3.69
21.9.- 1.11.86	42	123.28	1.52°	47.29	0.20°
		1.61	.75	3.16	3.83
10.2.-11.3.86	30	126.54	3.12°	55.20	-9.89°
		3.34	1.51	7.12	7.34
6.3.-4.4.87	30	125.73	2.19°	40.12	3.65°
		3.53	1.61	6.40	9.14
20.3.-18.4.87	30	125.30	3.55°	39.35	1.71°
		2.23	1.02	4.88	7.11
19.4.-18.5.87	30	123.44	3.88°	47.16	9.96°
		4.59	2.13	10.78	13.10
20.5.-20.6.87	32	125.39	2.26°	48.08	-1.64°
		2.96	1.35	5.48	6.53
21.6.-20.7.87	30	126.06	3.85°	46.52	-3.71°
		2.97	1.35	3.51	4.31
21.7.-19.8.87	30	131.82	2.06°	42.92	-10.88°
		2.78	1.21	3.83	5.12
20.8.-16.9.87	28	124.94	3.05°	37.19	-2.69°
		3.76	1.72	7.22	11.12

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table 2

Tiefenort station — NS strainmeter

N 2: 25 m wire strainmeter, inductive transducer
N 1: 11.1 m wire strainmeter, inductive transducer
N 3: 3.11 m quartz tube str., capacitive transducer

recording periods	recording days
13.9. - 1.11.1986	50
10.2. - 18.05.1987	98
20.5. - 16.09.1987	120
	268 days

measuring place	$e_{\theta\theta}$ (M2) A × 10^{-10}	$\varkappa$	$e_{\theta\theta}$ (O1) A × 10^{-10}	$\varkappa$
N 2	148.63	6.21°	50.77	1.86°
	0.94	40	1.19	1.41
N 1	124.71	5.38°	42.82	4.07°
	1.06	48	1.71	2.11
N 3	125.49	2.75°	54.13	-1.65°
	1.14	52	2.12	2.69

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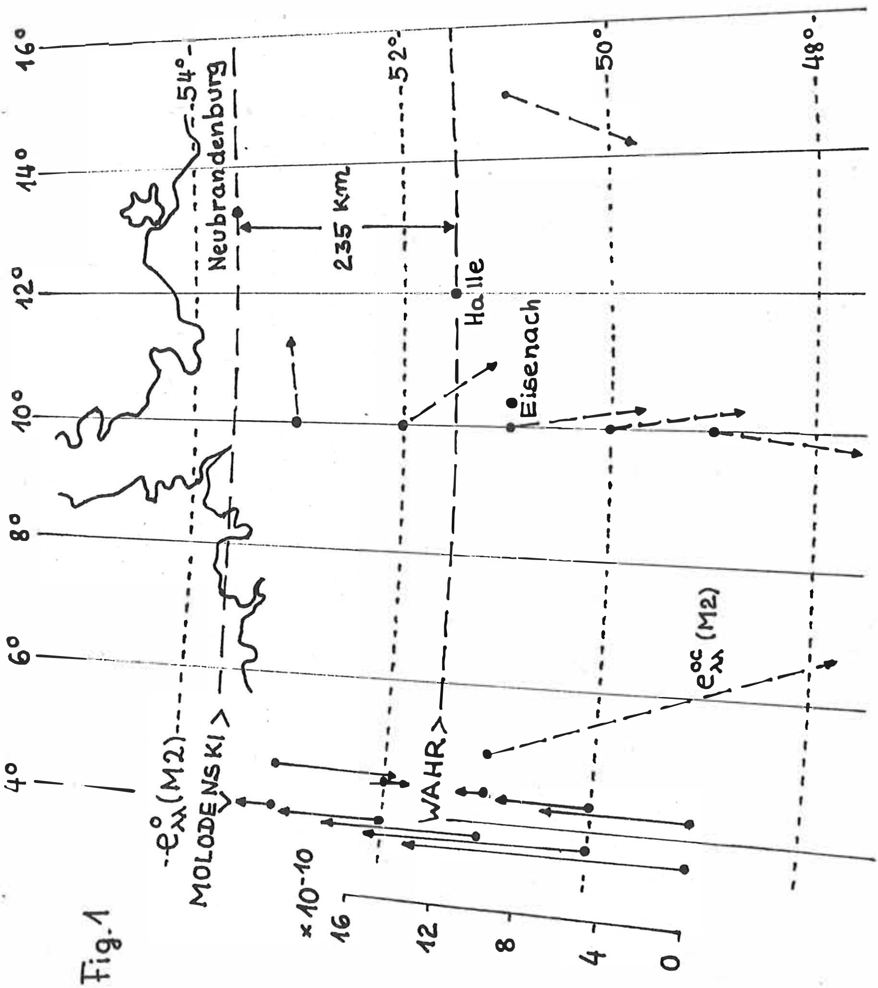

Fig. 1

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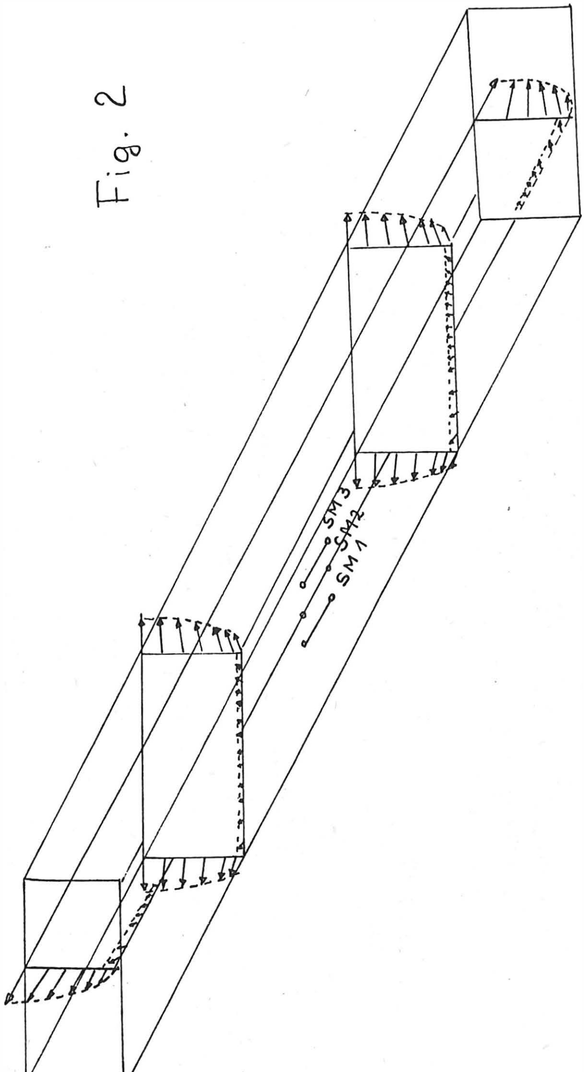

Fig. 2

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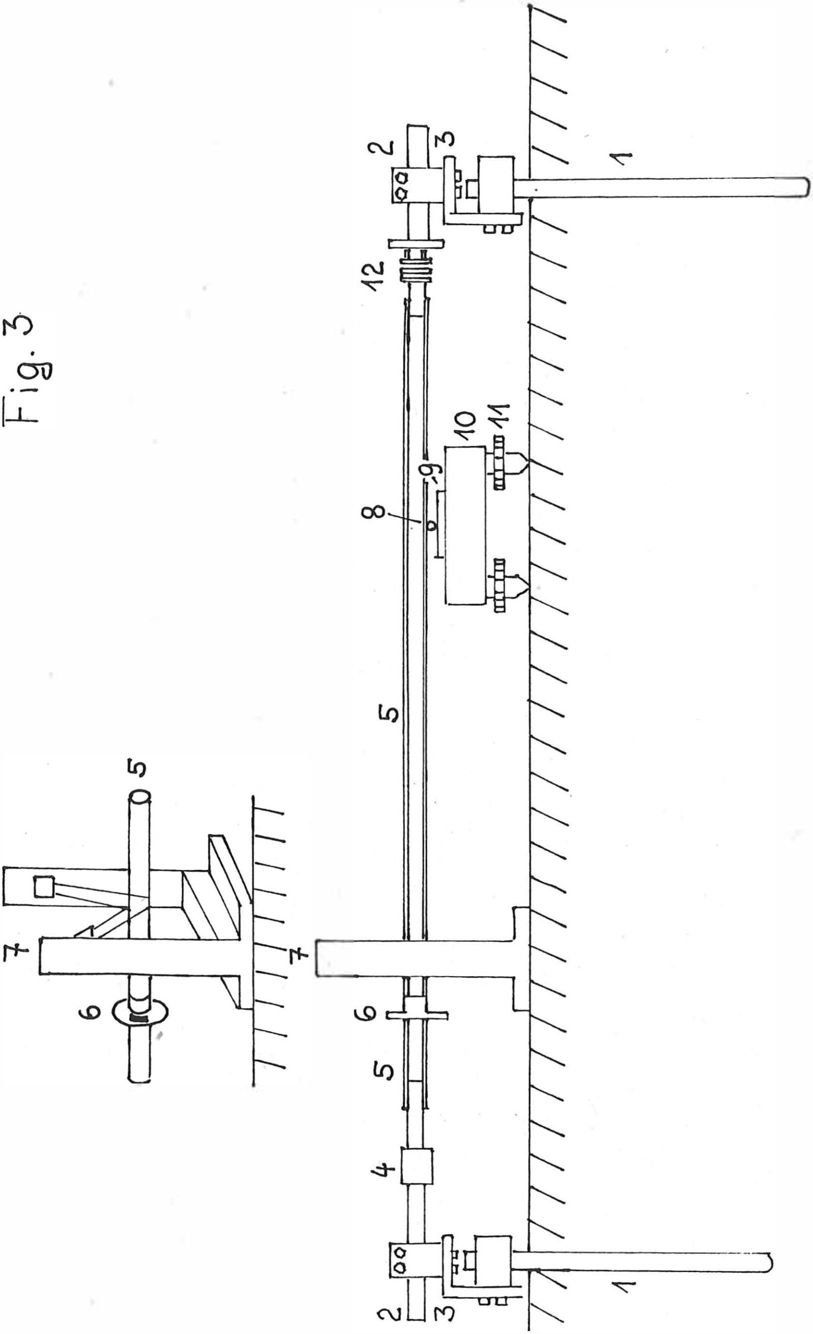

Fig. 3

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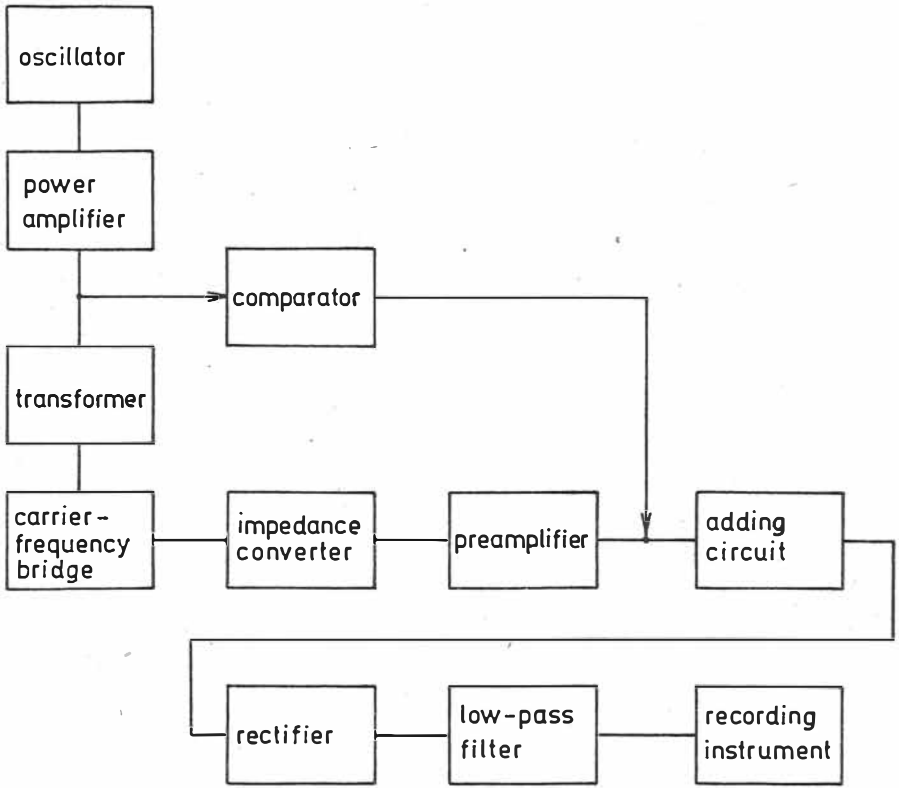
Fig. 4



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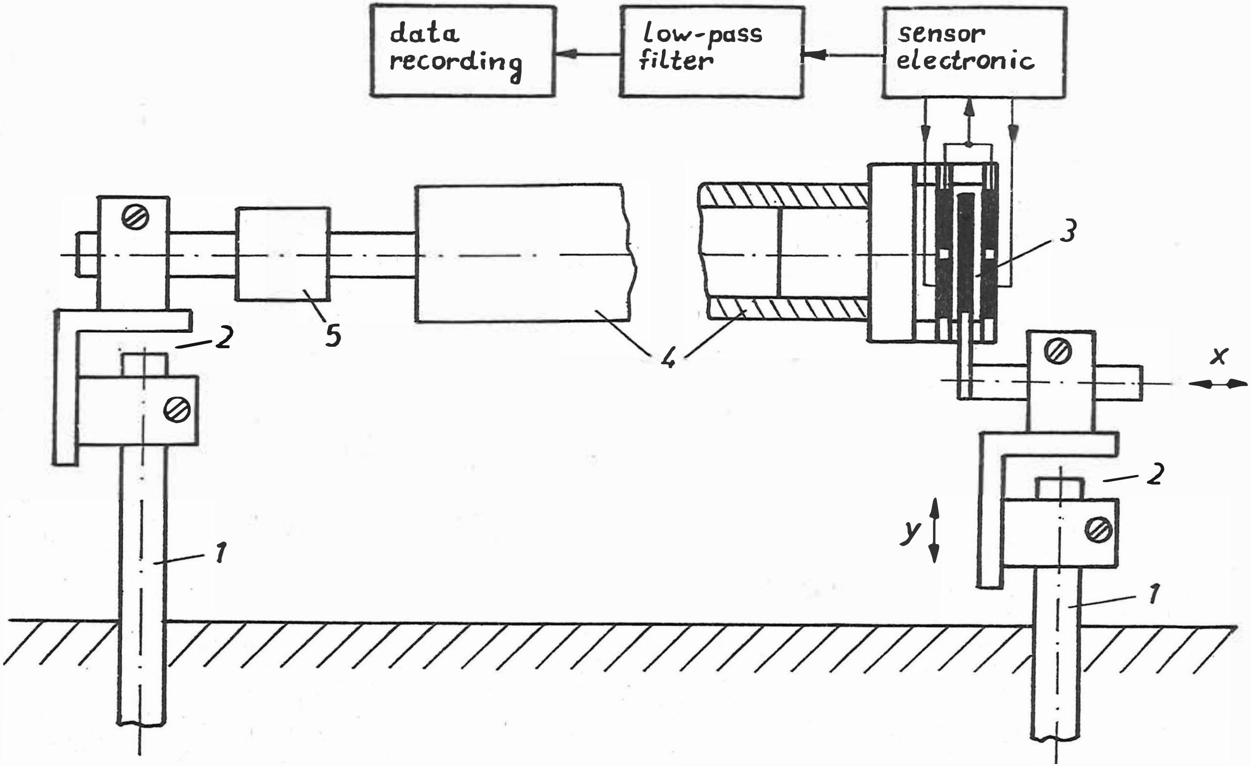

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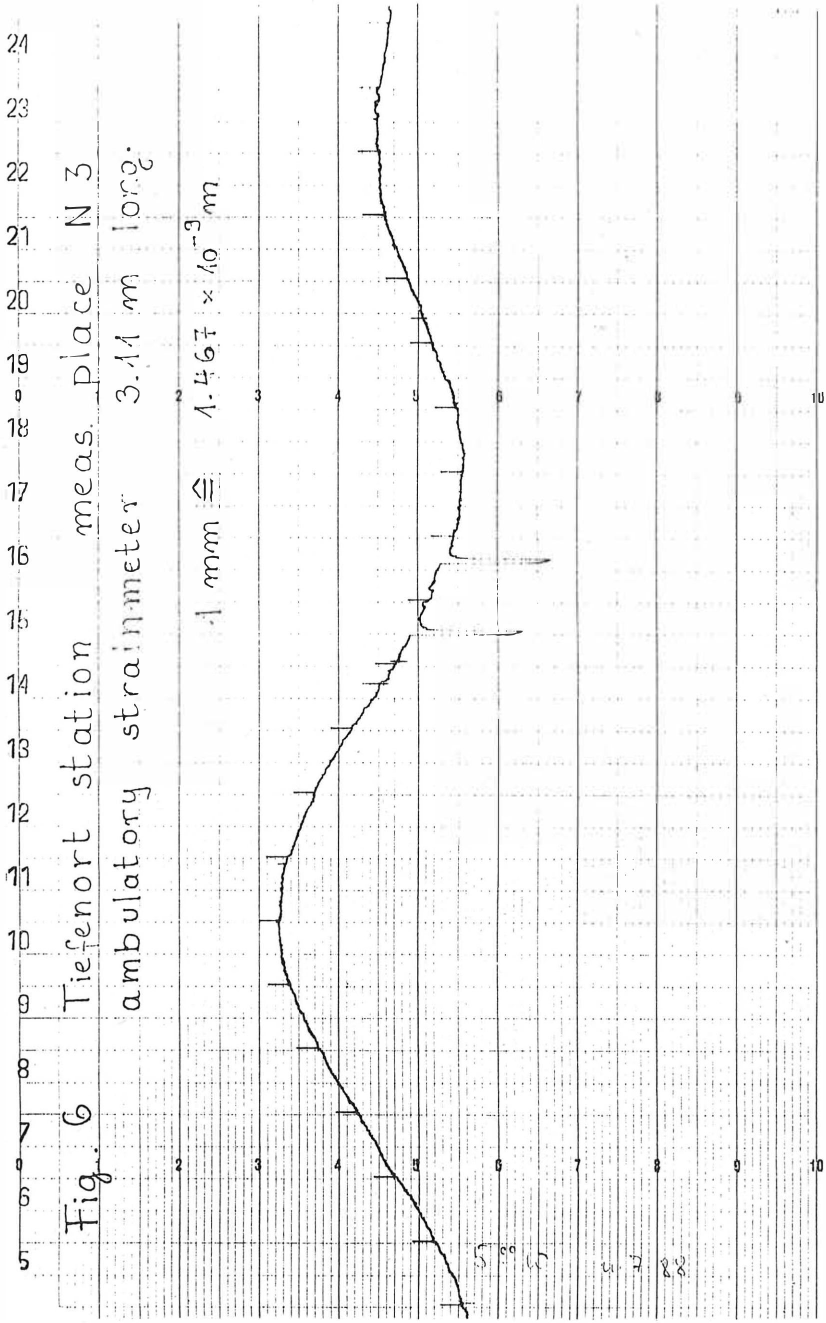

