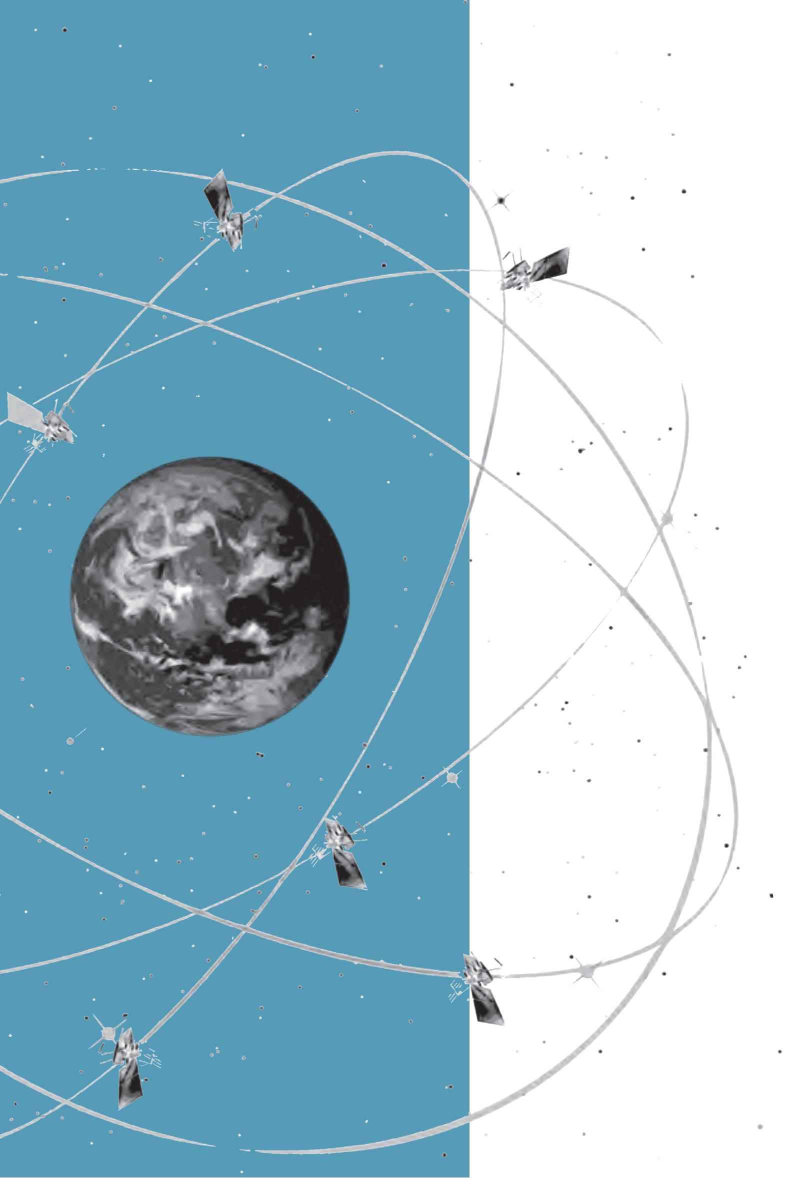
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2018



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Abstract

Applications of the Global Navigation Satellite Systems (GNSS) to Earth Sciences are numerous. The International GNSS Service (IGS), a voluntary federation of government agencies, universities and research institutions, combines GNSS resources and expertise to provide the highest–quality GNSS data, products, and services in order to support high–precision applications for GNSS–related research and engineering activities.
This *IGS Technical Report 2018* includes contributions from the IGS Governing Board, the Central Bureau, Analysis Centers, Data Centers, station and network operators, working groups, pilot projects, and others highlighting status and important activities, changes and results that took place and were achieved during 2018.

This report is available in electronic version at
ftp://igs.org/pub/resource/pubs/2018_techreport.pdf.

The IGS wants to thank all contributing institutions operating network stations, Data Centers, or Analysis Centers for supporting the IGS. All contributions are welcome. They guarantee the success of the IGS also in future.

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G. Johnston

IGS Governing Board Chair, Geoscience Australia

1 Introduction

2018 was an important year for the IGS. For the first time the IGS community celebrated it biannual members workshop Asia, with the event being hosted by Wuhan University in the lovely city of Wuhan, China. This workshop, held in October 2018, bought together researchers from all over the world, with a very strong contingent from China, to discuss the current work program of the IGS and plans for the future. The geographical location of the workshop also made it appropriate to strongly consider the role of Beidou in the multi-GNSS future that the IGS is embracing. The workshop was a real success and the IGS extends its thanks to Wuhan University for hosting such a fine event.

2018 also signaled a changing of the guard within the IGS Central Bureau (CB), with the long standing Director of the CB, Ruth Neilan, moving on to other endeavors after serving the IGS community since its inception, and before. The contribution Ruth has made to science and society through the IGS cannot be underestimated. The IGS wish her well for the future. Thanks also go out to Steve Fisher who finished up with the CB after many years of service.

Allison Craddock has now taken on the role of Director of the IGS CB. Please join with me in congratulating Allison and providing her with as much support as possible. The IGS is an extremely diverse collaborative program, and it is the CB that provides the coordination that keeps it together. Thanks also go to JPL / NASA for their continued support of the CB function.

Lastly, I'd like to acknowledge the appointment of Felix Perosanz to Vice Chair of the

IGS Governing Board. The Vice Chair position has been created as an acknowledgment of the increasing outreach role of the Governing Board, and the increasing diversity of participation in the IGS. The Vice Chair, Working closely with the Chair and Executive committee, will assist with the representation of the IGS at the many forums where IGS participation is of value.

2 IGS Highlights in 2018

2.1 IGS 2018 Workshop in Wuhan, China

The latest IGS Workshop, with the theme of ”Multi-GNSS through Global Collaboration” took place 29 October to 2 November, 2018. The workshop was hosted locally by Wuhan University at the East Lake Conference Center in Wuhan, China, and was the first IGS Workshop to be held on the Asian continent. Over 300 individuals participated in the sessions.

The workshop featured two keynote presentations:

- ”Introduction to BeiDou-3 Navigation Satellite System” presented by Yuanxi Yang of the State Key Laboratory of Geo-Information Engineering, based in Xi’an, China.
- ”BeiDou Augmentation and its Future” presented by Liu Jingnan, an Academician of the Chinese Academy of Engineering, based at Wuhan University in Wuhan, China.

Videos, posters, and plenary presentation slides will be made available on the IGS website.

2.2 Membership Growth and Internal Engagement

In 2018, IGS membership reached 329 Associate Members, representing 45 countries. The 36-member IGS Governing Board guides the coordination of over 200 contributing organizations participating within IGS, including 108 operators of GNSS network tracking stations, 6 global data centers, 13 analysis centers, and 4 product coordinators, 21 associate analysis centers, 23 regional/project data centers, 14 technical working groups, two active pilot projects (i.e., Multi-GNSS and Real-time), and the Central Bureau.

In order to best understand who among the listed members are still active, the Central Bureau and Elections Committee Members conducted an online campaign asking all Associate Members to verify their continued interest in participating in the IGS, and to update their contact information. Further engagement with the Associate Membership included removing the 10-person-per-organizaiton cap in favor of a case-by-case review of Associate Member applications.

A comprehensive overhaul of Associate Member engagement documents, including elections and other mentions in the IGS Terms of Reference, will take place in 2019.

2.3 New Working Group on Precise Point Positioning Ambiguity Resolution

A new IGS working group that will focus on PPP with ambiguity resolution (PPP-AR) was established at the IGS Workshop in Wuhan. It will be chaired by Simon Banville from NRCan in Canada. An important issue of IGS orbits and clocks is its use in PPP in response to user requirements for ambiguity resolution in areas such as LEO satellites, frequency transfer, ionosphere tomography, coordinate time series, and surveying. As proposed, a PPP AR WG would analyze the feasibility of combining products.

3 IGS Operational Activities

3.1 Network Growth

As of the end of 2018, the IGS Network has 507 stations, of which 280 are multi-GNSS (63 stations added multi-GNSS capabilities this year) and 195 are real-time GNSS. Delivery of core reference frame, orbit, clock and atmospheric products continued strongly, with further refinement of the Real-Time Service and considerable efforts being targeted towards development of standards. Development of the IGS capacity to operate with multiple GNSSs also continued, with additional Galileo and BeiDou satellite launches bringing those constellations closer to operational status.

Over 500 IGS Network stations are maintained and operated globally by many institutions and station operators, making tracking data available at latencies ranging from daily RINEX files to real-time streams available for free public use. The transition of the IGS network to multi-GNSS capability was highlighted in the 2018 Workshop, with all working group chairs introducing multi-GNSS topics in their splinter sessions. Significant effort on behalf of the MGEX Pilot Project and Working Group has also continued, with approximately 55% of IGS network stations being capable of tracking multiple GNSS constellations (GPS + GLONASS + one other) (December 2018).

3.2 Product Generation and Performance

Joint management of the IGS ACC by Michael Moore of Geoscience Australia and Tom Herring of the Massachusetts Institute of Technology continued, with operations based at Geoscience Australia in Canberra, Australia. The ACC combination software is housed on cloud based servers located in Australia and Europe, and coordination of the IGS product generation continues to be carried out by personnel distributed between GA and MIT.

The IGS continues to maintain a very high level of product availability.

3.3 Preparation for a Third Reprocessing

At the 2018 workshop, it was decided to carry out a third reprocessing, in time for a contribution to the ITRF2020. In light of this, the ACCs (Moore, Herring) are planning a 3-day workshop to take place April 2019 at the German Research Centre for Geosciences (Deutsches GeoForschungsZentrum, GFZ) in Potsdam, Germany. Representatives from IGS Analysis Centers will also participate in a joint GGOS-IERS Unified Analysis Workshop to take place October 2019 at Université Paris Diderot in Paris, France.