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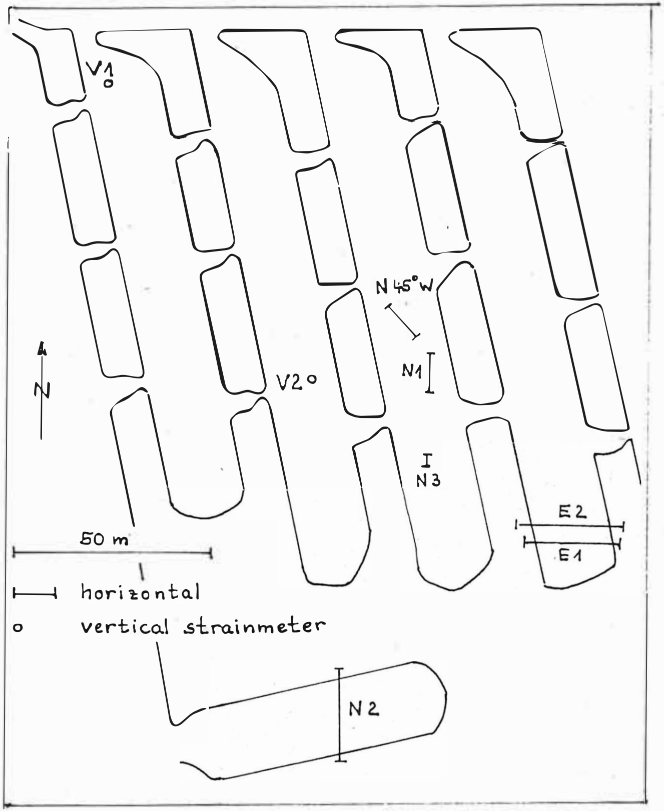
Fig. 7 Tiefenort station



observed $e_{\theta\theta}(M_2)$ waves ($A \times 10^{-10}$; $\varkappa$)

$e^{obs}_{\theta\theta}(M_2) = 148.6 ; 6.21°$ (instr. N2)

$e^{obs}_{\theta\theta}(M_2) = 124.7 ; 5.38°$ (instr. N1)

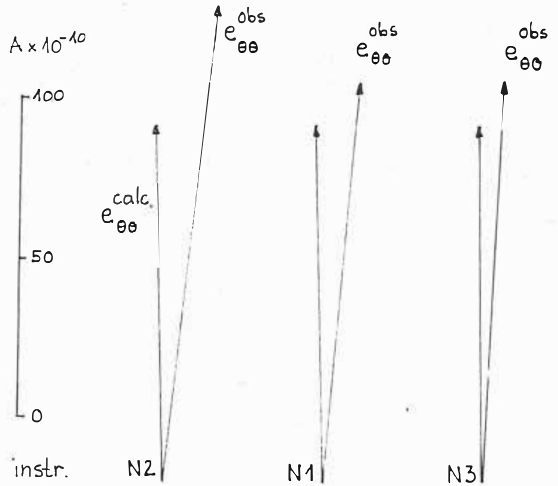
$e^{obs}_{\theta\theta}(M_2) = 125.5 ; 2.75°$ (instr. N3)

calculated $e_{\theta\theta}(M_2)$ waves ($A \times 10^{-10}$; $\varkappa$)

$e^{o}_{\theta\theta}(M_2) = 106.001 ; 0°$ (body strain; WAHR model)

$e^{oc}_{\theta\theta}(M_2) = 5.444 ; 326.96°$ (ocean tide induced strain)

$e^{calc}_{\theta\theta}(M_2) = e^{o}_{\theta\theta}(M_2) + e^{oc}_{\theta\theta}(M_2) = 110.61 ; -1.54°$



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ON THE MODULATION OF THE M2 GRAVITY TIDE

by SCHWAHN, W.*; ELSTNER, C.*; SAVIN, I.V.**

Abstract

The residual spectrum of gravimetric time series of three stations in Western and Central Europe (Brussels, Frankfort/Main, Potsdam) are considered. Using high frequency resolution methods the spectrum in the range of the semi-diurnal tides was investigated.

A yearly and a nearly monthly modulation of the M2-tide were detected.

The yearly modulation in Brussels and Potsdam differs in their character from each other (Potsdam: Phase modulation ε = 1.7 -03 rad; Brussels: Phase and amplitude modulation ε = 7.1 -04 rad, $\approx$ 25 nGal[1]) respectively.

The nearly monthly period may be described for Brussels and Potsdam by the same model. There significant time-varying amplitudes in the order of 40 ... 50 nGal exist for the frequencies 0.078978 cph ($\approx 2\tau - (s-N)$) and 0.082044 cph ($\approx 2\tau + (s-N)$). A systematic deviation against the cited tidal frequencies of -+2 -06 cph was obtained. Therefore a modulation period of 27.18 days instead of 27.21 days was found.

The origin of these modulations are not yet clear. The oceanic tides must be proved for such constituents. An amplification in the region of the L2-tide alone cannot be confirmed.

[1] 1 nGal = 1 -11 ms^{-2}

Zusammenfassung

Die Residualspektren der gravimetrischen Messreihen von drei Stationen in West- und Mitteleuropa (Brüssel, Frankfurt/Main und Potsdam) wurden betrachtet, wobei unter Verwendung von hochauflösenden Methoden der Spektralanalyse das Spektrum im Bereich der halbtägigen Tiden untersucht wurde.

Es wurden eine jährliche und eine nahezu monatliche Modulationsperiode der M2-Welle aufgefunden.

Die Jahresmodulation unterscheidet sich in ihrem Charakter für Brüssel und Potsdam voneinander (Potsdam: Phasenmodulation ε = 1.7 -03; Brüssel: Phasen- und Amplitudenmodulation ε = 7.1 -04 rad bzw. 25 nGal.

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Die monatliche Modulation kann für Brüssel und Potsdam durch das gleiche Modell beschrieben werden. Es existieren signifikante zeitlich variable Amplituden in der Größenordnung von 40...50 nGal für die Frequenzen 0.078978 cph ($\approx 2\tau - (s-N)$) und 0.082044 cph ($\approx 2\tau + (s-N)$). Es wurde eine systematische Abweichung von -+2 -06 cph festgestellt. Daher wurde die Modulationsperiode mit 27.18 Tagen anstatt 27.21 Tagen bestimmt.

Die Ursachen dieser Modulationen sind noch ungeklärt. Die Ozeangezeiten sollten auf diese Modulationen überprüft weren. Eine Amplitudenverstärkung im Bereich der L2-Tide allein kann nicht bestätigt werden.

1. Introduction

This paper will inform you on some news from the world of the nanogal. The nanogal - this is 10 **-12 of the mean gravity force. In gravity the accuracy of ten nanogal for the phaenomenon under investigation corresponds for instance with an accuracy of the Earth's radius of 0.03 millimeter.

From his famous measurements 75 years ago in 1913/1914 in Potsdam SCHWEYDAR (1914) derived an inner accuracy for the determination of the M2-tide in the order of 1 *10 **-01. Today we reach accuracies in the range of 1...2.*10 **-04. It means the inner reliability increases by a factor of thousend! In accordance with the goal of our symposium this paper will provide you with an impression on the manner in which one can use this improved level of accuracy for the investigation of new geodynamic phaenomena.

2. Starting points

At the first time on the Madrid Symposium on Earth Tides in 1985 spectra of gravimetric tidal residua were presented, which exhibit distinct spectral lines instead of the expected smooth noise level. The power spectrum of the superconducting gravimeter in Brussels, obtained by DE MEYER and DUCARME (1985) provides a good example. In the range of the semidiurnal waves you can remark lines, characterized by the symbols L2 and N2 resp.

Also the variance spectrum for the gravimeter GS15 Nr. 222 (Fig. 1), which was obtained by PLAG (in ASCH et al.(1985)), shows the same lines for the gravimetric time series at Potsdam. These distinct lines exeed the general noise level (15 nGal) by the factor 3...4., i.e. the amplitudes reach up to 40...50 nGals.

These values cannot be explained by neglected terms in the harmonic development of the tides. Fig. 2 and 3 show the contributions of the third order harmonics of the sun and the fourth order ones of the moon to the tidal spectrum (TAMURA (1987)). We can state that all the additional waves do not exeed a threshold of 10 nGals.

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Using the notation of ASCH et al.(1985) and neglecting the S2-line (Fig.1) these lines may be arranged according to their nearly equal amplitudes in three pairs:

H1 and H2, i.e. alpha2 and beta2,
N2 and L2
2N2 and K2 .

With regard to the frequencies all these pairs have the same point of symmetry f_{PS}:

$$f_{PS} = 0.0805 \text{ cph.}$$

It is the frequency for M2 !

The facts that these lines occure though the observations were adjusted by the least squares method and the surprising symmetry were the starting point for our investigations.

3. Some basic considerations

At first some explanations on the residual spectrum and the modulation phenomena: If one observe a spectral line at the frequency f_J with the amplitude A_J in the residual spectrum then this is caused by either constituents with frequencies outside the used tidal model or, for frequencies inside the model, by additional, up to now unknown , contributions . Naturally one suppose hereby that the grouping follows the physical properties of the model and its set of frequencies is complete. The difference of the used development against that of TAMURA (1987) in the order of a few nanoGals may be neglected with respect to the magnitude of the above noted lines.

It is well known that as well the amplitude as the phase modulation produce for periodic modulation functions symmetric features in the spectrum (WOSCHNI(1960)). There are products of sinus- and cosinus-terms of the carrier frequency f_o and the modulation frequency f_1, $f_1 \ll f_o$. By addition theorems we obtain for the arguments frequency sums and differences $f_{L,R} = f_o \pm f_1$. These new frequencies appeare on the left hand side (f_L) and the right hand side (f_R) of the carrier frequency f_o (Fig. 4).The **amplitude modulation** yields only **one pair** of frequencies. On the other hand the **phase modulation** leads to a **manifold** of pairs in the manner of $f_{k(L,R)} = f_o + k*f_1$, k = 1,2,...,n. The value n depends on the range of the phase deviation ε . In our consideration holds $\varepsilon \ll 1$. The amplitudes are reflected in the following manner: In the case of the **amplitude modulation** we obtain for the amplitude A_1 of the modulation wave in the spectrum the amplitude $A_1/2$ at the frequencies f_L and f_R. In the case of phase modulation BESSEL-functions of the first kind describe in dependence on the value of the phase deviation the amplitudes for the different k. For $\varepsilon \ll 1$ holds n=1, i.e. only one **symmetric** side band. The amplitude is $(A_o * \varepsilon)/2$ in the spectrum .

A nice method to distinguish the amplitude modulation from the phase modulation is the pointer table. In the pointer table, after Sidney CHAPMAN the socalled harmonic dial, for the frequency f_o the carrier is described by the amplitude A_o and the phase lag $\varkappa$. Around this tip the points are situated, which represent the instantaneous amplitude of the modulation wave in the course of the period T_1. If a pure amplitude modu-

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lation (ε = 0) occure, then the points are arranged in a straight line in the **same direction** as the vector of the carrier frequency. For pure phase modulation (A_1 = 0) with small phase deviation also a straight line results, but **perpendicular** to the vector.

If the harmonic dial for the frequency f_o shows a **circle** with the radius A_D in the course of the time span T_B, then a **single** additional wave occures in the spectrum at the frequencies $f_D = f_o \pm f_B$, whereby + is valid for the counter-clockwise rotation, - for the clockwise ones. The amplitude in the spectrum is equal to the radius A_D. If the time span T_B , the beat period, is very long, then the frequencies f_o and f_D are very close to each other and methods with a high frequency resolution are needed.

3. Results

We investigated the narrow-band structure in two ranges:

- in the nearest surroundings (0.0796 ... 0.0814) of M2 (f_o = 0.0805114 cph) for **yearly** modulations,
- in the wider range (0.076 ... 0.085 cph) of M2 for **monthly** modulations.

3.1 Yearly modulation

Fig. 5 represents the power spectrum of the residuals for the time series at Potsdam from the time interval March 1982 till October 1986 using the demodulation procedure and subsequent maximum entropy method (MEM) (SAVIN (1985),SAVIN (1987)). By the narrow-band analysis and the excellent noise suppression very clearly can be seen the **symmetric** frequency difference Δf = 1.147 * 10**-4 against M2. The difference results a modulation period of 363 days. For the amplitude estimation the harmonic dial is used (Fig. 6). One point represents the mean tidal parameter for the corresponding month in the course of 12 years 1974 - 1986 of registration at Potsdam. Here exists a significant variation of the phase lag $\varkappa$, see the error bars for June and December respectively.The winter and sommer are charaterized by a larger phase deviation than the spring and autumn, which are situated near the long-term vector A_o. A phase modulation with a phase deviation ε = 0.095° = 1.65 -03 rad can be derived from fig. 6.From the symmetry in the spectrum and the straight line perpendicular to A_o with an amplitude of 55 nGal one can deduce a phase modulation with ε = 55/32.700 = 1.68 -03 rad and an amplitude $A_o * \varepsilon /2 \approx 27$ nGal in the spectrum. This value is in a very good agreement with the surrounding amplitudes nearby M2 in figure 9.

For Brussels the high resolution power spectrum (Fig.7) in the very close surrounding of M2 does not exhibit a symmetry. Only **one** line at the **right** hand side in a distance Δf= 1.131 *10**-4 equals 368 days is remarkable. On the left hand side a very near line hints on a long periodicity of 6.45 years. According to the single line the points of the hodograph (Fig. 8) are arranged in a first approximation along a circle. His radius is in the order of ≈ 25 nGal, the amplitude is $A_D = A_1 = A_o * \varepsilon$ = 25 nGal, ε = 7.1 -04 rad. From fig. 8 a phase

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deviation of $\varepsilon = 0.04^{\circ} = 7.0$ -04 rad may be obtained. This model for the yearly modulation confirmes that one of DUCARME, VAN RUYMBEKE and POITEVIN (1986).

One may conclude: In both the series the yearly modulation exists, but the character is very different. Further investigations are needed.

3.2 Monthly modulation

The figures 9 and 10 show the FOURIER-spectra of the gravimetric residuals for Potsdam March 1982 till October 1986 and for Brussels June 1982 till October 1986, i.e. for the same time interval. The amplitudes in the **range** of L2 and N2 form very sharp spikes.

With respect to the question, whether these are tidal or nontidal frequencies the parameters of the phenomena were determined as precise as possible.

Table 1: MONTHLY MODULATION OF THE M2-TIDE
Potsdam March 1982 - Oct. 1986
Brussels June 1982 - Oct. 1986

N2 - range			Brussels	Potsdam
	Frequency	cph	0.078978	0.078980
	Period	h	12.6617	12.6614
FOURIER	Amplitude	nGal	50.0	45.0
spectrum	Phase	deg	45.4	21.9
	Frequ. resol.	cph	4 * 10**-6	
	Noise level	nGal	4	7
Demod.&	Frequency	cph	0.078978	0.078977
MEM	Period	h	12.6616	12.6619
	SNR	dB	20	15
L2 - range			Brussels	Potsdam
	Frequency	cph	0.082045	0.082045
	Period	h	12.1883	12.1884
FOURIER	Amplitude	nGal	48.1	35.0 (Leak.?)
spectrum	Phase	deg	- 42.5	- 38.4
	Frequ. resol.	cph	4* 10**-6	
	Noise level	nGal	4	7
Demod.&	Frequency	cph	0.082041	0.082045
MEM	Period	h	12.1890	12.1883
	SNR	dB	17	17

Mean parameters for the modulation

Frequencies:	0.078978	0.082044
Periods:	12.66165	12.1885
Phasediff. N2 -L2:	87.9 Brussels,	60.3 Potsdam

Diff. to M2: Frequ: $f_1 = 1.5332$ -03 cph
Period of modulat.: T_1 **= 652.199 h**
= 27.175 d
Mean **amplitude of modulation: 89 nGal.**

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The nearest important period of the moon is the draconic period of 27.21 d, symbolized by the signature s - N. The other periods are even longer (tropic 27.32 and anomalistic 27.55 d). This draconic period results symmetrically to the M2 - frequency (symbol 2τ) two frequencies in the groups

N2	2τ - (s-N)	{245.545}	0.078980 cph	12.6614 h
L2	2τ + (s-N)	{265.565}	0.082042 cph	12.1888 h.

With respect to our results (see table 1) for the frequency in the N2-region no other tidal wave lies in a reasonable neighbourhood to the above noted values, whereas in the L2-region a tidal wave with the DOODSON-numbers {265.645} and the values 0.082043 cph, 12.1884 h should be taken in the consideration. With respect to the amplitudes should be noted that for the tides {245.545} and {265.565} a relation r = 1.02 holds. On the basis of the empirical spectrum a value r = 1.04 was obtained. This relation seems to be an argument for a tidal origin. On the other hand a deviation of 2 -06 cph exists in the direction to the lower frequencies for {245.545} and to higher frequencies for {265.565} . This results a larger frequency difference to M2 and therefore we obtain for the modulation period the above noted value of 27.175 days. This seems to be a nontidal one.

There are further arguments for a non-tidal origin:

- On the basis of the pointer tables for L2 and N2 (DITTFELD 1988) one can conclude from the time span T_B in the order of 6...10 years the existence of two additional waves at the frequency ranges $f_D = f_o \pm f_B$. The sign - holds for the clockwise rotation for the carrier N2 (0.078999 cph) and the sign + holds for the counter-clockwise rotation for the carrier L2 (mean frequency 0.082027 cph of the L2-group in the years 1982 - 1986).