3.4 Data Management

The Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center registered the following user activity in 2018:

- Total of 1.4B files equating to 121 TBytes GNSS data
- Total of 16M files equating to 43 TBytes GNSS products
- Average of 116M files equating to 10 TBytes GNSS data from 18.8K hosts per month
- Average of 16.4M files equating to 3.5 TBytes GNSS products from 13.8K hosts per month

3.5 Standards Development Support and Adoption of RINEX V3.04

The IGS continues to contribute to the development of international standards related to GNSS, principally through participation within the RTCM (Radio Technical Commission for Maritime Service), where IGS leads the RINEX working group, as well as participating within the standards activities related to real time systems. Maintenance and further development of the RINEX data exchange standard continues to take place in cooperation with RTCM-SC104, and has led the recent release of RINEX 3.04. The GB agreed in 2018 to adopt the official RINEX V3.04 format, handling the ability for 9-character id and fixing the definition of GNSS reference time scales. The RINEX Working Group has assumed leadership in maintenance and further development of the RINEX data exchange standard, in cooperation with RTCM-SC104, and has led the recent release of RINEX 3.03. The RINEX Working Group has worked in cooperation with the IC to prepare a plan to transition from RINEX 2.x to RINEX 3.x. The IGS Network map was enhanced to provide information about stations providing data in RINEX 2 and RINEX 3 formats, which may be viewed in real time at: http://www.igs.org/network . Additional work is being undertaken to determine the best path forward for compressional algorithms and the associated utilities that are compliant with modern Operating Systems.

As announced by RINEX Working Group Chairman Ken MacLeod (of Natural Resources Canada) in IGSMAIL-7713, The International GNSS Service (IGS) and Radio Technical Commission Maritime Service, Special Committee -104 (RTCM SC-104) RINEX Working Group announce the availability of RINEX 3.04. Data Center Working Group is working on integrating long filenames, RINEX3 data into operational archives. The Troposphere WG is also incorporating long names in its SINEX.

The Receiver INdependent EXchange (RINEX) is an internationally recognized Global Navigation Satellite System (GNSS) observation and navigation data format. The first version of RINEX was developed in 1989, to support a European, Global Positioning System (GPS) data collection campaign. The key objective was to develop an open and human readable (ASCII) GNSS data format that removed the need of specialized decoders/interpreters for each GNSS receiver type. Under the leadership of Werner Gurtner (Astronomical Institute, University of Bern, Switzerland) and Lou Estey (UNAVCO, Boulder, Colorado, USA), RINEX evolved from version 1 to 2 and then to 3. Since 2013 (RINEX Version 3.02) the RINEX GNSS format has been maintained by the RINEX Working Group, which consists of members from the International GNSS Service (IGS), Radio Technical Commission for Maritime Service, Special Committee 104 (RTCM-SC104) and the GNSS industry.

The current RINEX 3.04 release supports all publicly available signals, including the United States' GPS, Russia's GLONASS, Europe's Galileo, China's BeiDou, Japan's Quasi Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS) constellations. RINEX 3.04 contains updates to support planned GLONASS CDMA signals, as well as new BeiDou III and QZSS II signals. In addition to the new signals, the RINEX 3.04 text has been edited to improve the description of messages, fields and overall readability. The RINEX 3.04 data standard documentation is available from the following addresses: `ftp://igs.org/pub/data/format/rinex304.pdf`, `ftp://igs.org/pub/data/format/rinex304-release-notes.pdf` and `http://www.rtcm.org/differential-global-navigation-satellite--dgnss--standards.html`.

3.6 Scientific Applications of IGS Data and Analysis Products Session at AGU 2018

The IGS organized a session at this year's American Geophysical Union (AGU) in Washington, DC. The Session, number G021: "Scientific Applications Enabled by the International GNSS Service (IGS) and by Improvements to GNSS Products," was convened by Gary Johnston on behalf of former Governing Board member Geoffrey Blewitt of the University of Nevada Reno, USA, with IGS Governing Board and Executive Committee member Rolf Dach of the University of Bern, Switzerland.

The description of the session is as follows: "For nearly 25 years, products of the International GNSS Service (IGS) have increasingly enabled a broad diversity of scientific applications, such as Earth rotation, tectonophysics, seismology and the earthquake cycle, glaciology and glacial isostatic adjustment, global environmental change, sea level, terrestrial water storage, time transfer, space weather and atmospheric science, natural hazards and tsunami early warning, and fundamental physics. The recent inclusion of Galileo (Europe) and Beidou (China) to the established GNSS – GPS(US) and GLONASS (Russia) – will eventually increase the number of satellites to >100, offering potential new scientific applications. Moreover, the continuous development and improvement of IGS products in this fast-moving field with new GNSS satellites, systems, signals, models, and GNSS data analysis methodology is a scientific challenge. For this session we solicit presentations on scientific applications that are enabled by IGS products, and on improvements to quality and breadth of GNSS products that will enable new science."

The IAG Global Geodetic Observing System, of which IGS is a component, also held a session, focusing on essential geodesy. The session conveners were led by Kosuke Heki of Hokkaido University, Japan; with Michael Pearlman of the Harvard Smithsonian Center for Astrophysics, USA; and IGS GB member Richard Gross of the Jet Propulsion Laboratory, USA.

3.7 Communications Development and Guidance

Numerous news pieces covering IGS contributing organizations, IGS activities, and other announcements were developed in collaboration with Governing Board members and their respective contributing organizations, with an emphasis on invited content and collaborative, short "news bite" articles. Governing Board members are routinely encouraged to connect their agency or organization's social media or communications teams with the Central Bureau to ensure optimal collaboration and mutual public relations support.

An IGS 2018 Update poster was developed by the Executive Committee with assistance from the Central Bureau Secretariat, and presented in the GGOS session at the 2018 EGU. The poster may be viewed and downloaded here: http://kb.igs.org/hc/en-us/articles/360022363911-EGU-2018-Poster.

3.8 Key Publications on Multi-GNSS and Satellite Physical Properties

The IGS Multi-GNSS Working Group, led by Oliver Montenbruck, released a White Paper, titled "Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products." The paper discusses the parameters needed to ensure the highest possible performance of IGS products for all constellations and motivates the need for provision of satellite and operations information by the GNSS providers. All information requested by the IGS is considered to be sufficiently abstract such as to neither interfere with the GNSS providers' safety and security interests nor with intellectual property rights. The paper is available for download here: http://bit.ly/MGEXwhitepaper, with complete information available on the MGEX website: http://mgex.igs.org/.

MGEX has also recently published a comprehensive paper detailing its achievements in the last five years, future prospects, and challenges. "The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges," published in Advances in Space Research, Volume 59, Issue 7, 1 April 2017, Pages 1671–1697, discusses:

- Multi-GNSS products derived from the IGS monitoring station network
- Work towards full integration of new constellations into routine GNSS processing
- Progress made within the MGEX project including BeiDou, Galileo, and QZSS for precise point positioning, atmospheric research, and other applications.
- Biases; standards and conventions

Due to copyright restrictions, a pre-print previous version of the article is available here: http://bit.ly/MGEXasr

The International GNSS Service: 25 years on the path to multi-GNSS, authored by Craddock and Johnston, was published in the September issue of GPS World magazine: http://gpsworld.com/the-international-gnss-service-25-years-on-the-path-to-multi-gnss/

3.9 Official IGS Citation Updated to Chapter in 2017 Springer Handbook of Global Navigation Satellite Systems

In response to ever-growing applications for precise GNSS data as a public utility, the work of the IGS and its constituent elements continues to increase in relevance, especially as applications that essentially rely on IGS data and products expand both within and outside of the sciences.

As it enters its second quarter-century, the IGS is evolving into a truly multi-GNSS service. For 25 years, IGS data and products have been made openly available to all users for use without restriction, and continue to be offered free of cost or obligation. In turn, users are encouraged to participate within the iGS, or otherwise contribute to its advancement and to include a reference to the IGS in their citations.

The IGS Governing Board recently updated the official citation for acknowledging IGS data, products, and other resources in scholarly publications. The new official citation is the IGS chapter in the 2017 Springer Handbook of Global Navigation Satellite Systems.

The IGS Central Bureau gratefully acknowledges the contributions of IGS Governing Board and Associate members in the drafting of this article, as well as to Geoscience Australia for financially supporting the authorship. Special thanks to the article's authors, Governing Board Chairman Gary Johnston, as well as to Anna Riddell and Grant Hausler.

Johnston, G., Riddell, A., Hausler, G. (2017). The International GNSS Service. In Teunissen, Peter J.G., & Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed., pp. 967-982). Cham, Switzerland: Springer International Publishing DOI: 10.1007/978-3-319-42928-1

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The book is currently available for purchase and download on the Springer website: https://www.springer.com/us/book/9783319429267

A special pre-print version of this document was made available in the IGS Knowledge Base: https://kb.igs.org/hc/en-us/articles/360018811151-The-International-GNSS-Service-chapter-excerpt-from-the-2017-Springer-Handbook-of-Global-Navigation-Satellite-Systems-

3.10 IGS Governing Board Meetings in 2018

The Governing Board discusses the activities and plans of various IGS components, sets policies, and monitors the progress with respect to the agreed strategic plan and annual implementation plan. It is customary to hold two GB meetings during any IGS Workshop – the second of which typically focusing on workshop recommendations and other debriefing from the week's activity.

8 April 2018	Governing Board Business Meeting, held prior to the 2018 European Geosciences Union meeting	Vienna, Austria
28 October 2018	50th Governing Board Meeting (1 of 2 sessions), held immediately before the 2018 IGS Workshop	Wuhan, China
2 November 2018	50th Governing Board Meeting (2 of 2 sessions), held immediately after the 2018 IGS Workshop	Wuhan, China
8 December 2018	51st Governing Board Meeting, held prior to the 2018 American Geophysical Union meeting	Washington, District of Columbia, United States

4 IGS Advocacy and External Engagement

4.1 Official Recommendations to the International Laser Ranging Service

At the request of the International Laser Ranging Service (ILRS, a sister service within the International Association of Geodesy) the IGS has issued two official recommendations. These recommendations were presented to the ILRS and its service providers at their meeting in Canberra, Australia, as well as the International Committee on GNSS Working Group on Reference Frames, Applications, and Timing at their meeting in Xi'an, China, in November 2018.