Table 2: Additional frequencies f_D determined on the base of the carrier frequency and the time span for one rotation in the harmonic dial

rotation	5	6	7	8	9	years
carr. N2	7.8976	7.8980	7.8982	7.8984	7.8986	-02 cph
carr. L2	8.2049	8.2046	8.2044	8.2041	8.2040	-02 cph

Comparing the thick printed frequencies with the values of the mean parameters for the modulation (table 1) one can remark the good agreement. It means that indeed these frequencies exist. The figures dont show as well a constant radius as a constant length of the arc for equal spaced time intervals. Both these facts hint on different amplitudes and slightly varying frequencies.

- This temporal variability can be seen also in the fig.5 of the paper by ASCH et al.(1986). In the range of 0.079 and 0.082 cph broader frequency bands with time-varying amplitudes exists.

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- After the complex decomposition and filtering in the gravimetric time series appear very clearly a time-dependent weak stochastic variation of the amplitude and of the phase.

- From the spectrum in the publication by RICHTER (1987) (fig. 11) one can derive a period of 27.28 days for the time interval August 1981 till April 1984. This result is also an indication on the non-stationarity in this frequencies.

The analysis of the three different gravimetric time series at Brussels, Bad Homburg and Potsdam leads to the **same model** for the the modulation.

Conclusions

A modulation of the M2 wave with a period of a year by oceanic tides must be proved. OOE and TAMURA (1985) have found yearly and half-yearly modulations in the seas around Japan.

The spectral regions 0.078978 cph ($\approx 2\tau - (s-N)$) and 0.082044 cph ($\approx 2\tau + (s-N)$) are characterized by significant time-varying amplitudes in the order of 40 ... 50 nGal. Therefore a origin of these frequencies by a non-tidal modulation of the M2 wave with a period of 27.18 d must be supposed. The consideration of a stochastic constituent must be included.

An amplification of the amplitudes in the region of L2 and Lambda2 **alone**, as discussed by HINDERER (1986) cannot be confirmed.

Other possibilities with respect to the amplitude of the monthly modulation are
- a monthly period of the polar motion in the order of 20 cm,
- a vertical movement of a tectonic block in the order of 0.3mm

Aknowledgement

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Fig. 1: Variance spectrum of the gravimetric time series at Potsdam 1972 - 1984 (ASCH et al.(1985)), residuals. The line S2 was eliminated. The three types of arrows characterize the three pairs of frequencies symmetrically to the M2-frequency.

Fig. 2: Amplitudes of the third order harmonics of the sun (TAMURA (1987)) for Potsdam. Compare the amplitudes at the three types of arrows with that of fig. 1.

Fig. 3: Amplitudes of the fourth order harmonics of the moon (TAMURA (1987)) for Potsdam. Compare the amplitudes at the three types of arrows with that of fig. 1.

Fig. 4: General representation and the types of modulation of the carrier frequency f_0 by a frequency f_1 in the pointer table (harmonic dial) and in the amplitude spectrum from the top to down:
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Fig. 5: Maximum entropy spectrum of the narrow-band analysis for the M2-frequency (f_0 = 0.0805114 cph) at Potsdam 1982 - 1986, residuals. The difference of the frequencies at the maximum against the M2-frequency leads to the modulation period of a year.

Fig. 6: Harmonic dial for the M2-frequency at Potsdam 1974 - 1986. One point represents the mean tidal parameter (without any corrections) for the corresponding month. One can remark the phase deviation $\varepsilon = 0.095^{\circ} = 1.7-03$ rad in the course of one year. The large crosses denote the r.m.s. error of the δ - values. The small cross indicates the 12-years mean value.

Fig. 7: Maximum entropy spectrum of the narrow-band analysis for the M2-frequency at Brussels 1982 - 1986, residuals, in the upper part in the absolute time scale, in the lower part relatively to the M2-frequency. There is only one peak (on the right hand side), which correponds to a yearly modulation. Note also the indication on a modulation of six years.

Fig. 8: Harmonic dial for the M2-frequency at Brussels 1982 - 1986. The points (tidal parameters for the corresponding month, without any corrections) discribe in the course of one year a circle with a radius A_D in the order of 25 nGal. The phase deviation is $\varepsilon =$ $= 0.04^{\circ} = 7.0-04$ rad. The large crosses denote the r.m.s. error of the δ - values. The small cross indicates the 4.5-years mean value.

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Fig. 9: Amplitude spectrum of the residuals at Potsdam 1982 - 1986. The sharp spikes in the region of the L2 and N2 tidal groups are caused by a modulation of the M2-tide in the order of 90 nGal with a period of 27.189 days.

Fig.10: Amplitude spectrum of the residuals at Brussels 1982 - 1986. Also here is a modulation of the M2-tide, now in the order of 100 nGal with a period of 27.166 days.

Fig.11: Amplitude spectrum of the residuals at Bad Homburg 1981-1984 (RICHTER (1987)) in the region of the M2-tide. The arrows point out the spectral lines which indicate the modulation of the M2-tide with a period of 27.28 days.

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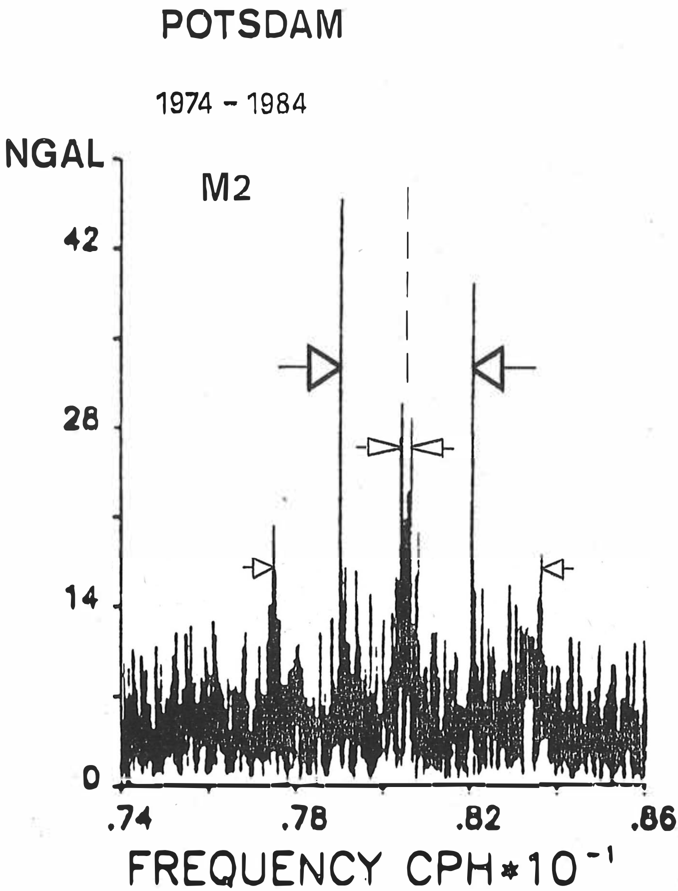

Fig. 1

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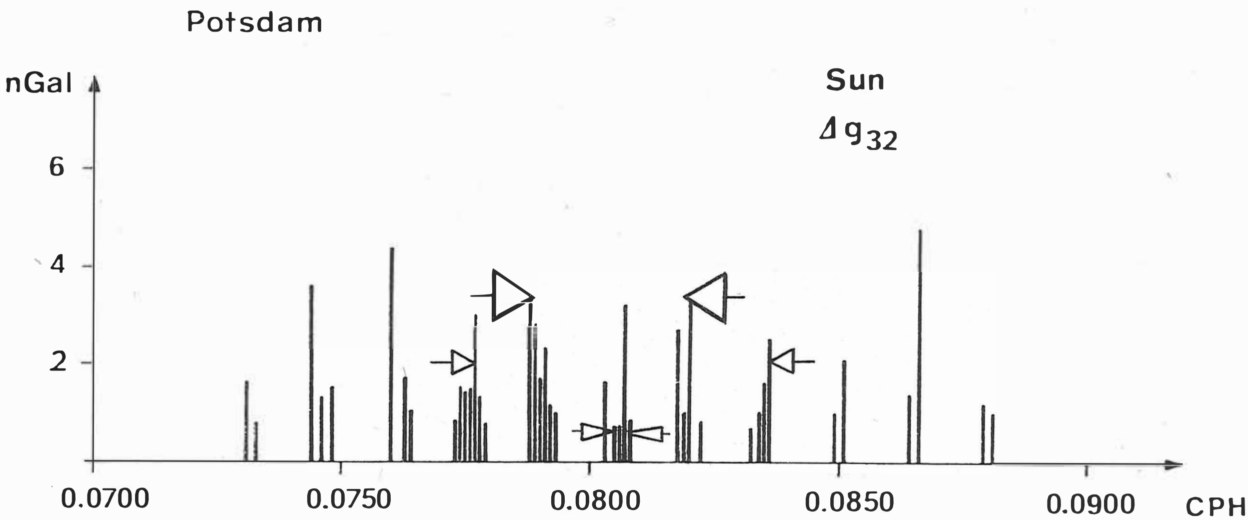

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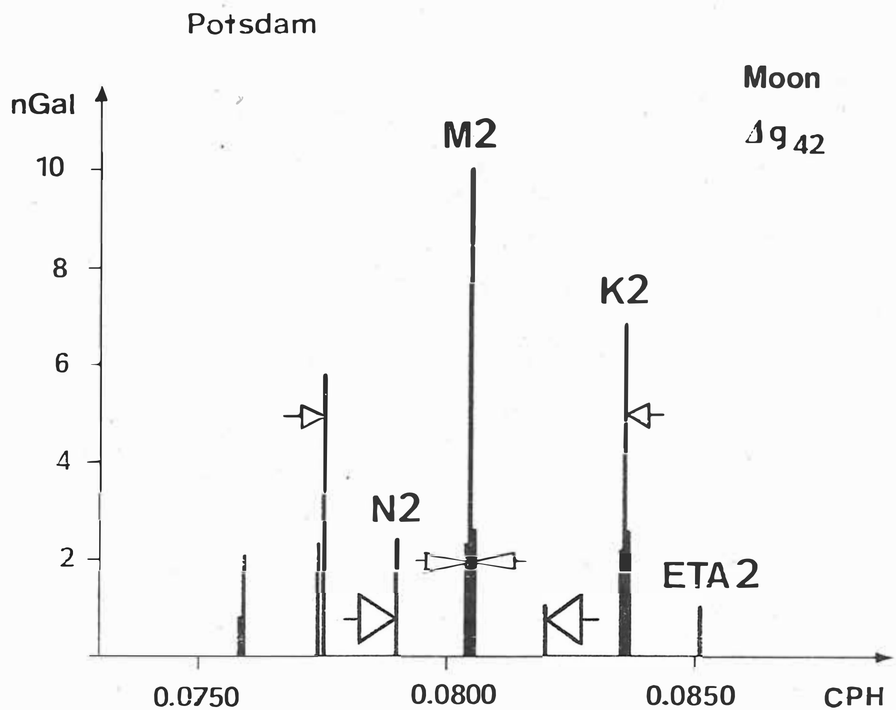

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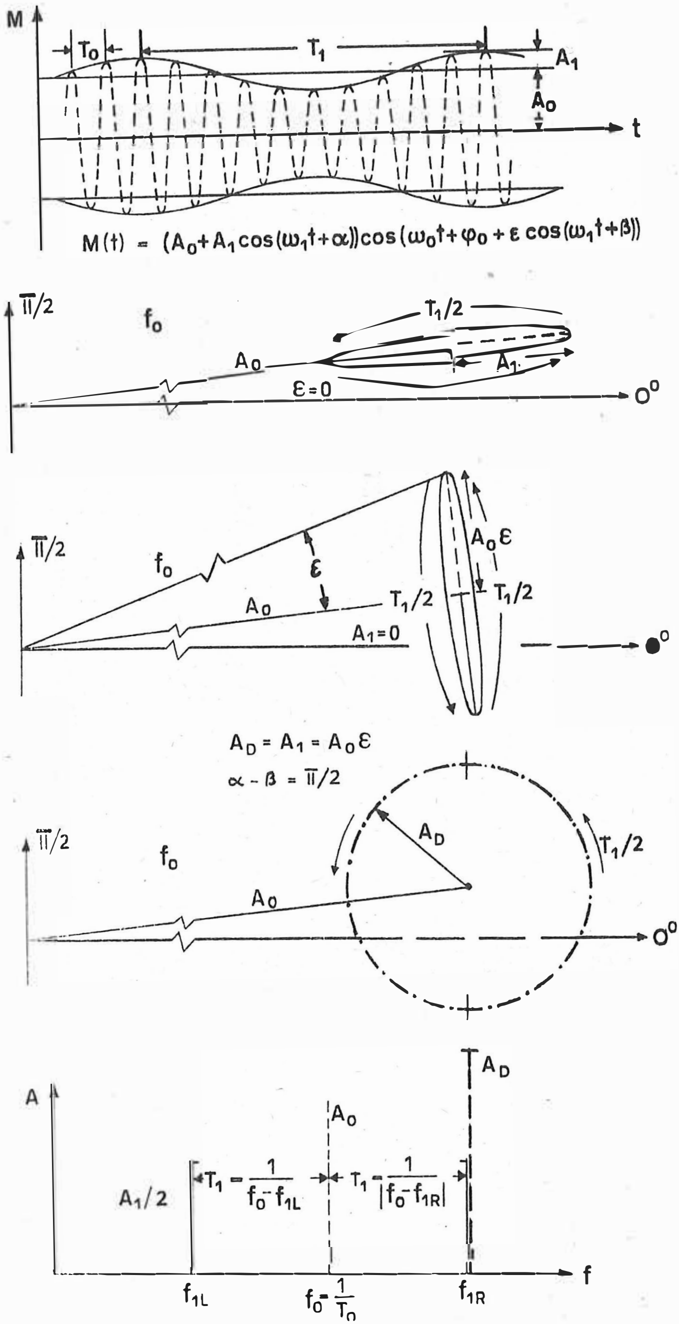

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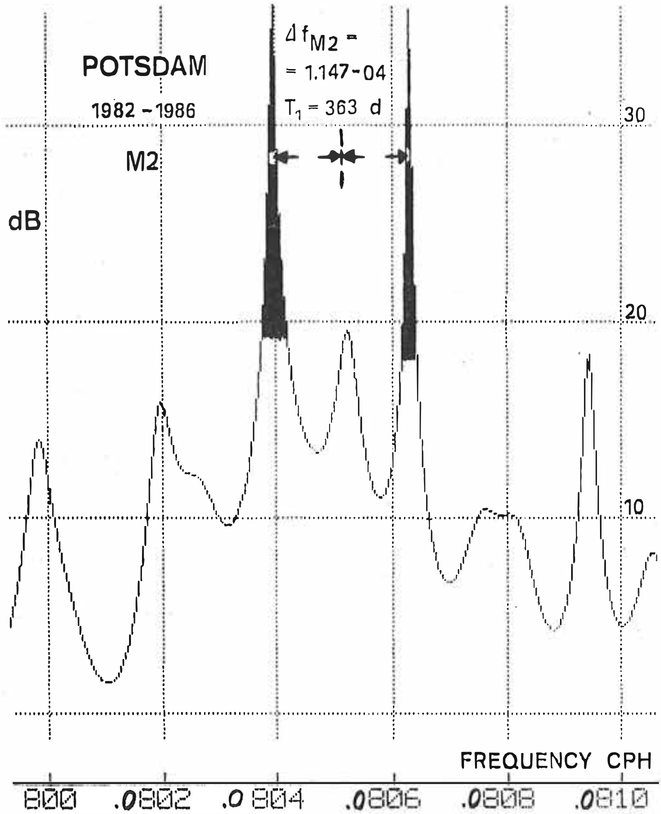

Fig. 5

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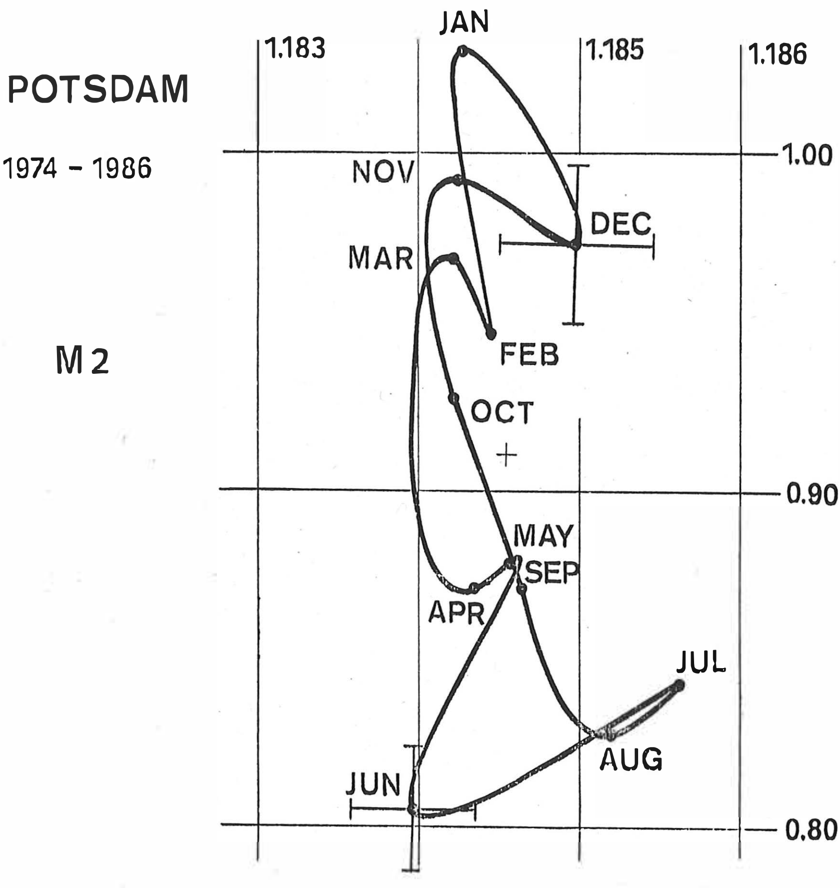

Fig. 6

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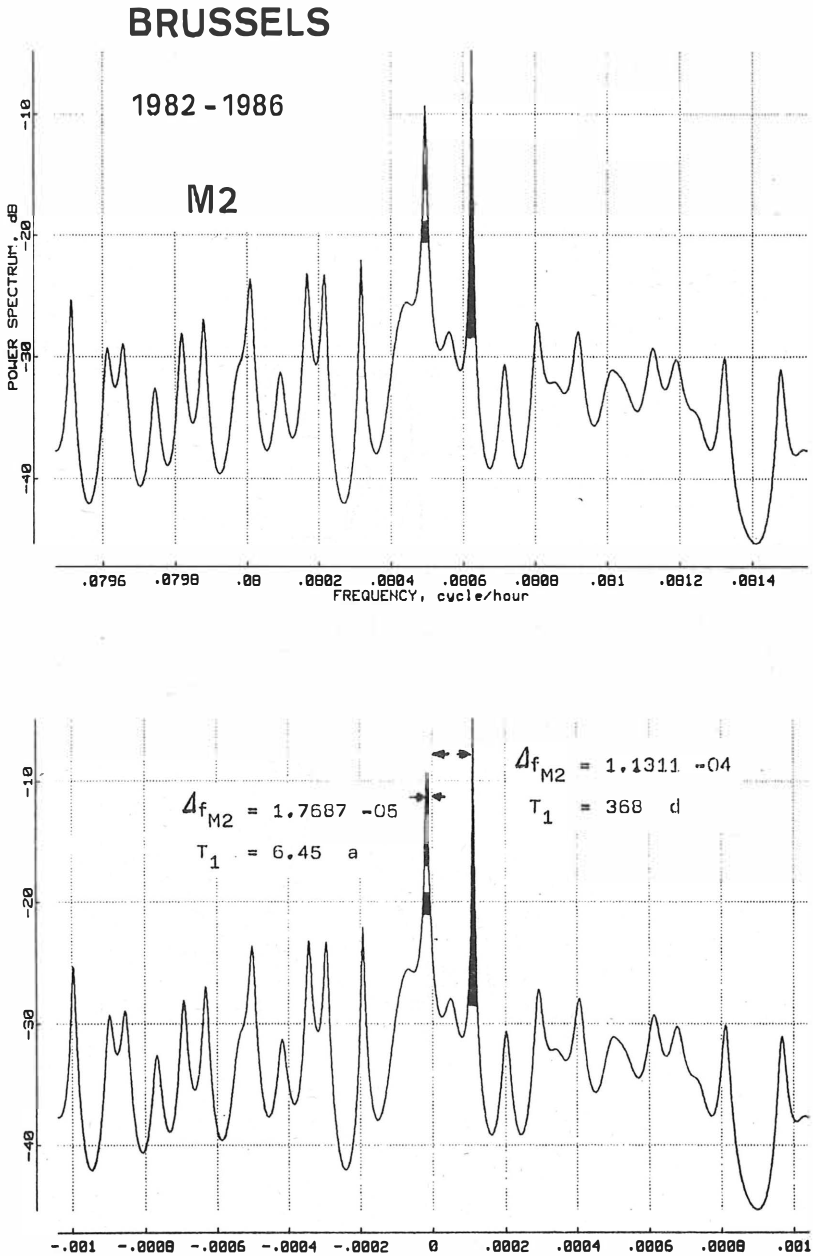

Fig. 7

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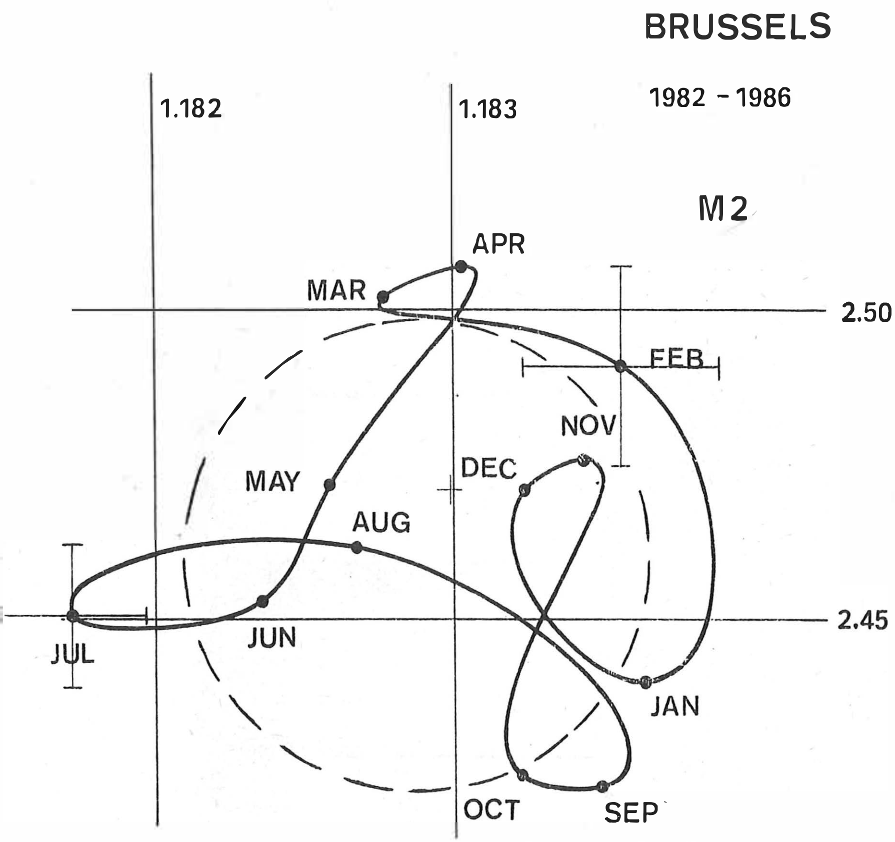

Fig. 8

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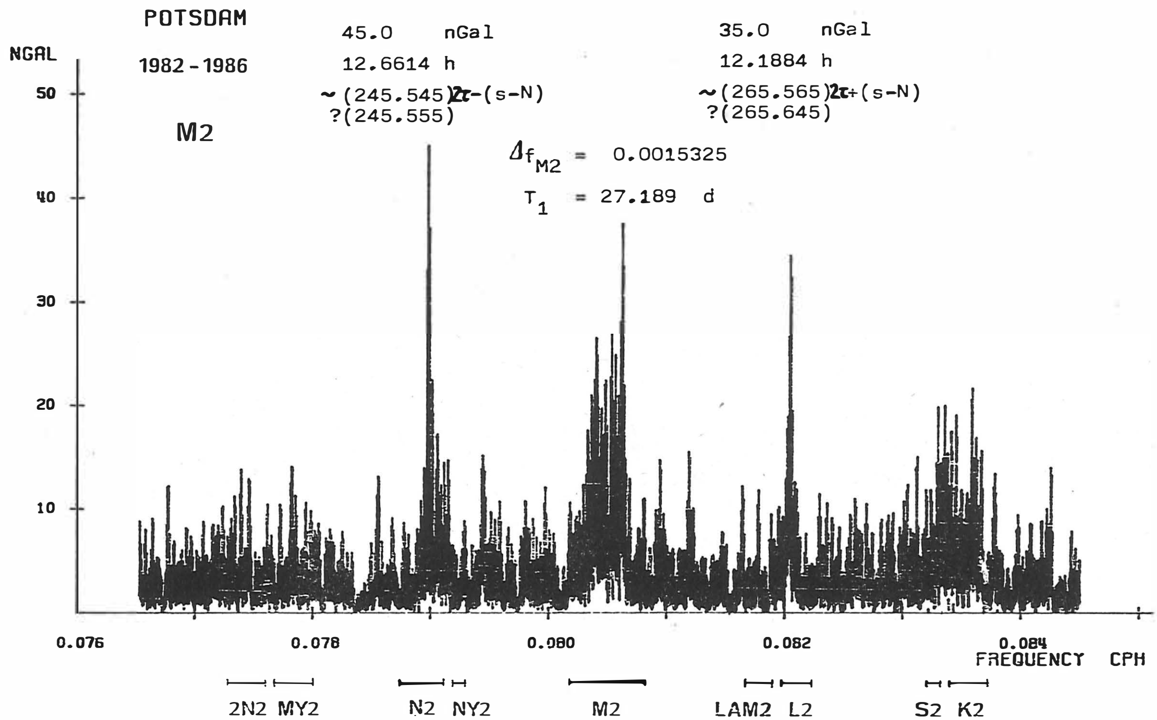

Fig. 9

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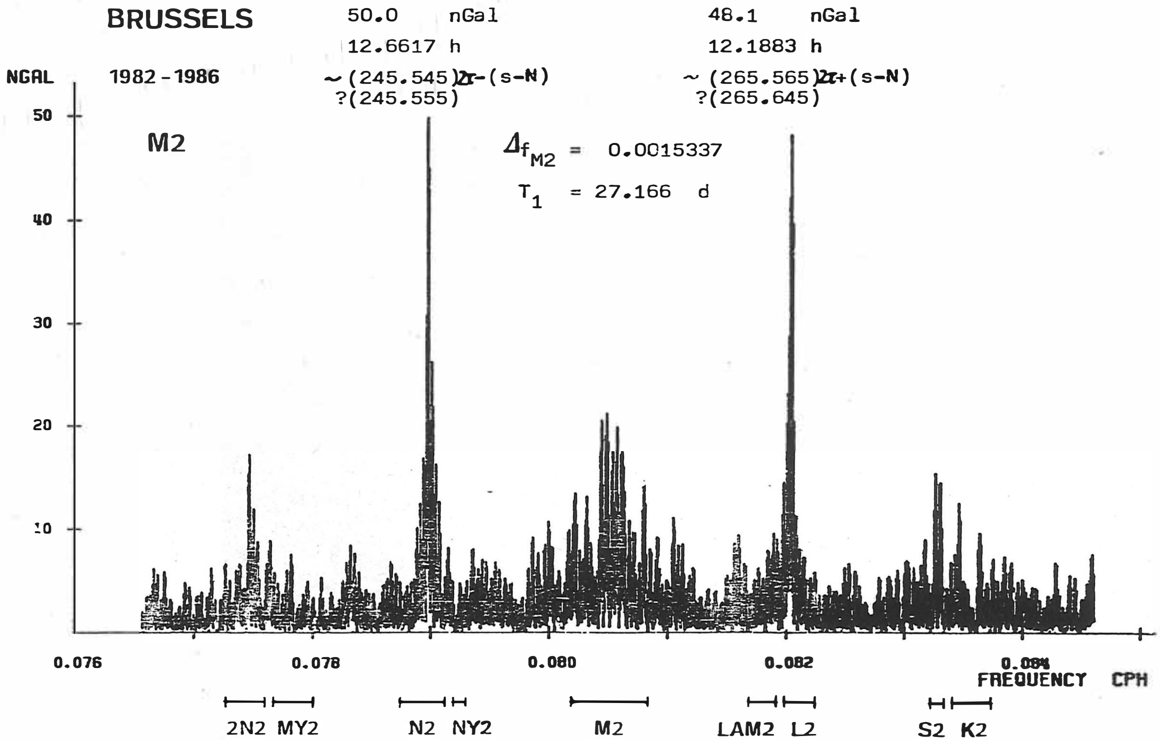

Fig. 10

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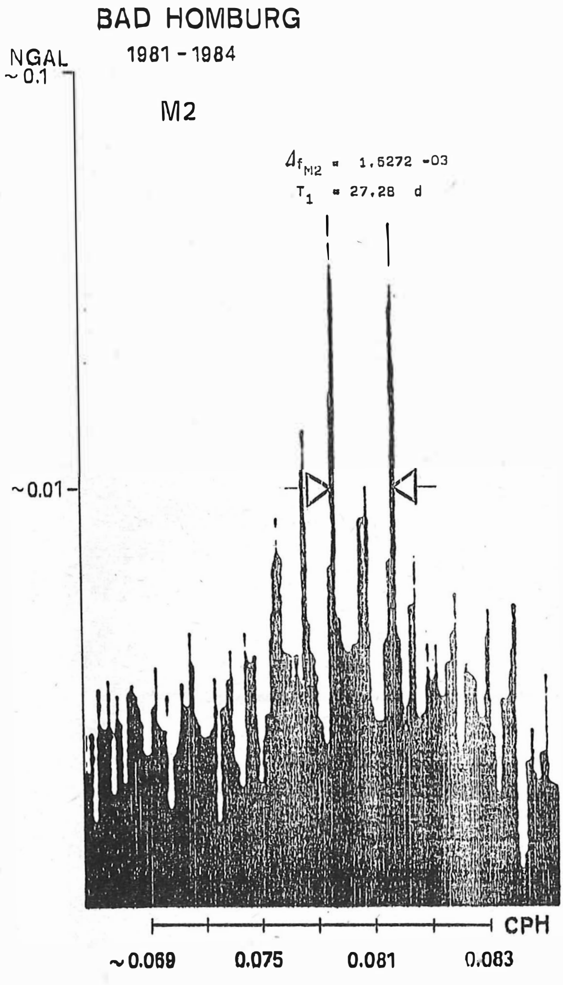

Fig. 11

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STUDY OF THE EARTH TIDES

Subprogramme II-5.3 KAPG in 1985 - 1988

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The international cooperation in the framework of KAPG Earth Tide Subprogramme has been concentrated mainly on the improvement of the measuring technique and technology and on the acquisition of reliable measuring data at the basic stations and their mathematical treatement. Also joint interpretations of the results were performed.

The Askania gravimeters are being used almost exclusively for registrations of the vertical component, namely Gs 15, BN and instruments equipped with a capacitive transducer at the Central Institute for Physics of the Earth of the AS GDR, Institute of the Earth Physics of the AS USSR or Geodetical and Geophysical Institute of the Hung. AS.

A more accurate theory of this type of gravimeters and the new KAPG manual for Earth tide measurements with them were elaborated. The main improvement of the measuring technology relates to the record calibration from which the influence of the micrometer non-linearity is eliminated. The efficiency of this technology may be shown on the results of the station Pecný. In Table 1 the results of long term measurements with three gravimeters at this station are presented for four main waves. All the measurements were analysed using the Venedikov's method M74. Although an excellent agreement of the δ factors of the O_1, K_1 and M_2 waves may be random to a certain extent, we may conclude from these results that Askania gravimeters are able to yield for the main waves an accuracy of the δ factors $1 - 2 \times 10^{-3}$ from long-term measurements. Comparative

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measurements at fundamental station are not necessary. Naturally, the reliability of the results implies the question if there are not systematic errors associated with all the instruments of this type.

A comparison of the results obtained at Pecný with the theoretical model Wahr-Dehant is given in Table 2. The measured values are δ_m , $\varkappa_m$, the load and attraction vectors (L, λ) were determined on the basis of Schwiderski´s ocean tide maps, δ_c and $\varkappa_c$ are the corrected tidal parameters, δ_{W-D} the model values of the gravimetric factor. The weighted mean of the differences $\delta_c - \delta_{W-D}$ from all 8 diurnal and semidiurnal waves is 0.0005 ± 0.0005. At the Potsdam station we have a mean difference 0.0028 ± 0.0007, at Budapest (only czechoslovakian measurement) 0.0018 ± 0.0007, at Sofia (soviet and czechoslovakian measurements) -0.0017 ± 0.0007. Thus, the results of these stations are in a good agreement with the new Wahr-Dehant model of the Earth tides.

An absolute method of record calibration by tilting the gravimeter was elaborated in the USSR and used also in Roumania. In Hungary an experiment is being prepared of record calibration by a torroidal gravitational mass.

Permanent registrations of the vertical component proceed at the basic stations Potsdam, Tiefenort (GDR), Pecný (CSSR), Warszawa (Poland), Budapest, Penc (Hungary), Caldarusani, Craciunesti-Deva (Roumania), Obninsk, Poltava (USSR). The longest accurate series are at Potsdam (14 years with only one interruption, digital record) and Pecný (12 years but wiht interruptions). The data of these stations are being studied from the point of view of the possible time changes of tidal parameters.

Up to now, the measurements on the euroasiatic tidal profile were performed at the stations Potsdam, Warszawa, Poltava, Obninsk, Orenburg, Novosibirsk, Irkutsk and Tallin. In the international cooperation the measurements at two further basic stations were conducted, namely at Budapest (Hungary - CSSR) and Warszawa (Poland - GDR).

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The nets of tiltmeter and extensometric stations have been further extended, particularly in the Carpatho-Balkan region. The instruments for tilt and strain measurements are being systematically improved by capacitive and inductive transducers and devices for automatical digital recording. An own quartz horizontal and a vertical pendulum were constructed in Roumania. Two types of vertical pendulums have been developed in the USSR. Also in Hungary an own horizontal pendulum was built with a capacitive transducer and an intelligent recording system. In the GDR a short-base transportable quartz extensometer was constructed in cooperation with the USSR and a niveauvariometer with a long base is being prepared. The methods of record calibration are being improved. In the CSSR an accuracy of 0.1 % was obtained using a titan dilatable crapaudine for tiltmeter calibration.

The effects of cavity and topography on the tilt and strain measurements were studied in international cooperation (GDR, CSSR, USSR) at the Tiefenort station. These effects can be diminished if the Harrison s rules for instrument installation are respected, but also by weakening the environmental connection by artificial clefts. Further, the thermoelastic effect was investigated (CSSR, GDR). The influence of tectonical structure on the results of strain measurements has been studied mainly in the USSR. In Roumania two perpendicular axis of crust blocs tilts were found in the area of Craciunesti-Deva and Pades-Gorj stations.

The interpretation of the extensometric results in the Carpatho-Balkan region still needs a determination of the topographic effect. But the preliminary results correspond to the conception of the enlargement of the Pannonia basin.

Applications of the tilt and strain measurements were found especially for the studies of the stability of dam walls (USSR) and of the hill-sides in the vicinity of great surface mines (CSSR). In the GDR the possibility of the use of these measurements for mining and recent crustal movement studies was

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shown. Besides tidal and seasonal variations the long-term registrations also contain linear systematic deformations. In active seismic regions the connection between the anomalies in the registrations and the earthquake occurence is being searched for. Free oscilations of the Earth were experimentally investigated in the USSR and Hungary.

In the KAPG the obligatory method of tidal analysis is the Venedikov´s method M74. The computations are being ensured by the Computing Laboratory in Sofia, but the computing programme was also distributed to the other countries. The Chojnicki´s method is widely being used too.

In the Computing Laboratory two very long and high accurate series of gravimetric registrations from stations Potsdam and Pecný have been analysed. From the data of Pecný the long-periodical wave M_f and the quarterdiurnal and quinquediurnal waves were also determined. For the determination of the M_f wave from Potsdam data several methods were applied. A disturbing non tidal wave was found in this frequency range. An original physically-empirical model for the barometric effect on tidal measurements was developed, which is already applied in connection with the M74 analysis method. A multichannel analysis method is being used also in Roumania.