> IGS Recommendation to the ILRS 2018.1:
> "Considering the increasing number of GNSS satellites in geosynchronous and geostationary orbit and the special challenges for determination and validation of the respective orbits; the IGS encourages the extension of SLR stations supporting high-altitude tracking, specifically in the Asia-Pacific region, and the transition to kHz laser systems enabling shorter normal point duration."

> IGS Recommendation to the ILRS 2018.2:
> "Recognizing the increasing load on ILRS stations caused by the increasing number of GNSS satellites equipped with laser retroreflectors; and the priority of geodetic laser satellites and as well as the needs from other missions; considering furthermore the importance of SLR tracking for orbit validation and analysis of GNSS satellites as well as the need to achieve a homogeneous coverage of all GNSS constellations, satellite types, orbital planes and individual spacecraft; the IGS recommends that the ILRS retains the general prioritization of geodetic laser satellites before GNSS satellites and satellites from other missions, and on request by the GNSS providers or the GNSS user community gives priority to dedicated campaigns for tracking of selected GNSS satellites at the expense of a reduced background tracking activity, and uses remaining tracking resources to select and track the remaining GNSS satellites in a randomized manor, where each statin can freely select a set of GNSS satellites for tracking on a weekly basis.

Language in these recommendations was formulated to be generic, rather than prescriptive.

4.2 United Nations GGIM Sub-Committee on Geodesy

IGS remains active in engaging with diverse organizations that have an interest in geodetic applications of GNSS. IGS Associate and Governing Board members continue to participate in contributing to five focus groups developed to draft the implementation plan for the United Nations Global Geodetic Information Management (GGIM) Global Geodetic

Reference Frame Roadmap. This implementation plan was tabled at the Eighth meeting of the UN GGIM in August 2018 at UN Headquarters in New York, and may be viewed here: http://ggim.un.org/meetings/GGIM-committee/8th-Session/documents/Road-Map-Implementation-Plan.pdf. Details and updates may be viewed on the UN GGIM website: http://ggim.un.org.

4.3 United States PNT Advisory Board

IGS continues to participate in the United States National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board (http://www.gps.gov/governance/advisory/), which in 2018 included presentations on key issues and IAG/IGS updates from former GB member Gerhard Beutler and CB Director/GB member Allison Craddock.

4.4 International Association of Geodesy Executive Participation

The IGS is represented in a variety of roles throughout the geodetic community. GB members Richard Gross and Chris Rizos serve as a member of the International Association of Geodesy (IAG) Executive Committee.

IGS Governing Board Members served on the Coordinating Board, Executive Committee, Consortium, and Science Panel of the IAG Global Geodetic Observing System (GGOS). Several of these members participated in the annual GGOS Days series of meetings, held at the GSI Headquarters in Tsukuba, Japan.

5 Outlook 2019

In 2020 the IGS workshop participants will travel to Boulder, Colorado. This workshop will be jointly hosted by UNAVCO and UCAR. After a series of annual workshops the governing board has decided to go back to the biannual model where the full workshop is planned every second year, with smaller thematic meetings held on the off years. In 2019 the thematic meeting will be focused on Analysis models and planning for Repro 3.

The Monitoring and Assessment working group will continue to develop the framework in which they can participate in the Broader ICG process, and undertake more extensive benchmarking and validation. The emergence of Precise Point Positioning Services transmitted by the GNSS system providers is likely to add another layer of complexity to this function, particularly as the IGS determines what role it would like to play in monitoring these systems, if any.

This issue, along with many others, creates a timely need for the IGS to once again consider its strategic plan. Accordingly the Governing Board will commence a review of the strategic plan in 2019, including consultation with associate members and stakeholders.

Lastly, the GB thanks all participants within the IGS for the efforts, with particular thanks going to those working group chairs ending their current terms. Without the contributions of all, the IGS could not have achieved the significant outcomes detailed in this report.

IGS Central Bureau Technical Report 2018

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1 Introduction

For twenty-five years, the International Global Navigation Satellite System (GNSS) Service (IGS) has carried out its mission to advocate for and provide freely and openly available high-precision GNSS data and products. IGS was first approved by its parent organization, the International Association of Geodesy (IAG), at a scientific meeting in Beijing, China, in August of 1993. A quarter century later, the IGS community gathered for a workshop in Wuhan, China to blaze a path to Multi-GNSS through global collaboration.

The mission of the IGS Central Bureau (CB) is to provide continuous management and technology in order to sustain the multifaceted efforts of the IGS in perpetuity. It functions as the executive office of the Service and responds to the directives and decisions of the IGS Governing Board. The CB coordinates the IGS tracking network and operates the CB information system (CBIS), the principal information portal where the IGS web, ftp and mail services are hosted. The CB also represents the outward face of IGS to a diverse global user community, as well as the general public. The CB office is hosted at the California Institute of Technology/Jet Propulsion Laboratory, Pasadena, California, USA, with the exception of the Network Coordinator, who is based at UNAVCO in Boulder, Colorado, USA. The CB is funded primarily by the US National Aeronautics and Space Administration (NASA), which contributes significant staff, resources, and coordination to advance the IGS. The following report highlights progress made by the Central Bureau in 2018.

The IGS is a critical component of the IAG's Global Geodetic Observing System (GGOS), where it facilitates cost-effective geometrical linkages with and among other precise geodetic observing techniques, including: Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS). These linkages are fundamental to generating and accessing the International Terrestrial Reference Frame (ITRF). As it enters its second quarter-century, the IGS is evolving into a truly multi-GNSS service, and at its heart is a strong culture of sharing expertise, infrastructure, and other resources for the purpose of encouraging global best practices for developing and delivering GNSS data and products all over the world.

2 Central Bureau Review

The IGS Governing Board, while meeting on 8 April 2018 at the Technical University of Vienna, Vienna, Austria, for Business Meeting 49.5 and during the Agenda point "CB Changes and Updates", proposed to convene a CB Review Panel which would review the functions of the CB and report to the GB at the following GB meeting in the Fall of 2018.

The CB Review Panel comprises three individuals from the GB and it was agreed by unanimous consent during the GB discussion that the volunteers; Dr. Chris Rizos (UNSW), Dr. Thomas Herring (MIT) and Dr. Ignacio (Nacho) Romero (ESA/ESOC) would compose the Panel and report back their findings and recommendations.

The CB has been based at JPL from the start of the IGS with Ruth Neilan as its founding Director and serving in this role until 2017. During this time the CB coordinated and managed the growth of the IGS (network, analysis capability, etc) and ensured it had high visibility, and contributed to specific tasks as appropriate, at national and international forums (such as GEO, UN-ICG, UN-GGIM, and conferences organized by the IAG, FIG, and others).

In 2017 Allison Craddock was appointed interim IGS CB Director and JPL/NASA have confirmed their ongoing support to the IGS CB staying where it is under Allison Craddock's leadership. The GB, under Chair Gary Johnston's direction, asked JPL to draft a new proposal for the CB. It was agreed that the JPL CB proposal should cover the explicit commitment of personnel and resources as needed to perform the CB duties, as well as proposals on how to meet the existing and upcoming challenges to the IGS.

The CB Review Panel and CB representatives Craddock and Mick Connally of JPL took part in a strengths, weaknesses, opportunities, and threats (SWOT) analysis as a means of structuring the initial evaluation and path forward. This exercise was considered to be a highly effective effort and yielded significant beneficial outcomes.

The CB Review Panel provided an analysis of the CB performance and any identified shortcomings, as well as possible areas of improvement, plus identifies new challenges that the CB should be addressing to better support the IGS as a whole. In alignment with the Terms of Reference, the performance of the CB is to be formally reviewed by the GB at least every five years.

3 Executive Management and Governing Board Participation

In an effort to document the tasks and procedures associated with a successful and functional CB, further work on an IGS Central Bureau Operations Plan describing the roles, responsibilities, and deliverables of each member of the CB and of the CB as a whole was carried out. These descriptions expand on and are consistent with description of the CB in the IGS Terms of Reference. The Operations Plan was provided to the IGS Governing Board Chair and made available to members of the Governing Board for review and comment.

The CB coordinated the necessary logistics and administrative organization for Governing Board (GB) meetings held in April (hosted by TU Wien in Vienna, Austria), October/November (hosted by Wuhan University in Wuhan, China) and December (hosted by the CB/UNAVCO in Washington, DC, USA) 2018. The Executive Committee (EC) met additionally by teleconference approximately every other month. Staff of the Central Bureau, as part of its work program carrying out the business needs of the IGS, implemented actions defined by the Governing Board throughout the year.

The CB supported the ongoing update of the Associate Members list in preparation of the Governing Board elections. The IGS Associate Members form the body of voters who elect the Governing Board, and play a vital role in the ongoing success and sustainability of the service. Associate Member and Governing Board Member lists are maintained by the CB on the IGS website (http://igs.org/about/organization).

The CB also continued to play an active role in supporting the organization of regular IGS Workshops, this year supporting the colleagues in Wuhan, China in preparations for their successful first IGS Workshop in Asia. In addition, the CB initiated contact with leadership organizing upcoming IGS Workshops, including a 2020 Workshop in Boulder, Colorado, USA, as well as holding a call for proposals for the 2022 workshop, which is expected to take place somewhere in Europe.

4 Strategic Planning and Progress

The 2017 Strategic Plan was published in early 2018; preliminary discussions regarding a 2020 strategic plan have commenced.

5 Communications, Advocacy, and Public Information

The Central Bureau continued to develop communications, advocacy, and public information initiatives on behalf of the Governing Board. Due to the 2018 Workshop taking place in the third quarter of 2018, no Open Associate Member meeting was held at AGU; however, one will be planned for December 2019.

An informative, general-audience article, "The International GNSS Service: 25 years on the path to multi-GNSS",was published in the September issue of GPS World magazine: http://gpsworld.com/the-international-gnss-service-25-years-on-the-path-to-multi-gnss/

The Central Bureau actively works with other IAG components to promote communications and outreach, including the IAG Communications and Outreach Branch and GGOS Coordinating Office. As representatives of the IAG, IGS CB members also participate actively in the United Nations Initiative on Global Geospatial Information Management (GGIM) Sub-Committee on Geodesy, Focus Group on Outreach and Communications.