In the CSSR a proposal is being prepared for evaluation of all tidal components for different global, regional and local Earth models. It will be also used in preparation of the manual for evaluation of tidal corrections of geodetic measurements. The basic principles of the determination of these corrections will be laid down in international cooperation.

Since 1985 three numbers of the KAPG Bulletin "Study of the Earth Tides" have been issued, the next number is under preparation.

The ocean tide corrections of the tidal parameters are being evaluated on the basis of Schwiderski´s maps. Also a viscoelastic Earth model is being used for this purpose (Poland).

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The barometric influence on different kins of tidal measurements is being studied intensively. The models of the ocean tide influence on the wave M_2 along an euroasiatic profile (approx. parallel 50^{o}N) were elaborated in international cooperation (GDR, Poland, FRG). With the Schwiderski´s maps the difference between the model and observations of the EW tilt component is up to 2 % in amplitude factors and $2\text{-}3^{o}$ in phase lags. The strain components $e_{\theta\theta}$, $e_{\lambda\lambda}$, e_{rr} were also evaluated for some shorter NS profiles. There is proposed to find the zero amplitude latitude of the $e_{\lambda\lambda}$ component and to use it for a control of the body tide and ocean tide models. The modulation of ocean M_2 wave found at three european stations could be explained as an influence of the modulation of the ocean M_2 wave by zonal waves (GDR, USSR).

In the seismic active region in Tadzhikistan a net of tiltmeter and extensometric stations was established. In two cases the precursors of the earthquake were found on the registrations. The relation between the Earth tide and microseismic activity and the triggering of earthquakes by Earth and ocean tides were studied in Hungary. In Roumania a correlation of earthquake occurence with maximum and/or minimum of the tidal curve was established in Vrancea region depending on the pertinence of the focus to one or the other of the two fault planes.

In the GDR the values of Love numbers h_2 and l_2 were determined from the LAGEOS laser ranging data obtained in the MERIT campagne which are in a good agreement with the results of classical methods. Also one term of the ocean M_2 wave was evaluated.

This brief outline of the KAPG results in earth tide research is not complete, because it does not contain the individual theoretical works of the participants. It also does not go in details, expecially in the cases, when separate papers were prepared for this symposium. The bibliography is very extensive, I intend to publish it in the bulletin "Study of the Earth Tides".

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Table 1. Station Pecný. Results of three gravimeters.

Instrument Period	δ			
	O_1	K_1	M_2	S_2
Gs 11 No. 131 70 09 02 - 80 02 04	1.1490 ± 12	1.1362 ± 7	1.1847 ± 6	1.1806 ± 13
Gs 15 No. 228 76 04 22 - 84 09 25	1.1486 ± 4	1.1362 ± 3	1.1848 ± 2	1.1861 ± 4
BN - 26 83 04 17 - 86 06 28	1.1484 ± 16	1.1362 ± 11	1.1852 ± 7	1.1787 ± 13

Table 2. Station Pecný. Comparison with the W-O model.

	δ_m	$\varkappa_m^\circ$	L	λ°	δ_c	$\varkappa_c^\circ$	δ_{W-D}	$\delta_c - \delta_{W-D}$
M_f	1.1584 ± 404	4.77 ±1.95	0.09	179.3	1.1769	4.69	1.1654	0.0115
Q_1	1.1525 ± 22	-0.28 ±0.11	0.04	212.8	1.1582	-0.10	1.1542	0.0040
O_1	1.1486 ± 4	-0.03 ±0.02	0.13	157.7	1.1525	-0.11	1.1542	-0.0017
P_1	1.1508 ± 8	0.10 ±0.04	0.04	73.2	1.1500	-0.04	1.1490	0.0010
K_1	1.1362 ± 3	0.10 ±0.01	0.11	58.8	1.1349	-0.01	1.1335	0.0014
N_2	1.1781 ± 10	1.43 ±0.05	0.23	62.7	1.1601	-0.24	1.1589	0.0012
M_2	1.1848 ± 2	1.03 ±0.01	1.14	45.6	1.1590	-0.24	1.1589	0.0001
S_2	1.1861 ± 4	0.30 ±0.02	0.37	17.3	1.1617	-0.07	1.1589	0.0028
K_2	1.1813 ± 17	0.42 ±0.08	0.10	13.7	1.1566	0.13	1.1589	-0.0023
					Mean D	-0.04 ±0.02	Mean	0.0005 ±0.0005
					SD	-0.21 ±0.04		

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A NEW EMPIRICAL METHOD FOR THE DETERMINATION OF THE LOVE NUMBERS AND OF THE OCEAN TIDE LOADING EFFECT

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Abstract

The different structures of the fields of both the body strain waves $e^{\varrho}_{\lambda\lambda}$(M2) and the ocean tide induced strain waves $e^{\varrho\varsigma}_{\lambda\lambda}$(M2) enable the determination of the LOVE numbers, h and l, separately. For this purpose strainmeter measurements along a NS profile in the zone between latitudes 49°N and 53°N are required. The model structure of the $e_{\lambda\lambda}$(M2) strain field was checked by different modellings for some profiles within Europe and Asia.
At latitude φ_o where the amplitude of the body strain wave $e^{\varrho}_{\lambda\lambda}$ (M2) disappears a direct measurement of the ocean loading strain wave $e^{\varrho\varsigma}_{\lambda\lambda}$(M2) is possible.

1. Introduction

As shown by SIMON (1981) the zero passages of the amplitudes of the semidiurnal body strain waves $e^{\varrho}_{\lambda\lambda}$ determined by strainmeter measurements along NS profiles between latitudes 49°N and 53°N respectively, can be used for the determination of the ratio of SHIDA's and LOVE's numbers l and h (spherical Earth model) or for a control of the parameters of the elliptical Earth model of WAHR (1981). Furthermore strain measurements along an EW profile located along that latitude where $e^{\varrho}_{\lambda\lambda}$(M2) = 0 enable a direct determination of the ocean tide loading effect. The latter generates the main part of the differences between the models and the measured tidal gravimeter, tiltmeter and strainmeter results. The uncertainty of the ocean tide loading model probabely results from influences of lateral inhomogenities of the Earth crust and mantle, eventual influences of the large regional tectonical zones of weakness (see JENTZSCH, KACZOROWSKI, SIMON (1988)). In this connection the special advantage of the measurements of the strain wave $e^{\varrho\varsigma}_{\lambda\lambda}$ at the amplitude zero of the corresponding body strain waves consists in the fact, that compared with gravimeter and tiltmeter records attraction and potential components of the ocean loading effect are absent. The pure ocean loading effect may be directly determined. Following the error discussion of SIMON (1981) the main part of the error of the latitude φ_o, where the body strain wave $e^{\varrho}_{\lambda\lambda}$(M2) disappears, are induced by

- inaccurate calculations of the ocean tide induced components of the measured strain waves,
- falsifications of the measuring results induced by cavity and topographic effects.

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In the present paper we check the distributions of the direct and indirect tidal strain waves $e_{\lambda\lambda}$ (M2) in the zone between latitudes 49° N and 53° N in order to find out a possibility for an essential diminishing of the errors of the first type. In a second paper (NEUMEYER, SIMON, KARMALEEVA (1988)) by the aid of parallel records of 3 NS strainmeters at the Tiefenort station is demonstrated that the errors induced by the cavity effect can be diminished significantly if certain rules concerning the location of the measuring places (HARRISON (1976)) are taken into account.

2. Distribution of the Parameters of the body strain wave $e^{o}_{\lambda\lambda}$ (M2) along a NS profile in the zone between latitudes 49°N and 53°N

Corresponding to the theory of A.E. LOVE for the tidal deformations of a spherical-symmetrical Earth model we find the following relation for the horizontal body strain wave $e^{o}_{\lambda\lambda}$ in the direction of the prime vertical:

$$(1) \quad e_{\lambda\lambda} = \frac{1}{gr}\left[h_2 W_2 - l_2\left(6\, W_2 + \frac{\partial^2 W_2}{\partial \theta^2}\right)\right]$$

(see ELSTNER, SIMON (1983))

W_2 – tidal potential
l_2, h_2 – LOVE's and SHIDA's numbers
g – constant mean acceleration of gravity at the Earth surface
r, θ, λ – geocentric coordinates of the measuring place
$\theta = 90° - \psi$; ψ – geocentric latitude
λ – longitude of the measuring place.

Insertion of the potential

$$(2) \quad W_2(M2) = 0{,}90809 \cdot G \sin^2\theta \cos 2\tau$$

G – Doodson constant, $\frac{G}{gR} = 4{,}193 \times 10^{-8}$,
τ – mean lunar time

yields for the semidiurnal lunar main wave $e^{o}_{\lambda\lambda}$ (M2) the relation

$$(3) \quad e^{o}_{\lambda\lambda}(M2) = 0{,}90809 \frac{G}{gR}\left[h_2 \sin^2\theta - 2\, l_2(1 + \sin^2\theta)\right]\cos 2\tau .$$

The corresponding formula for the elliptical Earth model of WAHR (1981) considering the mantle flattening is

$$(4) \quad e^{o}_{\lambda\lambda}(M2) = 0{,}90809 \frac{G}{gR}\left[S_1 \sin^2\theta - (1 + \sin^2\theta)\left[2\, S_2 + S_3(2 - 3 + \sin^2\theta)\right]\right]\cos 2\tau$$

with the constants $S_1 = 0{,}609$; $S_2 = 0{,}085$; $S_3 = 0{,}001$ calculated for the Earth model 1066 A of GILBERT & DZIEWONSKI. A comparison of (3) and (4) shows, that h_2 corresponds with S_1 but the constant l_2 is replaced by a function of θ which diminishes its amount from 0,086 at the pole to 0,0845 at the equator.

Table 1 contains the parameters of the $e^{o}_{\lambda\lambda}$ (M2) waves for 12 fictive observation places along a NS profile. For the calculations in correspondence with the relations (3) and (4)

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we used the parameters tabulated at the top of the table. Besides of the fictive measuring places with the latitudes φ = 49°, 50°, 51°, 52°, 53° in the table are included such ones too where for one of the 7 different Earth models the amplitude of the body strain wave $e^{2}_{\lambda\lambda}$ (M2) disappears. For the calculation of the latitudes ψ_0 = 90°- θ_0 of these places are used the relations

(5) $\sin^2 \theta_0 = 2\, l_2/(h_2 - 2\, l_2)$

and

(6) $3\, S_3 \sin^4 \theta_0 + (S_1 - 2\, S_2 + S_3)\sin^2 \theta_0 - 2(S_2 + S_3) = 0$

deduced from (3) and (4). The relation between the geographical and geocentric latitudes, φ and ψ, is given by

(7) $\psi = [\varphi \frac{\pi}{180^\circ} - \frac{\sin 2\varphi}{297}] \frac{180^\circ}{\pi}$.

The reasons for the choice of just these 7 models were the following:

- The MOLODENSKI (1961) model was used until 1983 as the official reference model of the PCET* especially for the interpretation of the measuring results of the diurnal tidal waves.
- By the modellings of ALSOP & KUO (1964) basing on the Earth model of GUTENBERG-BULLEN firstly it was shown that the second-order LOVE numbers are practically independent from
  - -- the presence of the inner core
  - -- the presence or absence of a low velocity channel in the upper mantle.
- To study further influences of the Earth's upper mantle FARRELL (1972) calculated two additional models formed by replacing the top 1000 km of the GUTENBERG-BULLEN A-model by oceanic and continental shield structures. Table 1 shows that the corresponding differences of the LOVE number did not have a remarkable influence on the location of the amplitude zero.
- More effective are regional differences of the LOVE numbers calculated by WILHELM (1977) for the regions W-Europe and SE-Europe. Here the corresponding latitude difference $\Delta\varphi$ reaches about 0,15° or 15 km.
- The consideration of the flattening of the mantle and of new elastic parameters resulting from the Earth model 1066 A of GILBERT & DZIEWONSKI led to the model of WAHR (1981) which was declared 1983 by the PCET as the new reference model for the interpretation of the measured Earth tide parameters.
  Table 1 shows differences of $\Delta\varphi$ = 2,16° or 235 km between the latitudes φ_0 calculated for both the old and the new reference models. Comparing with WILHELM's results the zero-latitude of the WAHR model is translated by 70-80 km to south.
  The amplitude variation along the profile to the North calculated as a mean of the corresponding values of the 7 models is equal to

  $-2{,}93 \times 10^{-10}$ between latitudes 49°N and 50°N
  and
  $-3{,}03 \times 10^{-10}$ between latitudes 52°N and 53°N.

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*) (PCET Permanent Commission of Earth Tides)

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3. Parameter distribution of the ocean tide induced strain wave $e^{oc}_{\lambda\lambda}(M2)$ in the zone between latitudes 49°N and 53°N

To investigate the properties of the ocean tide induced strain field the 3 components $e^{oc}_{\theta\theta}(M2)$, $e^{oc}_{\lambda\lambda}(M2)$, $e^{oc}_{rr}(M2)$ were calculated for 4 short NS profiles, N1,..., N4, and for a transcontinental EW profile along the latitude circle 51°N (see fig. 2).

The calculations based on the model m 2 which is most suitable for the interpretation of the European tiltmeter results (see JENTZSCH, KACZOROWSKI, SIMON (1988)).

The m 2 model applicates SCHWIDERSKI's ocean tide model transformed to fulfill the law of mass compensation and basing on the Earth model of GUTENBERG-BULLEN.

Table 2 contains the parameters calculated for the $e^{oc}(M2)$ waves along the 4 NS profiles and table 3 those ones of the EW profile. Fig. 3 shows the amplitude variations of the 3 strain waves along the profile E 1. Here the components $e^{oc}_{\lambda\lambda}(M2)$ have the relative largest amplitudes.

In the innercontinental part of our zone, for instance between the meridiane 35°E and 45°E and between latitudes 49°N and 53°N, respectively, the parameters of the ocean tide induced strain wave $e^{oc}_{\lambda\lambda}(M2)$ did not vary in both the directions NS and EW by more than 10^{-11}/degree in the amplitudes and 3°/degree in the phases. These special properties of the strain field induced by the ocean tides enable the application of the measuring methods described in the following section.

4. Methods for the determination of the parameters h_2 and l_2 and the ocean tide components by profile measurements

Fig. 4 explains the methods for the determination of the LOVE numbers. Starting with the more simple case of a spherical Earth we determine for this purpose by means of strain measurements along a NS profile (here N 3) two different combinations of the LOVE numbers:

- the combination (h_2-2 l_2) by means of a vectorial subtraction of the $e_{\lambda\lambda}$ (M2) waves measured at 2 different stations. The first one must be located southern to the latitude of the amplitude zero, the second one northern to the latter;
- the combination (h_2/l_2) by the localization of the latitude φ_0 characterized by the amplitude zero of the body strain wave using equation (5).

The left side of fig. 4 shows the situation along the NS profile N 3 before the start of the calculations. Both the components of the "measured" waves at any station are drawned separately as vectors.

At the right side of the same figure we find the result of the vectorial subtraction of the waves measured at the stations located at latitudes 49°N and 53°N. The opposite signs of the body strain waves lead to an addition of their amounts. At the other hand the components induced by the ocean tides have at

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both the stations approximately the same parameters. Consequently the resultant body strain wave has an amount which is more than 100 times larger than that one of the residual of the ocean tide components.

The numerical result of this vectorial subtraction is included too in table 4. As shown in the same table, if we subtract the measuring results of other stations located southern and northern to φ_o from each other the relative error of the calculated resultant of both the body strain waves is always not larger than 1%

Considering in accordance with ZSCHAU (1978) that the tidal friction has a neglectable small effect on the phase $\varkappa_o$ of the body strain waves , what means that $\varkappa_o<0,1°$, the vectorial subtraction of the waves measured at the 2 stations, at Θ_S and Θ_N, yields

(8)
$$e^{obs}_{\lambda\lambda}(M2)|_{\Theta_S} \cos \overset{obs}{\varkappa}|_{\Theta_S} - e^{obs}_{\lambda\lambda}(M2)|_{\Theta_N} \cos \overset{obs}{\varkappa}|_{\Theta_N} =$$
$$= 0,90809 \frac{G}{gR}(h_2-2\,l_2)(\sin^2\Theta_S - \sin^2\Theta_N) + e^{oc}_{\lambda\lambda}(M2)|_{\Theta_S} \cos \overset{oc}{\alpha}|_{\Theta_S} -$$
$$- e^{oc}_{\lambda\lambda}(M2)|_{\Theta_N} \cos \overset{oc}{\alpha}|_{\Theta_N} .$$

Due to the relative small residuals of the ocean tide induced strain waves one can neclect the latter in equation (8) and receive the following equation for $(h_2 - 2\,l_2)$:

(9)
$$(h_2 - 2\,l_2) = \frac{gR}{0.90809 \cdot G} \; \frac{e^{obs}_{\lambda\lambda}|_{\Theta_S} \cos \overset{obs}{\varkappa}|_{\Theta_S} - e^{obs}_{\lambda\lambda}|_{\Theta_N} \cos \overset{obs}{\varkappa}|_{\Theta_N}}{\sin^2\Theta_S - \sin^2\Theta_N} .$$

The second relation

(10)
$$e^{obs}_{\lambda\lambda}|_{\Theta_S} \sin \overset{obs}{\varkappa}|_{\Theta_S} - e^{obs}_{\lambda\lambda}|_{\Theta_N} \sin \overset{obs}{\varkappa}|_{\Theta_N} =$$
$$= e^{oc}_{\lambda\lambda}|_{\Theta_S} \sin \overset{oc}{\alpha}|_{\Theta_S} - e^{oc}_{\lambda\lambda}|_{\Theta_N} \sin \overset{oc}{\alpha}|_{\Theta_N}$$

did not contain - in accordance with our supposition concerning $\varkappa_o$ - a contribution of the body strain waves.

The method for the localization of the amplitude zero latitude φ_o of $e^{o}_{\lambda\lambda}$ (M2)may be illustrated by the middle column of fig. 4. We determine this latitude by an approximation in several steps. Every step starts with a measurement at the latitude φ_B which is considered as to be the actually best approximation of φ_o. At such a measuring place we can assume that the observed wave must be identically with the ocean tide induced strain wave $e^{oc}_{\lambda\lambda}$(M2).