Social media has been actively maintained by CB staff and continued to grow in followers in 2018, due in part by growing and maintaining mutually beneficial links to IGS Contributing Organization communications representatives and increased frequency of posting, as well as enhanced content. Increased cross-linking with IGS website and knowledge base content, as well as promoting video resources available on the IGS website, will continue in 2019. IGS Social Media accounts and follower statistics are as follows:

- Twitter (898 followers): https://twitter.com/igsorg
- Facebook (1309 followers): https://www.facebook.com/internationalGNSSservice
- Instagram (93 followers): http://instagram.com/igsorg
- LinkedIn Group: http://www.linkedin.com/groups/International-GNSS-Service-7455133
- YouTube (83 subscribers): http://www.youtube.com/igsorg

6 New Official IGS Citation

The IGS chapter in the 2017 Springer Handbook of Global Navigation Satellite Systems was recently deemed the official citation paper for those acknowledging the IGS in scholarly research and other work:

> Johnston, G., Riddell, A., Hausler, G. (2017). The International GNSS Service. In Teunissen, Peter J.G., & Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed., pp. 967-982). Cham, Switzerland: Springer International Publishing
> DOI: 10.1007/978-3-319-42928-1

The book is currently available for purchase and download on the Springer website: https://www.springer.com/us/book/9783319429267

7 Network Coordination and User Community Support

With the assistance of the CB Network Coordinator, the IGS network added 14 stations and decommissioned 12 stations in 2018, bringing the total to 507 stations. For additional statistics and information about the IGS Network, please refer to the Governing Board chapter of this report.

In early 2018, the CB Network Coordinator updated the Site Log Manager database and website to accommodate the 9-character station codes. All internal Central Bureau operational scripts were also updated to accommodate the 9-character station codes. Later in 2018, the Central Bureau real-time caster was updated to use the 9-character station codes

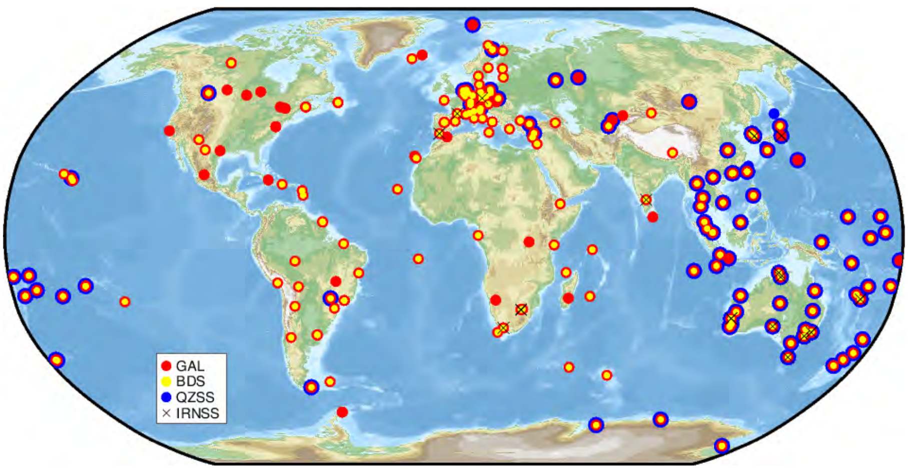

Figure 1: IGS Multi-GNSS Tracking Network map, courtesy of Geoscience Australia.

as recommended by the Real Time Working Group. Throughout the year, the CB Network Coordinator worked with station operators on various topics including recommended firmware upgrades, antenna alignment, receiver constellation tracking, and missing station photos. The CB Network Coordinator worked with the TIGA Working Group and the Infrastructure Committee to incorporate Tide Gauge information into the Site Log Manager database and the station pages on the IGS web site.

The CB Network Coordinator supported the IGS user community by reviewing and accepting 487 IGS site log updates. In collaboration with the Antenna Working Group Chair the CB Network Coordinator worked with equipment manufacturers to provide 54 changes to the rcvr_ant.tab and antenna.gra equipment files. During 2018 approximately 150 new user accounts were added to the Central Bureau real time caster. The CB Network Coordinator also added 10 new user accounts to the Site Log Manager. When necessary, the CB Network Coordinator will assist users with mailing list support issues. The CB Network Coordinator also responds to various inquiries about data, products, or general IGS information.

8 Project, Committee and Working Group Support and Participation

The Central Bureau provides administrative and information technology support to IGS Working Groups, and has been involved in aspects of the following initiatives:

- Support of IGMA and other ICG initiatives.
- Further integration of Multi-GNSS stations into the IGS Network.
- Advocating for RINEX 3.04 and its support of all GNSS constellations.
- Support of 2018 Governing Board meetings and elections.
- Verification of IGS Associate Member contact information and participation through both personal and automated processes.

9 Governing Board Elections Coordination and Support

Elections for the Governing Board positions of Network Representative and Data Center Representative took place in the latter half of 2017. CB staff worked with the GB Elections Committee to ensure nominations and voting processes were successfully carried out.

10 IGS Workshop Support

The theme of the 2018 workshop – "Multi-GNSS through Global Collaboration" – was echoed through ten plenary sessions, posters, and working group splinter meetings. The Central Bureau provided frameworks, templates, timelines, and other existing resources, as well as advice and guidance to workshop organizing committees. Central Bureau staff also attended the workshop to provide on-site organizational support and other assistance. For additional information about the 2018 Wuhan Workshop, please see the Governing Board chapter of this report.

11 External Participation

The Central Bureau participates in, and interacts with, many IGS stakeholder organizations. A continuing highlight is the CB staff activity within the United Nations GGIM Sub-Committee on Geodesy (formerly Global Geodetic Reference Frame Working Group). For more information, please visit the UN-GGIM website: http://ggim.un.org/UN_GGIM_wg1.html.

The CB Director continues to be a role that is active in a number of stakeholder organizations, with A. Craddock serving on the GGOS Executive Committee and in the GGOS Coordinating Office as Manager of External Relations. Significant progress was also made in supporting the development of a cooperative plan with the United Nations Office for Outer Space Affairs (UNOOSA), International Committee on Global Navigation Satellite Systems (ICG) to monitor performance and interoperability metrics between the different GNSSs, embodied by a joint IGS-ICG working group on monitoring and assessment. IGS continues to co-chair the ICG Working Group on Reference Frames, Timing and Applications jointly with IAG (C. Rizos and Z. Altamimi) and the International Federation of Surveyors (FIG, represented by M. Lilje and S. Choy), in close collaboration with BIPM (G. Petit).

The CB Director was invited to present an IGS update to the US Federal Advisory Board for Space-based Position, Navigation and Timing (PNT) in December 2018. Other IGS representatives presenting at the PNT Advisory Board meetings include IGS Founding Governing Board Chairman Professor Gerhard Beutler (University of Bern, Switzerland). To view presentations made at PNT Advisory Board meetings, please visit: http://www.gps.gov/governance/advisory/.

12 Publications

- Craddock, A. and Johnston, G. (2018, September). The International GNSS Service: 25 years on the path to multi-GNSS, published in GPS World magazine and

online: http://gpsworld.com/the-international-gnss-service-25-years-on-the-path-to-multi-gnss/

- IGS 2017 Technical Report, IGS Chapter
- NASA SGP/ICPO annual progress update, NASA internal publication
- Johnston, G., Neilan, R., Craddock, A., Dach, R., Meertens, C., Rizos, C. (2018, April). International GNSS Service Update. Poster session presented at the meeting of the European Geophysical Union, Vienna, Austria.

13 Acknowledgements

The Central Bureau gratefully acknowledges the contributions of our colleagues at the Astronomical Institute of the University of Bern, who edit, assemble, and publish the IGS Annual Technical Report as a service to the Central Bureau and IGS community.

We would also like to express our thanks to Paul Ries of the NASA Jet Propulsion Laboratory and Michael Moore of Geoscience Australia for their assistance to the CB this year.

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2018

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1 Introduction

The role of the IGS Analysis centre coordinator (ACC) is to take the products provided by individual analysis centres and combine these to produce an official IGS product, as well as providing an oversight to the submitted products. The IGS products have and continue to performing at a consistent level, and in general the individual analysis centres contributing their solutions are maintaining a consistent level of performance.

2 Product Quality and Reliability

For 2018, with a few exceptions the delivery of ultra-rapid, rapid and final products have been well within the expected latency. There were some recent outages with the rapid products, this was due to a pole file not updating correctly, which would then cause the combination to crash due to the missing information. The scripts that run this process have been updated, and the problem has not resurfaced so far.

2.1 Ultra-rapid

The ultra-rapid is one of the heaviest utilized IGS products, and often used for real-time and near-real time application. Currently the IGS is receiving 8 submissions from different ACs for combined IGS ultra-rapid products (see Table 1 to see which ACs are currently weighted in the solution). The combined IGS ultra-rapid can be split into two components, a fitted portion based upon observations, and a predicted component reliant upon forward modelling of the satellite dynamics. The fitted portion of the ultra-rapid orbits continue to agree to the rapid orbits at the level of 8 mm (see Figure 1) and has been consistently at

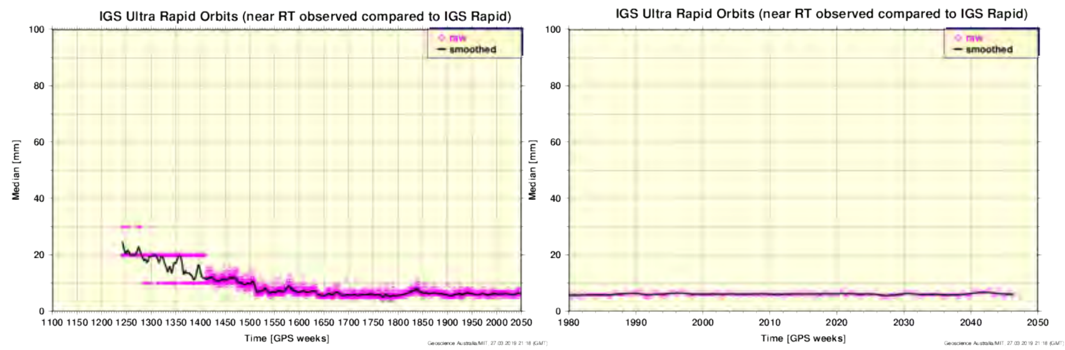

Figure 1: The median difference of the fitted component of the IGS ultra-rapid (IGU) combined orbits with respect to the IGS rapid (IGR) orbits. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

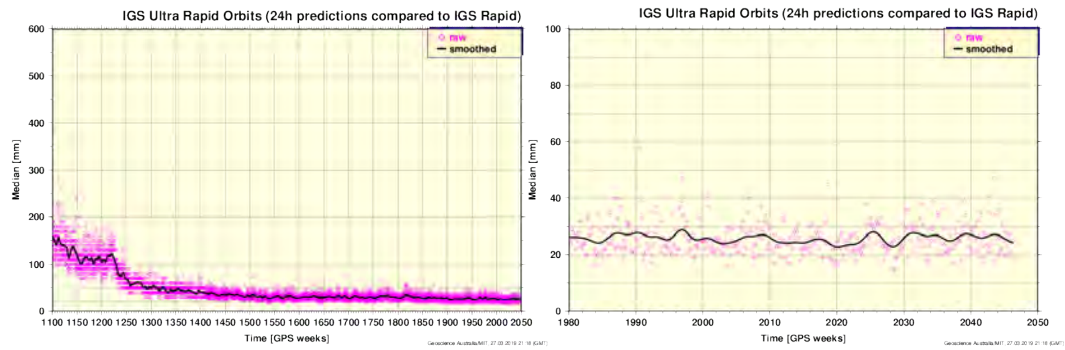

Figure 2: Median of IGU combined predicted orbits compared to IGR. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

this level since GPS week 1500. In addition over the last year there has been little change in the agreement between the ultra-rapid predicted orbits compared to the IGS rapid orbits (see Figure 2) hovering around the 25 mm level. Recently there was an issue with the GFZ ultra-rapid orbit products starting from GPS week 2038, the solution was de-weighted (see Figure 3). The issue was due to a bug in the network selection algorithm used. Once this was resolved the GFZ orbits returned to their previous level of performance by GPS week 2042, and were subsequently re-weighted into the ultra-rapid combination. Wuhan's orbit and ERP solutions was also added as a weighted solution from GPS week 2039.

2.2 Rapid

There are nine individual analysis centres contributing to the rapid IGS products (see Table 2). There has been no significant change in the difference between the combined IGS rapid orbits and the combined IGS final orbits. This has consistently been at a level

Table 1: ACs contributing to the Ultra-rapid products, *W* signifies a weight contribution, *C* is comparison only. The SIO ERP solution is weighted, with the exception of the length of day estimate which is excluded from the combination.

Analysis Centre	SP3	ERP	CLK
COD	W	W	W
EMR	W	W	W
ESA	W	W	W
GFZ	W	W	W
NGS	C	C	C
SIO	C	W (LoD C)	C
USN	C	C	C
WHU	W	W	C

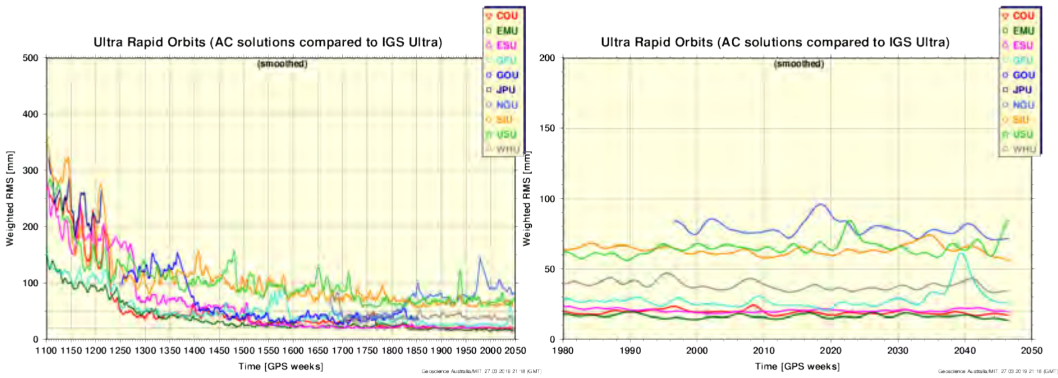

Figure 3: Median of AC Ultra-rapid predicted orbits compared to IGR

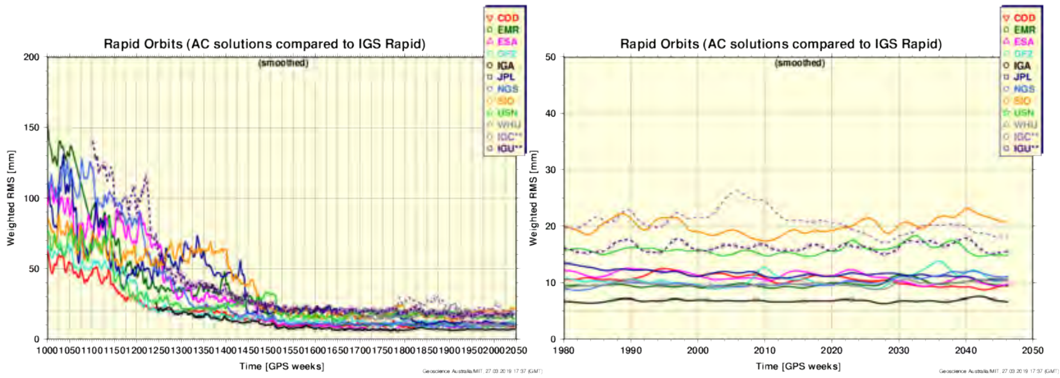

Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed)

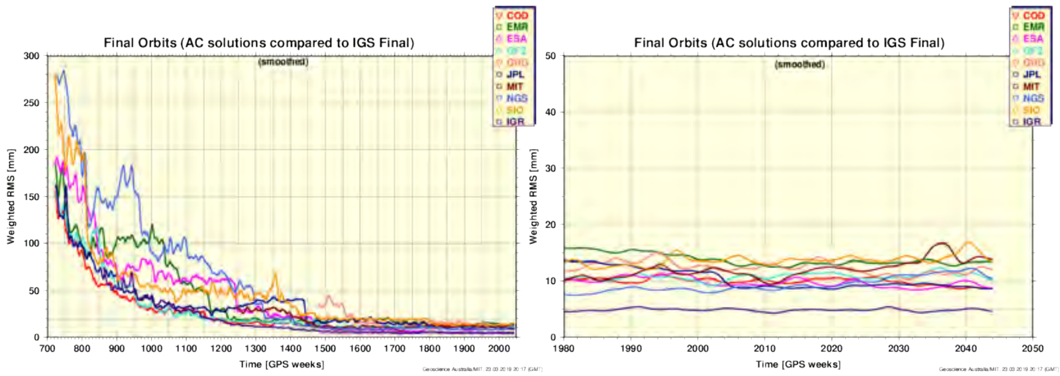

Figure 5: Weighted RMS of IGS Final orbits (smoothed)

of 6-7 mm since approximately GPS week 1500. Only minor changes have been applied to the IGS rapid products, recently the CODE ERP solution has been re-weighted back into the rapid products.

2.3 Final

There are nine individual ACs contributing to the IGS final products (see Table 3). Most AC final solutions are comparing at less than 5 mm to each other (see Figure 5). Upon JPL completing their internal reprocessing run for IGS14, their contributions were then re-weighted back into the IGS final products. The comparability of the ACs, in terms of orbits, are clustered in 3 groups of 3 as can be seen in Fig: 5. The analysis centres ESA, JPL and COD track very closely to each other, followed by NGS, GRG and GFZ forming another set, and then MIT, SIO and EMR.

Table 2: ACs contributing to the IGS Rapid products, *W* signifies a weight contribution, *C* is comparison only. The USN ERP solutions is not weighted into the combination, with the exception of the length of day estimate, which is a weighted value.

Analysis Centre	SP3	ERP	CLK
COD	W	W	W
EMR	W	W	W
ESA	W	W	W
GFZ	W	W	W
JPL	W	W	W
NGS	W	W	C
SIO	C	C	C
USN	C	C	C (LoD-W)
WHU	W	W	C

Table 3: ACs contributing to the IGS Final products, W signifies a weight contribution, C is comparison only. The SIO ERp solution is weighted, with the exception of the LoD estimate which is excluded from the combination.

Analysis Centre	Orbit	ERP	Clock
CODE	W	W	W
EMR	W	W	W
ESA	W	W	W
GFZ	W	W	W
GRG	W	W	W
JPL	W	W	W
MIT	W	W	C
NGS	W	W	C
SIO	W	W (C LoD)	C

3 Development to ACC Combination Software

We are currently testing the existing ACC orbit combination software to run some trial multi-gnss combinations, and are investigating the preliminary results. At this stage it looks like a multi-GNSS orbit combination is possible, however there is need for further analysis and significant work remains before we are in a position to set up a trail combined MGEX product.

Center for Orbit Determination in Europe (CODE) Technical Report 2018

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1 The CODE consortium

CODE, the Center for Orbit Determination in Europe, is a joint venture of the following four institutions:

- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland
- Federal Office of Topography swisstopo, Wabern, Switzerland
- Federal Agency of Cartography and Geodesy (BKG), Frankfurt a. M., Germany
- Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG, TUM), Munich, Germany

The operational computations are performed at AIUB, whereas IGS–related reprocessing activities are usually carried out at IAPG, TUM. All solutions and products are generated with the latest development version of the Bernese GNSS Software (Dach et al. 2015).

2 CODE products available to the public

A wide range of GNSS solutions based on a rigorously combined GPS/GLONASS data processing scheme is computed at CODE for the IGS legacy product chains. The products are made available through anonymous ftp at:

ftp://ftp.aiub.unibe.ch/CODE/ or
http://www.aiub.unibe.ch/download/CODE/

Since the beginning of MGEX in 2012 CODE is contributing. With the beginning of 2014 CODE's contribution to IGS MGEX is a five-system solution considering GPS, GLONASS, Gelileo, BeiDou, and QZSS. Meanwhile it is included in the operational processing and is published with the same schedule as the final product series. The related products are published at:

ftp://ftp.aiub.unibe.ch/CODE_MGEX/ or
http://www.aiub.unibe.ch/download/CODE_MGEX/

An overview of the files is given in Table 1.