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In order to control this assumption we sum up vectorially the measuring results of two other stations situated southern and northern to the first one. The purpose of this summing-up is to eliminate the body strain components. In the simplest case the amounts of both the body strain waves are just the same (see table 4, stations φ_S = 49,95°N and φ_N = 53,1703°N). If the assumption concerning the locality of the amplitude zero latitude was correct, than the vectorial sum of the waves measured at the stations φ_S and φ_N, after a division by 2, must be practically identical with the measuring result at the latitude φ_B.

In the case of a significant discrepancy ($\varphi_B \neq \varphi_o$) the step must be repeated. That means a new observation place φ_B is to check in the same manner. After some steps of this kind with decreasing discrepancies the latitude φ_o will be determined with an acceptable error.

In the usual case the choice of the localities of both the stations φ_S and φ_N depends on the existence of mines or other artificial or natural cavities. Here we compensate the non-fitting localities by the multiplication of the measured waves by a factor K determined by the model curve for the amplitude variation of the body strain wave $e^{B}_{\lambda\lambda}$ (M2) along the profile.
A look at table 1 shows that there are only small deviations between the latter variations calculated for the 7 different Earth models. Assuming that the latitudes of both the stations are φ_S = 49°N and φ_N = 53°N, the amplitude variations between them are in units of 10^{-10}:
11,525 (WAHR), 11,541 (ALSOP & KUO), 11,541 (WILHELM/SE), 11,557 (WILHELM/W), 11,643 (FARRELL/OC), 11,684 (FARRELL/CT), 11,859 (MOLODENSKI), respectively.

Excluding the value of the MOLODENSKI model influenced by the relative old structure model which was available in 1961 for the modellings of MOLODENSKI (see WAHR (1981)) we receive a mean of 11,582 x 10^{-10} for the mentioned amplitude variation. The 6 single values differ from this mean by not more than 1%.

After the elimination of the body strain components by means of the factor K we must divide the result by (1 + K) instead by 2 in order to receive a result which is comparable with the strain wave measured at the latitude φ_o.
After the determination of the amplitude zero latitude φ_o or φ_o = 90°- θ_o we can use the relation (5) for the determination of the ratio (h_2/l_2):

$$(11) \qquad (h_2/l_2) = \frac{2(1+\sin 2\theta_o)}{\sin^2\theta_o} \; .$$

By means of the equations (9) and (11) a separate determination of the LOVE numbers h_2 and l_2 for semidiurnal waves is possible. Furthermore we receive the parameters of the ocean tide induced strain wave $e^{OC}_{\lambda\lambda}$(M2) including those ones of the other semidiurnal waves of this type at the latitude φ_o. The latter enables a direct control of the ocean tide loading model.

In the case of the WAHR model there are only 2 equations for the determination of the 3 parameters S_1, S_2, and S_3.

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But if we introduce instead of S_2 and S_3 an average $\bar{S}_2 = \bar{l}_2$ value which is valid only for the zone between latitudes φ_1 = 49°N and φ_2 = 53°N, we can handle the case of the WAHR model in the same manner as the case of the spherical Earth model. From the equation (4) we receive

for φ_1 = 49°N, θ_1 = 41,1919° $S_2(\theta_1) = l_2(\theta_1)$ = 0,08535
for φ_2 = 53°N, θ_2 = 37,1854° $S_2(\theta_2) = l_2(\theta_2)$ = 0,08545

mean $\bar{S}_2 = \bar{l}_2$ = 0,08540

Equation (5) leads for the parameters $h_2 = S_1$ = 0,609, $l_2 = S_2$= 0,0854 to an amplitude zero latitude of φ_o = 51,444° which hardly differs from the value φ_o = 51,450° calculated for the WAHR model by application of the relation (6).

5. Possibilities for a diminishing of errors induced by the cavity and topographic effects

The measuring results of the strainmeter contain besides of the body strain and ocean tide components additional local waves induced by the so - called cavity and topographic effects (see HARRISON (1976)). The usual statement for such a local additional strain wave, here the wave $e^{Loc}_{\lambda\lambda}$(M2), is

$$(12)\quad e^{Loc}_{\lambda\lambda}(M2) = C^{\theta\theta}_{\lambda\lambda}\, e^{o}_{\theta\theta}(M2) + C^{\lambda\lambda}_{\lambda\lambda}\, e^{o}_{\lambda\lambda}(M2) + C^{\theta\lambda}_{\lambda\lambda}\, e^{o}_{\theta\lambda}(M2)$$

$C^{\theta\theta}_{\lambda\lambda}$, $C^{\lambda\lambda}_{\lambda\lambda}$, $C^{\theta\lambda}_{\lambda\lambda}$ constants (coupling factors)

$e^{o}_{\theta\theta}$, $e^{o}_{\lambda\lambda}$, $e^{o}_{\theta\lambda}$ body strain waves.

As a consequence of the relative small amplitudes of $e^{o}_{\lambda\lambda}$ (M2) in the zone between latitudes 49°N and 53°N the cavity effects concerning the $e_{\lambda\lambda}$ (M2) wave are in average smaller compared with other zones of the Earth surface. The errors of the determination of the LOVE numbers including the localization of φ_o and of the direct measurements of the ocean tide loading effect which are induced by cavity and topographic effects may be diminished:

- by additional measurements of the $e_{\lambda\lambda}$(M2) waves along the NS profile northern and southern of the latitude φ_o and by the calculation of average values,
- by the consideration of certain rules resulting from the model calculations of HARRISON (1976) concerning the localities of the measuring places, the measuring direction etc inside the adit (see NEUMEYER, SIMON, KARMALEEVA (1988)),
- by measurements in local arrays.

6. Conclusions

The experimental methods presented here for the checking of both the Earth models and the ocean tide loading model are basing on the results of modellings concerning the ocean tide loading effect. Considering the above mentioned problems of such modellings, we can not exclude that also in the innercontinental areas remarkable deviations exist between the calculated and the real ocean tide effects. But the assumption

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seems to be realistic that the variations of the parameters of the ocean tide induced waves along the innercontinental profiles, for instance along the NS profiles N 3 and N 4, hardly differ from the calculated ones. Since the ocean tide effects in the innercontinental areas can be considered as global characters. A sample of such an additional ocean tide loading effect was given in the contribution of JENTZSCH, KACZOROWSKI, SIMON (1988).

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table 1: Body strain waves $e^{0}_{\lambda\lambda}$(M2) calculated for different Earth models

geogr. latitude	geoc. pole distance	MOLODENSKI / 1961 /	ALSOP/KUO / 1964 /	FARRELL / 1972 /	FARRELL / 1972 /	WILHELM / 1977 /	WILHELM / 1977 /	WAHR / 1981 /
		spherical global m.	spherical global m.	spherical region. m. ocean mant.	spherical region. m. shield m.	spherical region. m. W-Europe	spherical region. m. SE-Europe	elliptical global m. S_3 = 0.001
φ	Θ	h_2= 0.6168	0.619	0.6149	0.6169	0.612	0.610	S_1 = 0.609
		l_2= 0.0808	0.088	0.0840	0.0842	0.0842	0.0835	S_2 = 0.085
/ °/	/ °/	A x 10^{-10}	A x 10^{-10}	A x 10^{-10}	A x 10^{-10}	A x 10^{-10}	A x 10^{-10}	A x 10^{-10}
53.6123	36.5720	0.0013	-7.1308	-3.5575	-3.4936	-4.1559	-3.7040	-5.8693
53.00	37.1854	1.7828	-5.3971	-1.8085	-1.7383	-2.4198	-1.9702	-4.1389
52.3974	37.7893	3.5471	-3.6800	-1.1444	0.0001	-0.7005	-0.2531	-2.4249
52.3707	37.8159	3.6251	-3.6042	0.0001	0.0769	-0.6245	-0.1773	-2.3491
52.3087	37.878	3.8071	-3.4270	0.1789	0.2562	-0.4471	-0.0002	-2.1723
52.1525	38.0344	4.2660	-2.9804	0.6294	0.7083	0.0001	0.4464	-1.7264
52.00	38.1872	4.8743	-2.3700	1.2358	1.3167	0.6036	1.0480	-1.1217
51.450	38.638	6.0427	-1.2513	2.3737	2.4589	1.7315	2.1755	0.0000
51.1155	39.073	7.3284	-0.0001	3.6360	3.7257	2.9845	3.4268	1.2494
51.00	39.1887	7.6711	0.3334	3.9724	4.0633	3.3184	3.7603	1.5825
50.00	40.19	10.6480	3.2306	6.8951	6.9965	6.2195	6.6574	4.4760
49.00	41.191	13.6418	6.1441	9.8342	9.9461	9.1369	9.5709	7.3865

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table 2: Ocean tide induced strain waves calculated on the base of model m 2 (see JENTZSCH, KACZOROWSKI, SIMON /1988/) for different NS profiles

profile geogr. long	geogr. lat.	$e^{oc}_{\theta\theta}$ (M2)		$e^{oc}_{\lambda\lambda}$ (M2)		$e^{oc}_{\gamma\gamma}$ (M2)	
λ °	φ °	$A x 10^{-10}$	α °	$A x 10^{-10}$	α °	$A x 10^{-10}$	α °
N 1	53	15.908	266.18	3.926	84.20	3.983	86.84
	52	9.613	291.54	5.159	145.25	2.008	83.25
10.1 E	51	5.595	320.01	6.441	171.36	1.114	51.63
	50	4.025	0.46	7.155	186.97	1.060	15.19
	49	4.486	32.47	7.781	197.82	1.204	359.56
N 2	53	2.306	51.60	3.559	152.10	1.287	296.26
	52	2.446	50.30	3.646	151.80	1.317	294.61
37 E	51	2.587	49.13	3.726	151.49	1.348	292.95
	50	2.727	48.08	3.796	151.18	1.376	291.28
	49	2.866	47.11	3.856	150.85	1.403	289.60
N 3	53	2.405	32.47	3.176	123.83	1.305	266.09
	52	2.551	32.14	3.193	123.56	1.337	264.23
45 E	51	2.692	31.76	3.210	123.17	1.370	262.41
	50	2.829	31.30	3.223	122.69	1.402	260.61
	49	2.960	30.81	3.233	122.15	1.433	258.84
N 4	53	1.918	0.59	2.466	67.86	1.217	218.98
	52	2.018	1.32	2.439	66.70	1.249	217.48
60 E	51	2.115	1.89	2.411	65.46	1.279	215.99
	50	2.20[illegible]	2.35	2.379	64.12	1.308	214.51
	49	2.296	2.68	2.342	62.70	1.335	213.01

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table 3: Ocean tide induced strain waves calculated on the base of model m 2 (see JENTZSCH, KACZOROWSKI, SIMON /1988/) for a transcontinental EW profile

profile geogr. latit. φ °	geogr. long. λ °	$e^{oc}_{\theta\theta}$ (M2) A$\times 10^{-10}$	α °	$e^{oc}_{\lambda\lambda}$ (M2) A$\times 10^{-10}$	α °	$e^{oc}_{\theta\lambda}$ (M2) A$\times 10^{-10}$	α °
E 1	5	9.965	225.0	17.187	160.6	7.744	3.3
	10.1	5.595	320.0	6.441	171.36	1.114	51.63
51 N	15	2.732	42.4	6.716	202.3	1.415	9.5
	20	1.865	64.0	5.391	196.4	1.448	357.9
	25	2.128	67.8	4.742	184.0	1.414	337.3
	30	2.357	62.7	4.386	173.3	1.390	321.5
	35	2.462	53.8	3.886	157.6	1.350	301.7
	37	2.587	49.13	3.726	151.49	1.348	292.95
	40	2.547	43.5	3.553	141.4	1.355	283.1
	45	2.692	31.76	3.210	123.17	1.370	262.41
	50	2.485	22.7	2.947	104.9	1.369	248.1
	60	2.115	1.89	2.411	65.46	1.279	215.99
	70	1.352	345.6	2.095	23.7	1.086	188.9
	80	0.553	318.4	1.993	341.6	0.834	156.6
	90	0.422	180.8	1.997	301.9	0.603	110.4
	100	1.213	148.3	1.923	266.1	0.576	47.7
	110	1.941	131.0	1.617	228.5	0.784	353.8
	120	2.492	115.4	1.301	172.0	1.126	314.1
	130	2.587	132.2	2.520	98.6	1.624	295.7
	135	5.305	171.5	5.723	67.1	2.249	296.5
	140	4.387	177.4	1.338	69.6	4.234	268.8

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table 4: Estimation of the errors induced by residual ocean tide effects along the NS profile N 3 (λ = 45°E)

$\vec{e}^{\,o}_{\lambda\lambda}$ (M2) - body strain waves WAHR model

$\vec{e}^{\,oc}_{\lambda\lambda}$ (M2) - ocean tide induced strain waves

λ, φ - geographical station coordinates

station nr.	φ [°]	$\vec{e}^{\,o}_{\lambda\lambda}$ (M2) $A\times10^{-10}$	$\varkappa^{o}$	$\vec{e}^{\,oc}_{\lambda\lambda}$ (M2) $A\times10^{-10}$	$\varkappa^{o}$
1	53.00	4.1389	180	3.176	123.834
2	52.00	1.1217	180	3.193	123.557
3	51.45 = φ_0	0.0000		3.202	123.361
4	51.00	1.5825	0	3.210	123.165
5	50.00	4.4760	0	3.223	122.690
6	49.00	7.3865	0	3.233	122.146
7	53.1703	4.6213	180		
8	49.95	4.6210	0		

1. Localisation of φ_0 / control cycle

$$\vec{e}^{\,oc}_{\lambda\lambda}(st.3) = (3.202 \times 10^{-10} ; 123.361°)$$

$$\vec{e}^{\,o}_{\lambda\lambda}(st.6) + K\vec{e}^{\,o}_{\lambda\lambda}(st.1) = 0 \; ; \qquad K = 1.78465$$

$$\vec{e}^{\,oc}_{\lambda\lambda}(st.6) + K\vec{e}^{\,oc}_{\lambda\lambda}(st.1) = (8.9002 \times 10^{-10} ; 123.221°)$$

$$(1/(1+K))[\vec{e}^{\,oc}_{\lambda\lambda}(st.6) + K\vec{e}^{\,oc}_{\lambda\lambda}(st.1)] = (3.196 \times 10^{-10} ; 123.221°)$$

$$(3.202 - 3.196)/3.202 = 0.0019 < 0.2\,\%$$

2. Determination of (h_2 - 2l)

$$\vec{e}^{\,o}_{\lambda\lambda}(st.6) - \vec{e}^{\,o}_{\lambda\lambda}(st.1) = (11.5254 \times 10^{-10} ; 0°)$$

$$\vec{e}^{\,oc}_{\lambda\lambda}(st.6) - \vec{e}^{\,oc}_{\lambda\lambda}(st.1) = (0.1102 \times 10^{-10} ; 115.9°)$$

$$\frac{0.1102}{11.5254} = 0.00956 < 1\,\%$$

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Fig. 1

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Fig. 2: EW profile E 1 ($\varphi = 51°N$)

Amplitudes A of the ocean tide induced strain waves $e^{oc}_{\theta\theta}(M_2)$, $e^{oc}_{\lambda\lambda}(M_2)$ and $e^{oc}_{rr}(M_2)$ versus geographical longitude λ

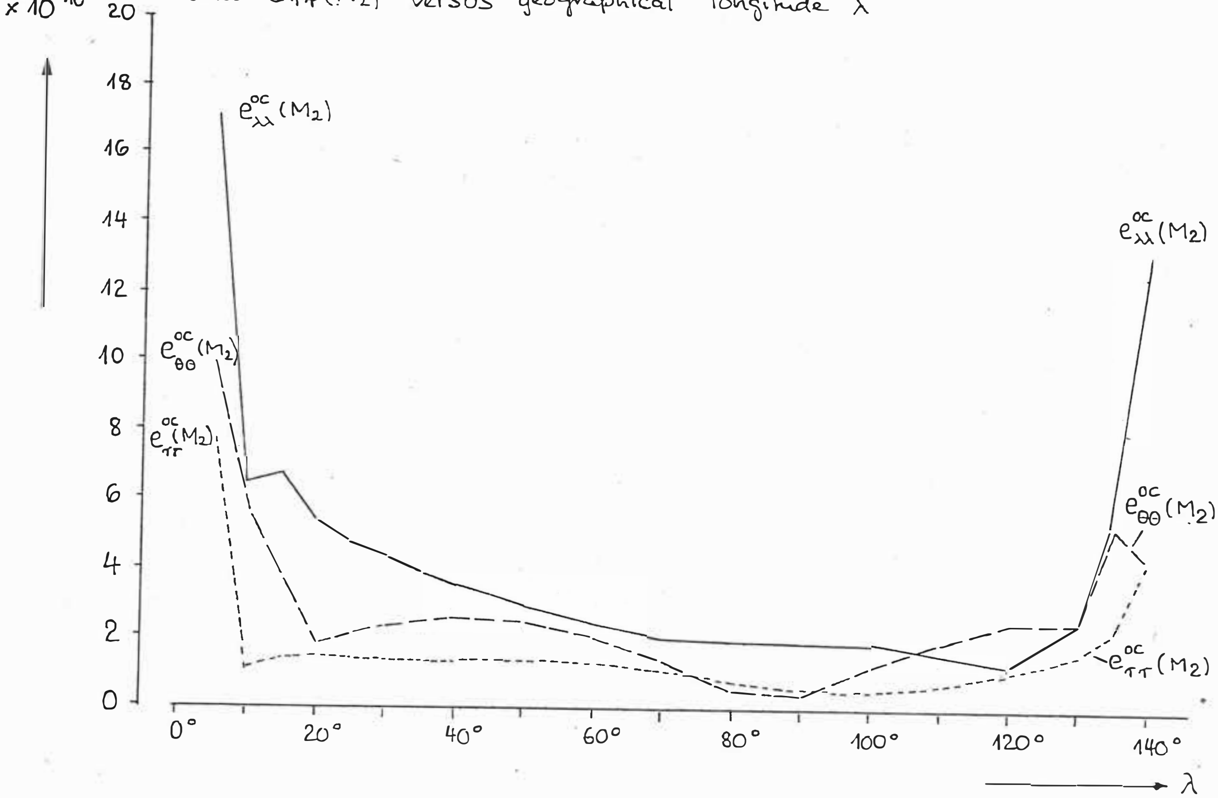

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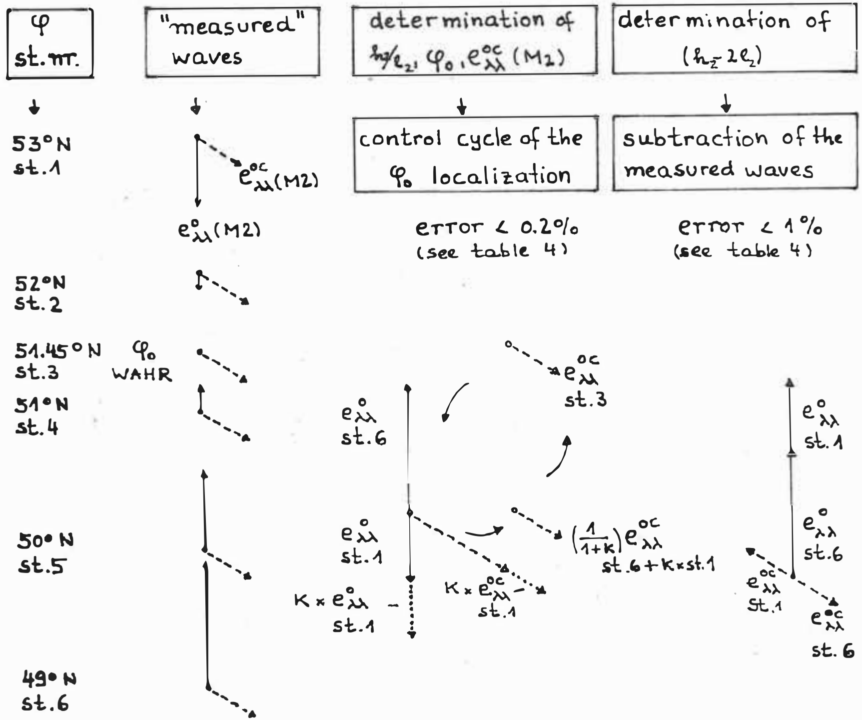
Fig.3



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Love Numbers and the Inner Structure of the Earth

P. Varga

There are a lot of papers dealing with the determination of Love numbers. It was pointed ont by different authors that theoretically the tidal deformations of a solid Earth with liquid core are also sensitive to heterogeneity around the point of measurements.