Within the table the following abbreviations are used:

`yyyy`	Year (four digits)	`ddd`	Day of Year (DOY) (three digits)
`yy`	Year (two digits)	`wwww`	GPS Week
`yymm`	Year, Month	`wwwwd`	GPS Week and Day of week

Table 1: CODE products available through anonymous ftp.

CODE *ultra–rapid* products available at ftp://ftp.aiub.unibe.ch/CODE	
`COD.EPH_U`	CODE ultra–rapid GNSS orbits
`COD.ERP_U`	CODE ultra–rapid ERPs belonging to the ultra–rapid orbit product
`COD.TRO_U`	CODE ultra–rapid troposphere product, troposphere SINEX format
`COD.SNX_U.Z`	SINEX file from the CODE ultra-rapid solution
`COD.SUM_U`	Summary of stations used for the latest ultra–rapid orbit
`COD.ION_U`	Last update of CODE rapid ionosphere product (1 day) complemented with ionosphere predictions (2 days)
`COD.EPH_5D`	Last update of CODE 5–day orbit predictions, from rapid analysis, including all active GPS and GLONASS satellites
`CODwwwwd.EPH_U`	CODE ultra-rapid GNSS orbits from the 24UT solution available until the corresponding early rapid orbit is available (to ensure a complete coverage of orbits even if the early rapid solution is delayed after the first ultra-rapid solutions of the day)
`CODwwwwd.ERP_U`	CODE ultra-rapid ERPs belonging to the ultra-rapid orbits

Table 1: CODE products available through anonymous ftp (continued).

CODE *rapid* products available at ftp://ftp.aiub.unibe.ch/CODE

CODwwwwd.EPH_M	CODE final rapid GNSS orbits
CODwwwwd.EPH_R	CODE early rapid GNSS orbits
CODwwwwd.EPH_P	CODE 24–hour GNSS orbit predictions
CODwwwwd.EPH_P2	CODE 48–hour GNSS orbit predictions
CODwwwwd.EPH_5D	CODE 5–day GNSS orbit predictions
CODwwwwd.ERP_M	CODE final rapid ERPs belonging to the final rapid orbits
CODwwwwd.ERP_R	CODE early rapid ERPs belonging to the early rapid orbits
CODwwwwd.ERP_P	CODE predicted ERPs belonging to the predicted 24–hour orbits
CODwwwwd.ERP_P2	CODE predicted ERPs belonging to the predicted 48–hour orbits
CODwwwwd.ERP_5D	CODE predicted ERPs belonging to the predicted 5–day orbits
CODwwwwd.CLK_M	CODE GNSS clock product related to the final rapid orbit, clock RINEX format
CODwwwwd.CLK_R	CODE GNSS clock product related to the early rapid orbit, clock RINEX format
CODwwwwd.TRO_R	CODE rapid troposphere product, troposphere SINEX format
CODwwwwd.SNX_R.Z	CODE rapid solution, SINEX format
CORGddd0.yyI	CODE rapid ionosphere product, IONEX format
COPGddd0.yyI	CODE 1–day or 2–day ionosphere predictions, IONEX format
CODwwwwd.ION_R	CODE rapid ionosphere product, Bernese format
CODwwwwd.ION_P	CODE 1–day ionosphere predictions, Bernese format
CODwwwwd.ION_P2	CODE 2–day ionosphere predictions, Bernese format
CODwwwwd.ION_P5	CODE 5–day ionosphere predictions, Bernese format
CGIMddd0.yyN_R	Improved Klobuchar–style coefficients based on CODE rapid ionosphere product, RINEX format
CGIMddd0.yyN_P	1–day predictions of improved Klobuchar–style coefficients
CGIMddd0.yyN_P2	2–day predictions of improved Klobuchar–style coefficients
CGIMddd0.yyN_P5	5–day predictions of improved Klobuchar–style coefficients
P1C1.DCB	CODE sliding 30–day P1−C1 DCB solution, Bernese format, containing only the GPS satellites
P1P2.DCB	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites
P1P2_ALL.DCB	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites and all stations used
P1P2_GPS.DCB	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing only the GPS satellites
P1C1_RINEX.DCB	CODE sliding 30–day P1−C1 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
P2C2_RINEX.DCB	CODE sliding 30–day P2−C2 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
CODE.DCB	Combination of P1P2.DCB and P1C1.DCB
CODE_FULL.DCB	Combination of P1P2.DCB, P1C1.DCB (GPS satellites), P1C1_RINEX.DCB (GLONASS satellites), and P2C2_RINEX.DCB
CODE.BIA	Same content but stored as OSBs in the bias SINEX format

Note, that as soon as a final product is available the corresponding rapid, ultra–rapid, or predicted products are removed from the anonymous FTP server.

Table 1: CODE products available through anonymous ftp (continued).

CODE *final* products available at ftp://ftp.aiub.unibe.ch/CODE/yyyy/

`yyyy/CODwwwwd.EPH.Z`	CODE final GPS and GLONASS orbits
`yyyy/CODwwwwd.ERP.Z`	CODE final ERPs belonging to the final orbits
`yyyy/CODwwwwd.CLK.Z`	CODE final clock product, clock RINEX format, with a sampling of 30 sec for the GNSS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/CODwwwwd.CLK_05S.Z`	CODE final clock product, clock RINEX format, with a sampling of 5 sec for the GNSS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/CODwwwwd.SNX.Z`	CODE daily final solution, SINEX format
`yyyy/CODwwwwd.TRO.Z`	CODE final troposphere product, troposphere SINEX format
`yyyy/CODGddd0.yyI.Z`	CODE final ionosphere product, IONEX format
`yyyy/CODwwwwd.ION.Z`	CODE final ionosphere product, Bernese format
`yyyy/CODwwww7.SNX.Z`	CODE weekly final solution, SINEX format
`yyyy/CODwwww7.SUM.Z`	CODE weekly summary file
`yyyy/CODwwww7.ERP.Z`	Collection of the 7 daily CODE-ERP solutions of the week
`yyyy/COXwwwwd.EPH.Z`	CODE final GLONASS orbits (for GPS weeks 0990 to 1066; 27-Dec-1998 to 17-Jun-2000)
`yyyy/COXwwww7.SUM.Z`	CODE weekly summary files of GLONASS analysis
`yyyy/CGIMddd0.yyN.Z`	Improved Klobuchar–style ionosphere coefficients, navigation RINEX format
`yyyy/P1C1yymm.DCB.Z`	CODE monthly P1−C1 DCB solution, Bernese format, containing only the GPS satellites
`yyyy/P1P2yymm.DCB.Z`	CODE monthly P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites
`yyyy/P1P2yymm_ALL.DCB.Z`	CODE monthly P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites and all stations used
`yyyy/P1C1yymm_RINEX.DCB`	CODE monthly P1−C1 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
`yyyy/P2C2yymm_RINEX.DCB`	CODE monthly P2−C2 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used

CODE *MGEX* products available at `ftp://ftp.aiub.unibe.ch/CODE_MGEX/CODE`

`yyyy/COMwwwwd.EPH.Z`	CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format
`yyyy/COMwwwwd.ERP.Z`	CODE MGEX final ERPs belonging to the MGEX final orbits
`yyyy/COMwwwwd.CLK.Z`	CODE MGEX final clock product consistent to the MGEX final orbits, clock RINEX format, with a sampling of 30 sec for the GNSS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/COMwwwwd.BIA.Z`	GNSS code biases related to the MGEX final clock correction product, bias SINEX format v1.00
`yyyy/COMwwwwd.DCB.Z`	GNSS code biases related to the MGEX final clock correction product, Bernese format

Table 2: CODE final products available in the product areas of the IGS data centers.

Files generated from three–day long–arc solutions:

CODwwwwd.EPH.Z	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a long–arc analysis
CODwwwwd.SNX.Z	GNSS daily coordinates/ERP/GCC from the long–arc solution in SINEX format
CODwwwwd.CLK.Z	GNSS satellite and receiver clock corrections at 30–sec intervals referring to the COD–orbits from the long–arc analysis in clock RINEX format
CODwwwwd.CLK_05S.Z	GNSS satellite and receiver clock corrections at 5–sec intervals referring to the COD–orbits from the long–arc analysis in clock RINEX format
CODwwwwd.TRO.Z	GNSS 2–hour troposphere delay estimates obtained from the long–arc solution in troposphere SINEX format
CODwwww7.ERP.Z	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COD–ERP solutions of the week in IGS IERS ERP format
CODwwww7.SUM	Analysis summary for 1 week

Note, that the COD–series is identical with the files posted at the CODE's aftp server, see Table 1.

Files generated from pure one–day solutions:

COFwwwwd.EPH.Z	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a pure one–day solution
COFwwwwd.SNX.Z	GNSS daily coordinates/ERP/GCC from the pure one–day solution in SINEX format
COFwwwwd.CLK.Z	GNSS satellite and receiver clock corrections at 30–sec intervals referring to the COF–orbits from the pure one–day analysis in clock RINEX format
COFwwwwd.CLK_05S.Z	GNSS satellite and receiver clock corrections at 5–sec intervals referring to the COF–orbits from the pure one–day analysis in clock RINEX format
COFwwwwd.TRO.Z	GNSS 2–hour troposphere delay estimates obtained from the pure one–day solution in troposphere SINEX format
COFwwww7.ERP.Z	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COF–ERP solutions of the week in IGS IERS ERP format
COFwwww7.SUM	Analysis summary for 1 week

Other product files (not available at all data centers):

CODGddd0.yyI.Z	GNSS hourly global ionosphere maps in IONEX format, including satellite and receiver P1−P2 code bias values
CKMGddd0.yyI.Z	GNSS daily Klobuchar-style ionospheric (alpha and beta) coefficients in IONEX format
GPSGddd0.yyI.Z	Klobuchar-style ionospheric (alpha and beta) coefficients from GPS navigation messages represented in IONEX format

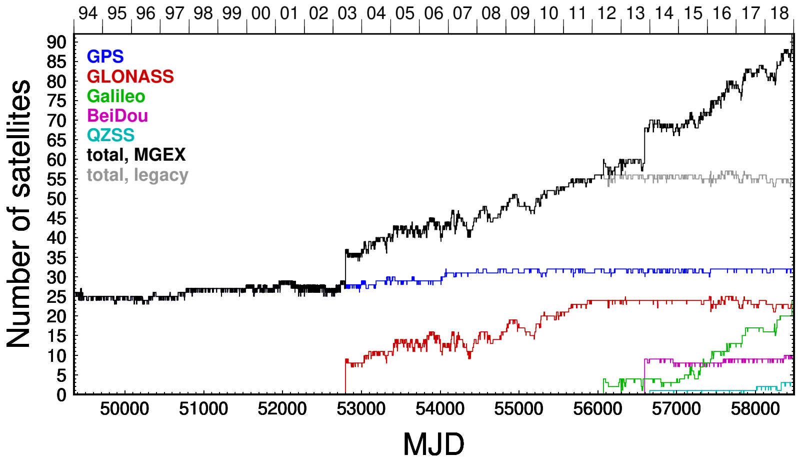


Figure 1: Development of the number of satellites in the CODE orbit products.

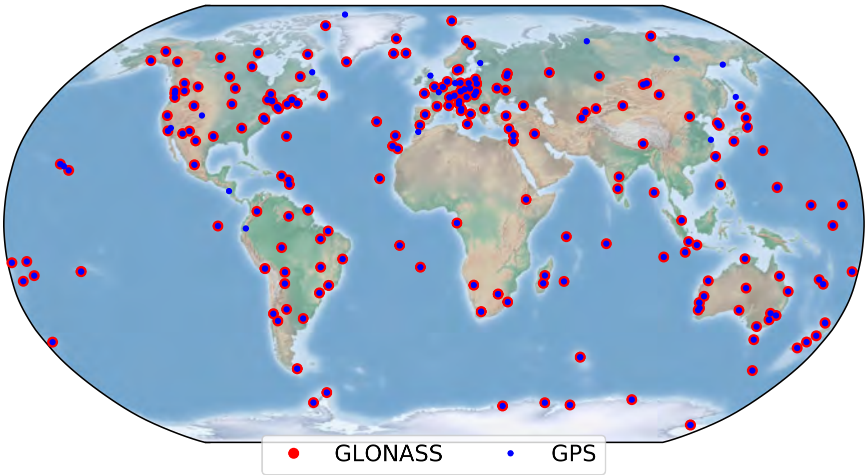
Statistics on the CODE solution

The development of the included satellite systems in the CODE solution is illustrated in Figure 1. Since May 2003 CODE is generating all its products for the IGS legacy series based on a combined GPS and GLONASS solution. Since 2012 the MGEX solution from CODE contains Galileo satellites and with beginning of 2014 also the satellites from the Asian systems BeiDou and QZSS. By the end of the year 2018 the MGEX solution did include up to 92 satellites – mainly due to the completion of the Galileo constellation.

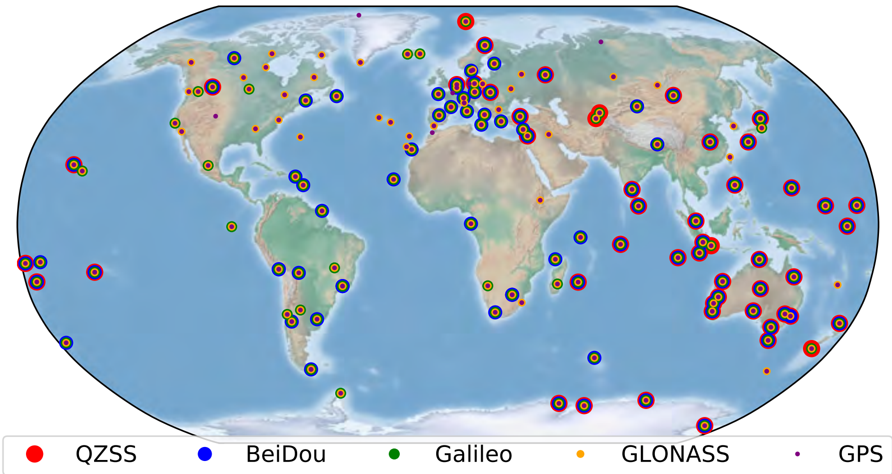
The network used by CODE for the final processing is shown in Figure 2. Less than 10% of the processed stations only provide GPS-data (blue dots without red circles). For the MGEX-solution a global coverage for three out of the four global systems has been achieved. Only for the second generation of BeiDou satellites (BDS-2), dual frequency data are available only to a sufficient amount for a reasonable orbit determination by the end of 2018. For that reason the BDS-3 satellites are not considered in CODE's MGEX solution so far.

An overview on the completeness and the performance of the clock products (final series with a sampling of 30 seconds) is provided in Figure 3 . The left hand plots show that nearly all records are complete. Only for a few days some epochs are missing, e.g., due to data availability issues. Since April 2018 the satellite R06 is tracked by many stations of the IGS network only on one frequency (or even not tracked at all anymore).

On the right hand plots the performace of the satellite clocks is shown. The RMS of a linear fit of all estimated clock corrections of a day is shown. The plots show the different performance of the satellites from the GPS and GLONASS constellations. Even for the GPS satellites there are a few satellites with a reduced performance: G28 is a 19 years old Block IIR-A satelite. Satellites G18 (since Jan. 2018) and G04 (since August 2018) are



(a) final solution



(b) MGEX solution

Figure 2: Network used for the processing at CODE by the end of 2018.

even a reactivated Block IIA satellites. But also newer Block IIF satellites (G08 and G24) are effected as well. Nevertheless, the other Block IIF satellites show – as expected – a better performance than the Block IIR satellites. In particular a periodic change of the linear fit RMS during the year (depending on the elevation of the Sun w.r.t. the orbital plane) is visible.

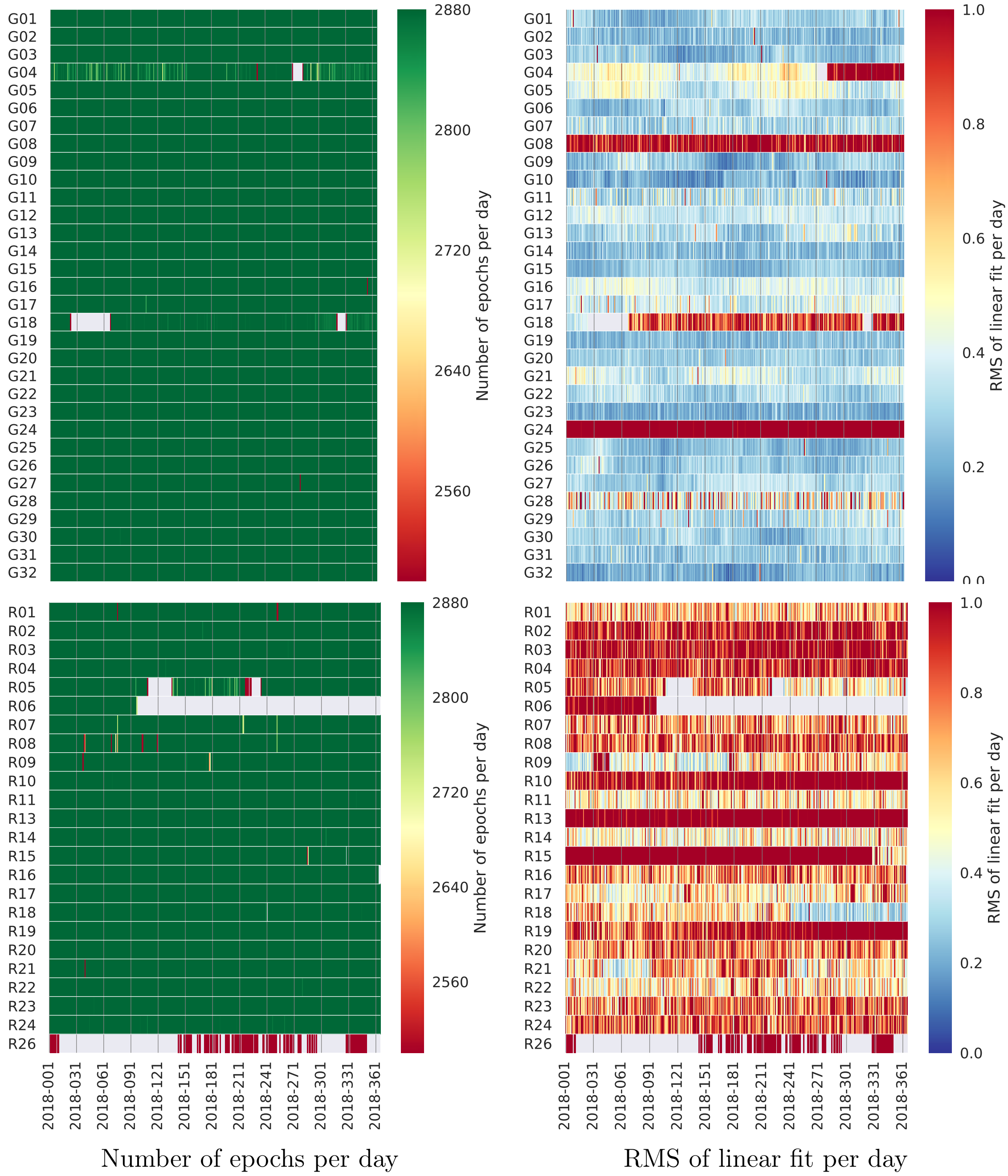


Figure 3: Completeness and performance of the GPS (top) and GLONASS (bottom) satellite clock corrections as provided in the CODE final solution (30-second sampling).