The first step of the investigation carried was the determination of the above mentioned parameters of the PREM. The calculations are based on the inhomogeneous system of differential equations by Molodensky (1953, 1961). For the solution the Runge-Kutta's fourth order method was in use with step 0.001 relative Earth radius r/a (a = 6371 km). The core-mantle boundary (CMB) was placed at relative dept r/a = =0.547. This value seems to be recently the most probable on the basis of different seismological data (Melchior, 1986). The value of the chosen depth of CMB leeds howerer to a slight change of the PREM where r/a=0.546 is accepted.

The results of the calculations for the orders n=2-10 can be found in Table 1. They show that with increasing the order of the deformations (n) the behave of the Earth became more and more rigid.

For the aims of present study naturally we need the second

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Table 1 Love numbers and their combinations

$$\delta_n = 1 + \frac{2}{n} h_n - \frac{(n+1)}{n} k_n \quad \text{and} \quad \gamma_n = 1 + k_n - h_n$$

for the orders n=2 - 10

n	k_n	h_n	l_n	δ_n	γ_n
2	0.2993	0.6053	0.0841	1.1564	0.6946
3	0.0925	0.2890	0.0147	1.0693	0.8036
4	0.0417	0.1758	0.0101	1.0358	0.8654
5	0.0244	0.1293	0.0084	1.0224	0.8951
6	0.0168	0.1069	0.0068	1.0161	0.9098
7	0.0126	0.0943	0.0054	1.0125	0.9184
8	0.0100	0.0859	0.0044	1.0102	0.9241
9	0.0082	0.0798	0.0035	1.0086	0.9284
10	0.0069	0.0750	0.0029	1.0074	0.9319

Table 2 Second order Love numbers and δ_2, γ_2 obtained on the basis of different models of the Earth.

Model	K_2	h_2	l_2	δ_2	γ_2
Gutenberg -Bullen /Kuo,1975/	0.3013	0.6102	0.0849	1.1583	0.6911
Molodensky I. /Molodensky, 1961/	0.3069	0.6216	0.0893	1.1612	0.6895
PREM-C	0.2993	0.6053	0.0841	1.1564	0.6940

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order term only. In order to estimate the reliability of our calculations we obtained h_2, k_2, l_2, δ_2, γ_2 values also for two earlier often used models of our planet (Table 2). It was concluded that our resulst coincide very well with results of Molodensky (1961) and Kuo (1975) for the models Molodenskii I and Gutenberg - Bullen respectively. Therefore our different result for PREM are presumebly not due to errors in the calculations.

It is interesting to know to extent of which the inner structure of the Earth can influence the Love numbers and the earth tidal parameters and how big lateral anomalies of these numbers and parameters can exist along the surface of the Earth. The guiding principle of the study of above problems was to vary one or more physical parameters of the PREM (Dziewonski, Anderson 1981) in the whole mantle or at different levels in order to describe how the physical parameters like ρ /r/, α /r/ or β/r/ can influence the value of the Love numbers and their combinations:

$\delta = 1+h-\frac{3}{2}k$ -to describe gravity variations

$\gamma = 1+k-h$ -to describe tilt variations

$D = a\frac{dh}{dr} + 4h-6l$ -to describe the dilatations

$A = 2h-n(n+1)l$ -to describe horizontal areal deformations

$S = a\frac{dh}{dr} + 2h$ -to describe the radial strain

In this paper ρ, α, β stands for the density and for the seismic speeds respectively.

Variations of the Love numbers and their combinations are shown in Table 3, where the original speeds used in the PREM or the bulk ($\varkappa$) and the incompressibility (μ)

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a./ $\alpha = \alpha_0(1+\varepsilon)$

ε%	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
-20	8,48	29,00	-64,59	12,15	-22,25	79,38	94,48	68,50
-10	2,31	7,58	-16,29	3,14	- 5,85	20,80	24,31	18,28
- 5	0,96	3,07	- 6,44	1,26	- 2,33	8,42	9,78	7,44
0	0	0	0	0	0	0	0	0
5	-0,51	-2,22	4,69	-0,90	1,64	- 6,10	- 7,02	- 5,43
10	0,12	-3,89	8,20	-1,60	2,95	- 10,71	-12,31	- 9,56
20	-1,99	-6,26	12,89	-2,56	4,74	- 17,21	-19,70	-15,43

b./ $\beta = \beta_0(1+\varepsilon)$

ε%	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
-20	26,89	22,38	50,87	1,16	-8,03	6,00	2,46	8,55
-10	12,28	9,89	23,56	0,36	-3,37	1,64	0,34	2,58
- 5	5,84	4,63	11,48	0,12	-1,53	0,45	-0,13	0,86
0	0	0	0	0	0	0	0	0
5	- 5,30	- 3,97	-10,90	0	1,18	0,41	0,89	0,06
10	-10,00	- 7,27	-21,57	0,16	2,00	1,85	2,78	1,17
20	-17,67	-10,97	-43,73	1,23	2,16	9,18	11,20	7,72

c./ $\mu = \mu_0(1+\varepsilon)$

ε%	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
-20	1,44	10,52	24,97	0,39	-3,60	1,82	0,42	2,83
-10	6,00	4,76	11,72	0,12	-1,58	0,47	-0,12	0,09
- 5	2,89	2,26	5,74	0,05	-0,73	0,13	-0,15	0,33
0	0	0	0	0	0	0	0	0
5	-2,60	-1,96	-5,39	-0,01	0,59	0,08	0,33	-0,09
10	-5,17	-3,89	-10,66	0	1,15	0,38	0,86	0,04
20	-9,67	-7,00	-20,63	0,14	1,94	1,67	2,56	1,02

d./ $\varkappa = \varkappa_0(1+\varepsilon)$

ε%	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
-20	1,22	3,89	-8,20	1,61	-2,95	10,28	12,43	8,43
-10	0,54	1,70	-3,51	0,70	-1,30	4,52	5,43	3,86
- 5	0,25	0,80	-1,61	0,32	-0,60	2,13	2,55	1,82
0	0	0	0	0	0	0	0	0
5	-0,22	-0,61	1,52	-0,29	0,55	-1,91	-2,28	-1,64
10	-0,41	-1,36	2,90	-0,56	1,04	-3,64	-4,34	-3,14
20	-0,77	-2,49	5,27	-1,02	1,88	-6,64	-7,89	-5,74

Table 3 Relative variations of the numbers and their combinations due to the variation of the seismic speeds (a. and b.) and due to the elastic parameter μ and $\varkappa$ (c. and d.). The basis of the comparison is the value obtained for the PREM model (ε = 0 %)

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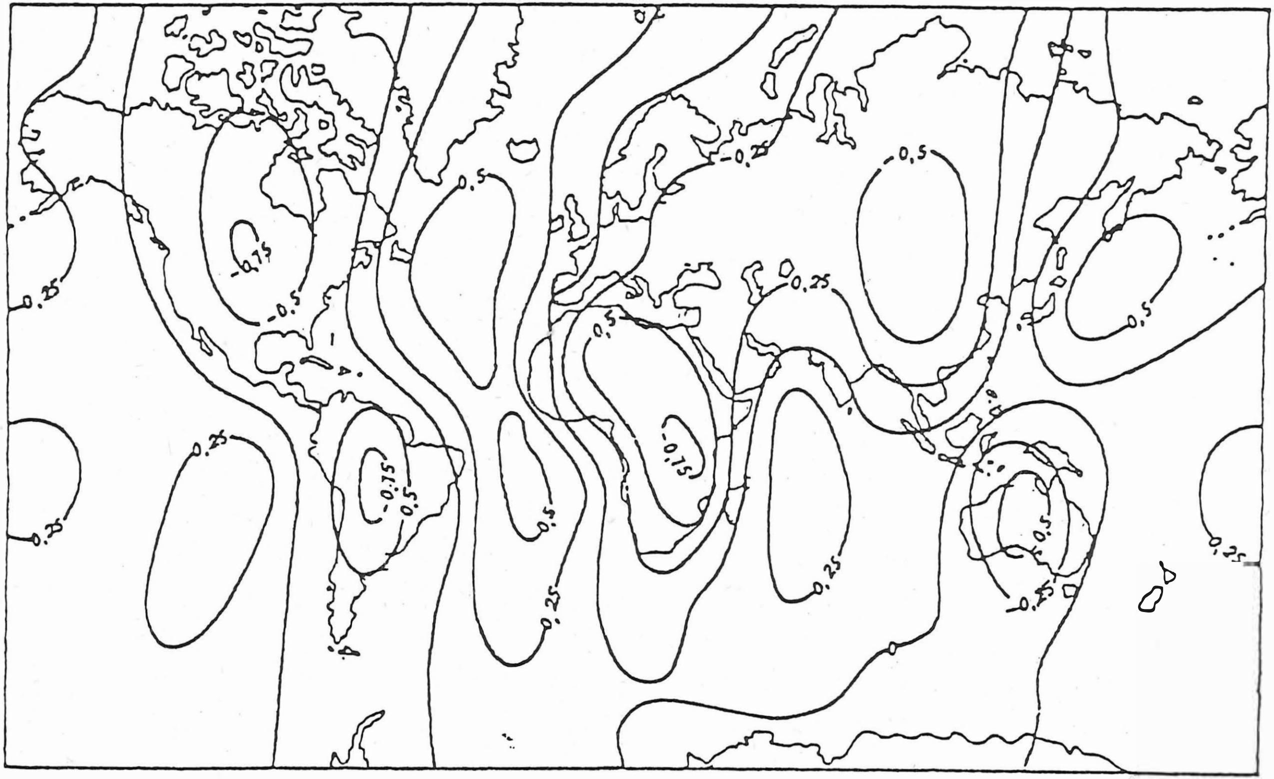

Fig. 1. Variations of gravity earth tide parameters in % according to Molodensky and Krämer /1980./

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values are perturbed by $\pm$ 20 %; $\pm$ 10 % and $\pm$ 5 % in the whole mantle.

The model calculation carried out show, that the alteration of the Love numbers and their combinations are not of linear and symmetrical character. It can be seen, that the increas of the speed of the seismic longitudinal waves α decreases the value of k, h and δ while increasing l and γ. The growth of α by 5 % producing an alteration of δ by % 0.91 %. Similar variations of δ have been obtained by Molodensky and Kramer (1980) for a laterally inhomogeneous model of the Earth. These authors have used heterogeneities represented by prime seismic speed (α) differences of 5 % extended to the whole mantle. In this artifical model the oceans are characterised by higher speed and the continents with lower on /Fig. 1/. The anomalies, obtained this way, can be characterised by the following features:

1./ The distributions of introduced lateral speed differences are followed by the areal distribution of the gravimetric earth tidal factor δ.
2./ The magnitude of the obtained variations in δ are practically independent from the bigness of the theritory where the α speed anomalies are introduced. (For example for Australia and Eurasia the map shows the same magnitudes).

The magnitude of the δ variation obtained by Molodensky and Kramer (1.00 %) is similar to our result when we increased α speed values relative to PREM model by 5 % (0.91 %). Considering the above features of the anomalies and also the similarity of the obtained variations, we can conclused that the influence of the lateral inhomogeninities on the

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Depth of the layer	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
1,00	-0,19	0,91	1,64	-0,41	0,73	-6,30	-2,69	-8,89
0,95	-0,28	-0,01	1,99	-0,43	0,79	-1,62	-3,11	-0,55
0,90	-0,32	-0,90	2,22	-0,38	0,72	-1,59	-3,16	-0,47
0,85	-0,25	-0,70	1,75	-0,28	0,53	-1,22	-2,45	-0,33
0,80	-0,16	-0,46	1,28	-0,19	0,34	-0,80	-1,64	-0,20
0,75	-0,06	-0,01	0,82	-0,10	0,18	-0,45	-0,93	-0,10
0,70	0	-0,08	0,30	-0,04	0,07	-0,17	-0,36	-0,03
0,65	0	0	0	0	0	-0,02	-0,06	0
0,60						0	0	0

b./ $\beta = 1.1. \beta_0$

Depth of the layer	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
1,00	-0,09	0,50	-1,17	0,38	-0,53	7,07	1,81	10,85
0,95	-0,19	0,40	-2,81	0,36	-0,46	1,07	2,68	-0,09
0,[illegible]	-0,44	0,11	-3,63	0,24	-0,30	0,86	2,72	-0,48
0,[illegible]	-0,80	-0,37	-3,63	0,12	-0,02	0,31	1,96	-0,89
0,80	-1,12	-0,83	-3,28	0,00	0,23	-0,32	0,95	-1,24
0,75	-1,48	-0,12	-2,81	-0,08	0,47	-0,95	-0,15	-1,52
0,70	-1,79	-1,27	-2,22	-0,18	0,70	-1,57	-1,28	-1,77
0,65	-2,08	-2,05	-1,64	-0,26	0,91	-2,16	-2,87	-2,00
0,60	-2,57	-2,62	-1,17	-0,37	1,20	-2,90	-3,58	-2,41

c./ $\nu = 1.1. \nu_0$

Depth of the layer	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
1,00	-0,06	0,24	-0,46	0,14	-0,23	3,30	0,79	5,11
0,95	-0,09	0,17	-0,12	0,13	-0,20	0,47	1,22	-0,06
0,90	-0,22	0,01	-0,16	0,10	-0,13	0,37	1,23	-0,25
0,85	-0,38	-0,19	-1,75	0,05	0	0,11	0,89	-0,45
0,80	-0,54	-0,41	-1,64	0	0,13	-0,18	0,43	-0,61
0,75	-0,70	-0,62	-1,28	-0,04	0,23	-0,47	-0,09	-0,75
0,70	-0,86	-0,82	-1,05	-0,08	0,34	-0,77	-0,62	-0,87
0,65	-1,02	-0,99	-0,80	-0,12	0,43	-1,05	-1,14	-0,98
0,60	-1,25	-1,27	-0,58	-0,18	0,57	-1,41	-1,73	-1,18

d./ $\varkappa = 1.1. \varkappa_0$

Depth of the layer	Δk %	Δh %	Δl %	Δδ %	Δγ %	ΔD %	ΔA %	ΔS %
1,00	-0,06	-0,28	0,50	-0,13	0,23	-1,93	-0,87	-2,69
0,95	-0,09	-0,32	0,70	-0,13	0,26	-0,53	-1,02	-0,18
0,90	-0,09	-0,30	0,70	-0,12	0,23	-0,51	-1,01	-0,15
0,85	-0,06	-0,22	0,50	-0,09	0,17	-0,39	-0,79	-0,11
0,80	0,02	-0,14	0,40	-0,06	0,11	-0,26	-0,54	-0,07
0,75	0,02	-0,08	0,20	-0,03	0,05	-0,15	-0,31	-0,03
0,70	0	0	0,10	-0,01	0,02	-0,05	-0,12	-0,01
0,65	0	0	0	0	0	0	0	0
0,60	0	0	0	0	0	0	0	0

Table 4 Influence of a spherial layer of 320 km thickness on the Love numbers and their combinations. Within this layer the seismic speeds (a. and b.) or the elastic parameters (c. and d.) are increased by 10 %. The depth of the layer is described by its upper boundarí expressed in relative depth r/a (a=6371 km). Variations are expressed in % relative to the PREM model.

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earth tidal deformations can be investigated on the basis of comparison of different, only radially inhomogeneous, models of the Earth. This means: it must be possible to make some realistic conclusions on the variations of Love numbers and their combinations along the Earth surface on the basis of comparison of different only radialdy inhomogeneous models of the Earth.
It is also of interest to investigate, how the Love numbers and their combinations are influenced by perturbation of seismic speeds (α and β) or elastic parameters ($\varkappa$ and μ) within a certain layer. The results of the study of this problem are plotted in the Table 4, where a layer of 320 km thickness was investigated at different depthes of the top of the layer. So the layer described with relative Earth radius r/a = 1.00 is directly on the surface of the Earth while the value r/a = 0,60 means that the corresponding layer lies practically on the core-mantle boundary. The introduced perturbation was in every case 10 %.
The plots of the calculated variations demonstrate that for case of alteration by 10 % of prime wave speed the biggest deviation from the PREM's reference values occur when the upper part of the investigated layer is between relative depthes 0.95-0.85. This conclusion is not true for the tilt, for the dilatation and for the radial strain components. Similar to case of prime wave speed conclusions can be drawn also for the case of bulk modulus.
The conclusions are more complicated when the transverse seismic wave speeds or the incompressibility undergo perturbation. The h and k values are decreasing monotonously. The same is true in case of dilatation and radial strain. For the l till r/a = 0.90 we can observe a diminution and for the areal horizontal deformations an increase. As far as the graviteric and tilt earth tide parameter is concerned the alteration of the depth of the speed anomaly can produce

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Table 5 Variation of the Love numbers and their combinations relative to PREM model based on the mapping of the mantle /Dziewonski, 1984; Woodhouse and Dziewonski, 1984/
/ α_O, β_O are the values used in PREM/

	Description of the model	Variations of the Love numbers and their combinations relative to PREM /in %/
Model A	$1.00 \geq r/a > 0.90$ $\alpha = 1.08\ \alpha_O$ $\beta = 1.05\ \beta_O$ $0.90 \geq r/a > 0.85$ $\alpha = 1.03\ \alpha_O$ $\beta = 1.02\ \beta_O$ $0.85 \geq r/a > 0.60$ $\alpha = 1.01\ \alpha_O$ $\beta = 1.01\ \beta_O$ $0.60 \geq r/a > 0.55$ $\alpha = 1.03\ \alpha_O$ $\beta = 1.02\ \beta_O$	$\Delta k = -1.80$ $\Delta h = -2.67$ $\Delta l = 0.82$ $\Delta\delta = -0.72$ $\Delta\gamma = 1.59$ $\Delta D = -4.99$ $\Delta A = -5.26$ $\Delta S = -4.79$
Model B	The same as Model A, but the density is decreased by 2 % overall in the Mantle	$\Delta k=-1.16$ $\Delta h=1.42$ $\Delta l=-1.76$ $\Delta\delta=-1.23$ $\Delta\gamma=-1.80$ $\Delta D=-3.69$ $\Delta A=-3.79$ $\Delta S=-3.62$

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variations 0.70 and 1.74 % respectively.
Similar behaviour as for the transverse wave speed can be observed in case of the perturbation of the incompressibility.
After the investigation of the influence of the above artifical seismic speed and elastic parameter perturbations we hawe to study a problem: how big variations of the Love numbers and their combinations along the surface of the Earth can be explained by lateral inhomogenities. For this purpose works of Woodhouse and Dziewonski (1984) and of Dziewonski (1984) has been used. In these papers the mapping of the upper and the lower mantle have been carried out respectively. The investigation of the upper mantle was based on the speed values of the secondary waves (β) while for the lower mantle prime wave velocities (α) have been used. In the first work a three dimensional modeling of the Earth structure has been carried out by inversion of seismic waveforms up to depth 670 km (r/a = 0.90) (Woodhouse and Dziewonski, 1984). Size of the detected transverse wave velocity anomalies at the depth 50 km is $\pm$ 8 %, at the depth 250 km $\pm$ 2.5 % and finally at the depth 650 km $\pm$ 2 %. /These lateral speed variations are comparable to the velocity jumps across the radial structural discontinuities in the upper mantle. In PREM at the Moho surface the jump is 15 % and at the depthes 220 km, 400 km and 670 km 6 % and 7 % respectivelly./
Dziewonski (1984) carried out the mapping of the lower mantle too with use of α prime wave speeds. The lateral velocity anomalies at the top of the lower mantle are of the order of 3 %. The same is the situation at the core-mantle boundary. In the other parts of the lower mantle the α wave speed anomalies are approximately 1 %. If we

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are introducing a simplification and suppose the equality of the Lamé parameters μ and λ in the whole mantle we shall have $\alpha = \sqrt{3}\,\beta$ and in this way we can rougly estimate the lateral variations of the α speed values in the upper mantle and the same for for the β velocities in the lower mantle. In this way became possible to complete an estimated model for the lateral inhomogenities in elasicity within the whole mantle, and to describe the magnitude of the possible variations of the Love numbers and their combinations along the surface of the Earth /Table 5/.
The result of the calculations carried out shows that for the realistic areal variation of the Love numbers we can accept areal anomalies up to 2-3 %,but for the most accuratelly measurable gravity earth tide parameter only 0.72 %. For the tilt we got 1.59 %. Much bigger variations we can expect for the dilatation and for the deformations.
According to Zharkov (1983) the uncertainty of the density function in the mantle is 1-2 %. Therefore we calculated a similar to the first model of Table 1 a second one too, where the density variation of 2 % (relative to PREM) was alloved everywhere in the mantle. Naturally during this operation the mass of the Earth and the momentum of inertia were conserved. Looking over the data obtained for this Model B of Table 5 it is easy to conclude that for the Love numbers we got somewhat smaller limits for the possible areal variations, but the variability of δ and γ parameters became bigger: 1.2 % and 1.8 % instead of 0.7 and 1.6 %. For the dilation and deformationswe got in this case variations 3-4 %.
In the course of the study of the influence of the Earth core on the Love numbers and on their combinations the following questions must be clarified:

a./ To what extent is the value of the Love numbers influenced by the density model of the core?

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b./ What is the relation between the Love numbers obtained using different density jumps at the core--mantle boundary (CMB)?

c./ To what extent the Love numbers can be influenced by the uncertainty of the position of the core-mantle boundary (CMB)?

d./ To extent of which the Love numbers are dependent on the possible rigidity of the outer core?

The first question can be investigated with the help of the comparison of very different theoretical density models for the Earth's core. In Table 6 the Love numbers obtained for the core constant density are compared with those obtained for the hydrostatic density distribution and for the PREM. In spite of the known core's inhomogenity due to, first of all, the presence of a solid inner core all models give practically the same Love number values. Therefore it can be concluded, that the density distribution in the core not influencing the value of the Love numbers in a remarkable extent.

Actually the density values of the core depend on the magnitude on the densiti jump at the core-mantle boundary. Figure 2 shows, that the density difference can vary the value of the Love numbers in a remarkable extent. Nevertheless the density values at the surface of the core is constrained to the narrow range by Press (1970) ((9.9-10.2) g/cm^3) from which the following variations of the Love numbers and their combinations can be obtained:

k=0.67 % h=0.40 % l=0.43 %

δ =0.22 % γ =0.18 %

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Table 6 Influence of the density distribution within the core upon the Love numbers. Variations are relative to PREM

	k	h	l	δ	γ
PREM	0.2993	0.6053	0.0841	1.1564	0.6940
	Δk	Δh	Δl	Δδ	Δγ
The Core has constant density %	-3.01	-1,52	4.76	0.37	0.03
The density distribution within the core is hydrostatic %	-0.46	-0.40	-0.24	-0.02	0.13

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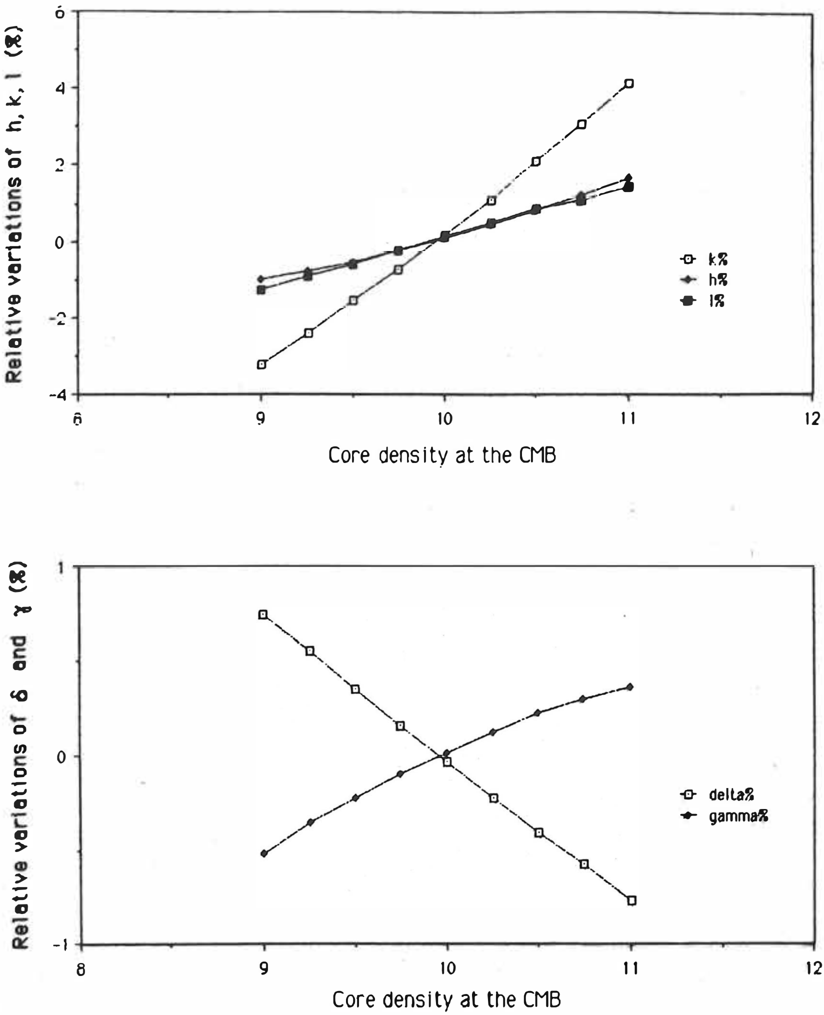

Figure 2 Influence of the density differences at CMB on the Love numbers and on the earth tidal gravity and tilt amplitude ratios. Densities in the mantle are according to PREM.

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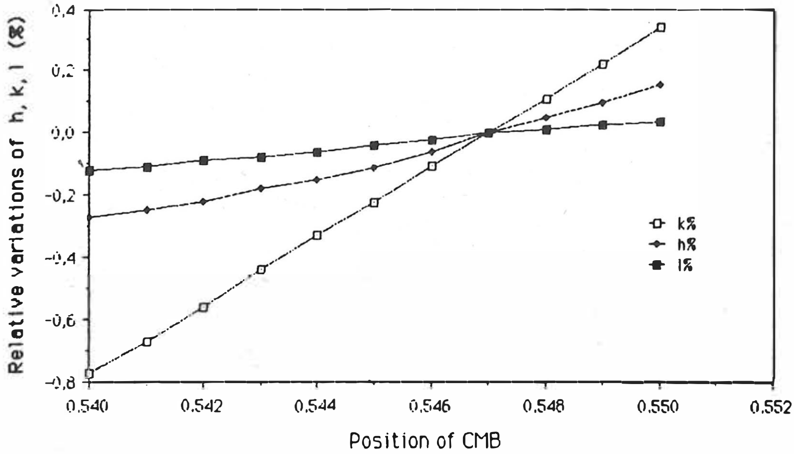

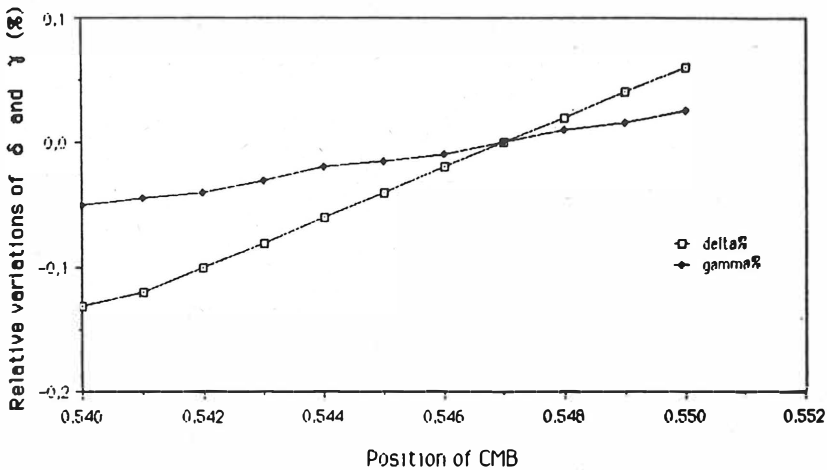

Figure 3 Influence on the value of the Love numbers and on the amplitude ratios of the position of CMB .

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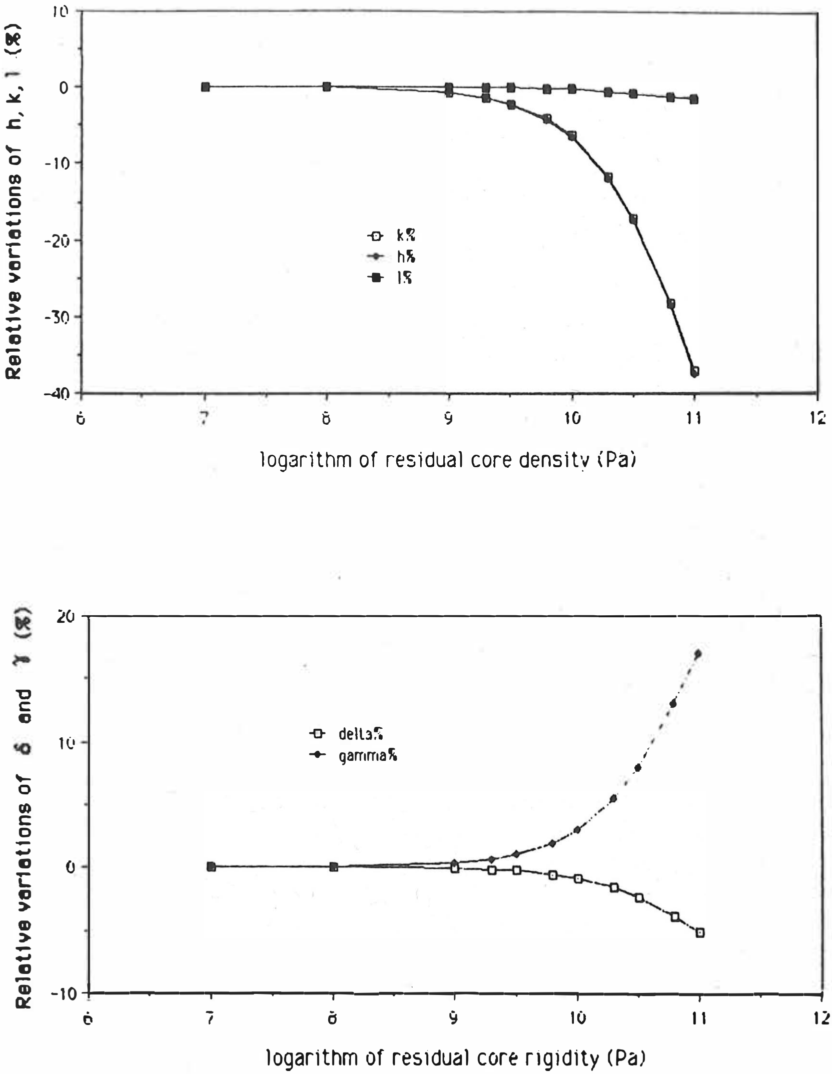

Figure 4   Core rigidity and the Love numbers

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The position of the CMB is relatively well known. On the basis of many theoretical works it can be concluded, that the mean value of, the core radius is known with accuracy ± 1-2 km (Melchior, 1986). But the core-mantle boundary has a topography with an elevation difference of 1o km. With the help of Figure 3 it can be concluded however that a variation at 10 km in the core-mantle boundary (New Scientist, 1986) position producing only, recently negligible uncertainties:

k=0.43 % h=0,21 % l=0.10 %

δ=0.06 % γ=.04 %

Since long time there is a discussion about the possible rigidity of the outer core. Therefore we calculated versions of the PREM, which consist certain rigidity in the outer core. The deviations from PREM are illustrated by Figure 4. Earlier it was supposed by different authors, that the order of the outer core rigidity is 10^9 N/m^2 (Sato, Espinosa, 1967; Ibrahim, 1973).
RecentlyKuo, Zhang and Chu (1985) show howerer that the outer core rigidity must be below 10^8 N/m^2. If it is so, the supposed core rigidity is not able to vary the value of the Love numbers.
On the basis of above discussed results of theoretical model calculations it can be concluded, that the Love numbers and their combinations only slightly depend on the conditions in the core, but they can be changed by the model alterations in the mantle. From the Tables 3, 4 and 5 it can be established that the h, k and l values are much rather dependent on the structure of the mantle as the measurable gravity and tilt earth tidal parameters.
The most isformative on the structure of the mantle earth

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tidal components are the dilatation, and the strain components which unfortunately can not be observed with needed accuracy due to calibration problems first of all. (The reliability of the calibrations is recently 3-5 %). It is important to add, that due to the complicated dependence of Love numbers and their combinations on the mantle structure the use of the earth tidal data for the study of the interior at our planet is an extremely difficult task.
At the moment the most promising way to study the structure of the mantle is the use of the gravity earth tidal measurements.
If we comparing our results obtained of gravity earth tide components of the PREM with the use of equations introduced by Molodensky (1953, 1961) with the value obtained by Dehant and Ducarme (1986) for O_1 wave using Wahr's theory (δ =1.1543) it can be concluded that practically there is no difference between theoretical results based on these two theories. (The exact value of the deviation of the calculated data is $2.1.10^{-3}$.)
There is however a much bigger divergence between the observed and theoretical values of gravity earth tide parameters. The mean of all measurements is for O_1 wave 1.161 (Mlechior, 1977). The discrepancy of observed and theoretical results -which is of about 0.5 % - can not be simply reladted to the calibration problems, although the calibration accuracy of **the** recording gravimeters is recently of the same order (Varga et al. 1985). The reason for such a disagreement can be found also in existing gaps in our knowledge on the internal structure of our planet, in the imperfectness of the accepted 2 D models used for the theoretical calculations. As it was shown above under "favourable" conditions the uncertainty of this origin can be as big 1.2 %.

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The results of above model calculations suggest, that the areal variations of the gravity earth tide parameters can not be essentially bigger as 1 %. If the areal deviations of measured amplitude ratios are exceeding this value it is probably due to not exactly excluded indirect effect of oceanic tides, meteorological and hydrological influences or they are connected to observational errors.
There are also problems recently in connection with the earth tidal correction needed in VLBI, where the recently not measurable h and the not exactly determined from measurements l Love numbers are in use. This neccesitate the use of the theoretically calculated values of these two Love numbers. As it was shown by our model calculations the value of h and l much more depend on the adopted model of the Earth and probably undergo much bigger areal variations as δ . The variations easily can be of the order of some per cent. That means that for vertical cordinate determinations recently we are not able to give better lunisolar corrections as 1 cm, and the needed accuracy for such a correction for VLBI measurements is 1 mm.

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