Referencing of the products

The products from CODE have been registered and should be referenced as:

- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2018). *CODE ultra-rapid product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75676.2 .
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- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2018). *CODE final product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75876.3 .
- Prange, Lars; Arnold, Daniel; Dach, Rolf; Schaer, Stefan; Sidorov, Dmitry; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2018). *CODE product series for the IGS MGEX project*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE_MGEX; DOI: 10.7892/boris.75882.2 .
- Steigenberger, Peter; Lutz, Simon; Dach, Rolf; Schaer, Stefan; Jäggi, Adrian (2014). CODE repro2 product series for the IGS. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2013; DOI: 10.7892/boris.75680 .
- Sušnik, Andreja; Dach, Rolf; Villiger, Arturo; Maier, Andrea; Arnold, Daniel; Schaer, Stefan; Jäggi, Adrian (2016). CODE reprocessing product series. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2015; DOI: 10.7892/boris.80011 .

3 Changes in the daily processing for the IGS

The CODE processing scheme for daily IGS analyses is constantly subject to updates and improvements. The last technical report was published in Dach et al. (2018).

In Section 3.1 we give an overview of important development steps in the year 2018. One of the highlights was certainly the introduction of the ambiguity resolution into CODE's clock product generation procedures what is described in Section 3.2 . The progress in the MGEX product chain is detailed in a dedicated Section 4 .

Table 3: Selected events and modifications of the CODE processing during 2018.

Date	DoY/Year	Description
22-Feb-2018	050/2018	Change troposphere gradient model from MacMillan (1995) to Chen and Herring (1997) in the MGEX solution (in order to be consistent with the other processing lines)
14-Mar-2018	070/2018	Revision of the ambiguity resolution scheme for GLONASS in order to make it more rubust.
28-Mar-2018	077/2018	UT1-UTC constraining changed in the three-day long-arc solution from first day to the begining of the middle day
17-Apr-2018	107/2018	Start considering RINEX 3 files for the ultra-rapid solution
17-Apr-2018	107/2018	During four days (103 to 107) flex-power was activated on all GPS Block IIR-M and IIF satellites. The effect was visible in some of the preprocessing protocols (e.g., reduced L1-only tracking events). No negative effect on the resulting products noticed.
04-Jul-2018	wk:2004	Start to • determine wide-lane (WL) and narrow-lane (NL) fractional phase biases, • perform undifferenced WL and NL ambiguity resolution, • compute ambiguity-fixed GPS clocks for the rapid and final clock products. See Section 3.2 for more details.
14-Jun-2018	161/2018	Add diverse checks for the zero-difference ambiguity resolution, e.g., regarding GPS quarter-cycle phase biases
22-Jun-2018	wk:2006	Start to • determine wide-lane (WL) and narrow-lane (NL) fractional phase biases, • perform undifferenced WL and NL ambiguity resolution, • compute ambiguity-fixed clocks. for the MGEX clock products considering GPS, Galileo, and QZSS.
03-Jul-2018	180/2018	Activate a dedicated orbit model for BDS and QZSS satellites in orbit normal mode (Prange et al. 2018)
05-Ju8l-2018	181/2018	Correct a bug in the phase bias computation for the zero-difference ambiguity resolution
02-Aug-2018	208/2018	QZS-4 included in CODE's MGEX solution after an update of the PCO values for all QZSS satellites.
29-Aug-2018	wk:2016	Update of the operating system for the computing cluster (to CentOS-7) where the IGS processing is performed; switch from g95 to gnu Fortran compiler for the operational processing
03-Sep-2018	246/2018	Switch to a reduced version of the new empirical orbit model for BDS-2 satellites in IGSO orbits (Prange et al. 2018)
26-Sep-2018	224/2018	Add the second midnight epoch to the ultra-highrate clock product files (5-sec sampling) for internal purposes
11-Dec-2018	345/2018	Use also RINEX 3 navigation files in the ultra-rapid processing if available
20-Dec-2018	354/2018	Recover the original priority order for using RINEX 3 files: merged hourly files are only used if they contain more epochs than the daily files (this was swapped unintentionally by the beginning of December).

3.1 Overview of changes in the processing scheme in 2018

Table 3 gives an overview of the major changes implemented during year 2018. Details on the analysis strategy can be found in the IGS analysis questionnaire at the IGS Central Bureau (ftp://ftp.igs.org/pub/center/analysis/code.acn).

Several other improvements not listed in Table 3 were implemented, too. Those mainly concern data download and management, sophistication of CODE's analysis strategy, software changes (improvements), and many more. As these changes are virtually not relevant for users of CODE products, they will not be detailed on any further.

Use of RINEX 3 data in the IGS final product generation

Since end of January 2017, CODE is using also RINEX 3 files to generate the IGS final products. A statistics on the number of RINEX files from different types is shown in Figure 4 . No RINEX file from streams or unknown source are considered for the generation of the final products. During the year 2018 also merged hourly RINEX 3 files are considered if they contain more epochs than the original RINEX 3 files generated at the stations. Unintentionally the merged file have been preferenced over the regular daily files with the same number of epochs during one month.

Overall by the end of 2018 nearly 60% of the observation data processed at CODE for the final product generation are taken from RINEX 3 files. In the rapid product chain it is about the same amount whereas in the ultra-rapid product generation still two third of the observations are coming from RINEX 2 files.

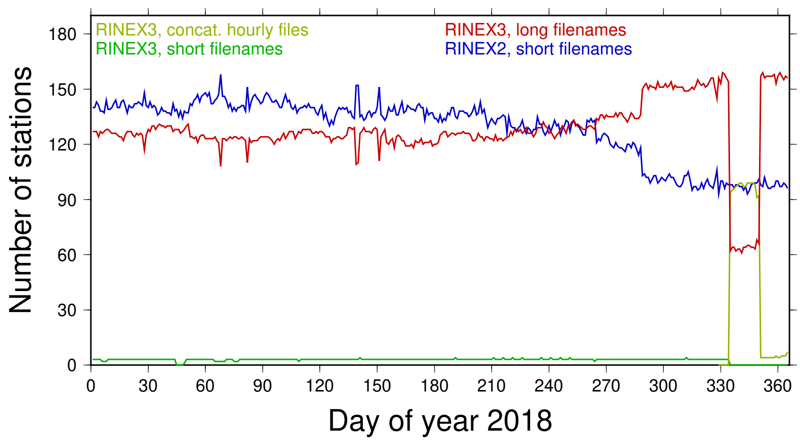

Figure 4: Usage of RINEX observations files for CODE final processing.

3.2 Ambiguity resolution in the clock product generation procedures at CODE

The ambiguity resolution concept that was implemented into the rapid, final and MGEX clock solutions provided to the IGS is illustrated in Figure 5. It consists of the follwoing steps:

1. A clock solution without ambiguity resolution is carried out.
2. Wide-lane (WL) phase biases for the Melbourne-Wübbena (MW) linear combination are computed.
3. Using these WL phase biases, the Melbourne-Wübbena linear combination is analyzed to resolve the WL ambiguities.
4. Narrow-lane (NL) phase biases are computed based on the clock solution (and resolved WL integers).
5. Using these NL phase biases (and resolved WL integers), the ionosphere-free linear combination of phase observations is analyzed to resolve the NL ambiguities.
6. The phase biases for the original frequencies (L1 and L2) are derived from the WL and NL phase biases.
7. A clock solution with fixed L1 and L2 phase ambiguity integers is generated.
8. The NL ambiguity resolution steps could be repeated by continuing at step 4 in order to start a NL phase bias determination and NL ambiguity resolution already with an ambiguity-fixed clock solution. Additional iterations turned out to be not necessary.

The phase biases in step 6 are represented following the principle of Obervation-Specific Biases (OSBs). This allows a flexible combination of results based on observations from different frequencies.

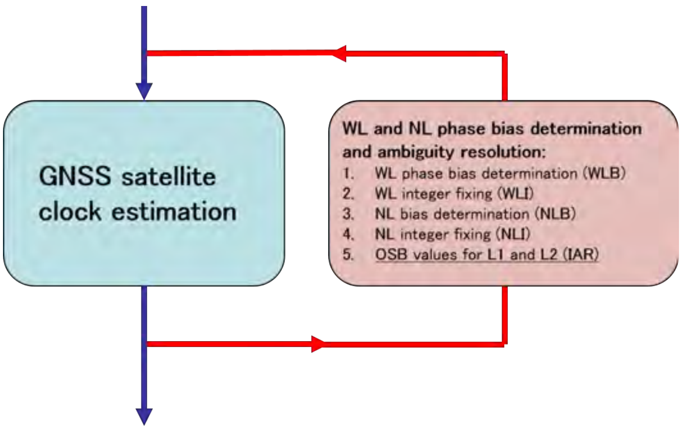

Figure 5: Principle of the single-receiver ambiguity resolution as performed in the clock analysis for the IGS at AIUB.

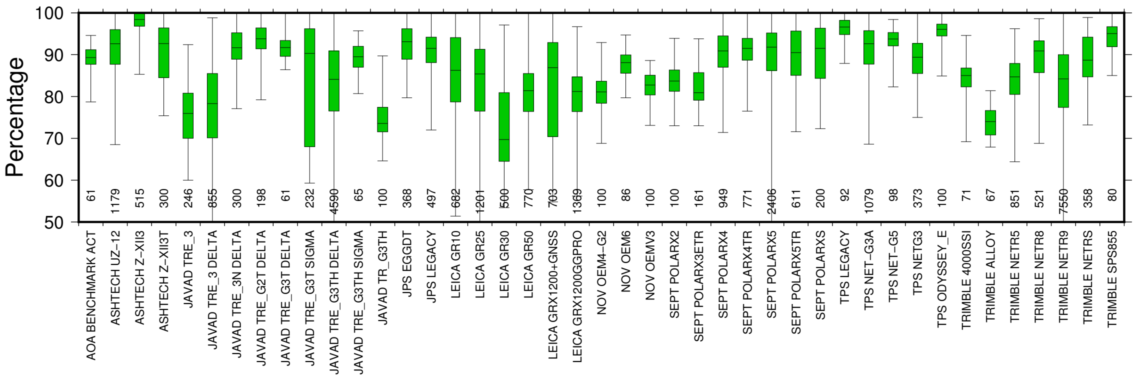

Figure 6: Percentage of resolved wide-lane ambiguities for GPS. The solutions for 300 stations over 100 days (day 200 to 299 of year 2018) are analysed. The numbers indicate the number of days/stations that have contributed to the statistics.

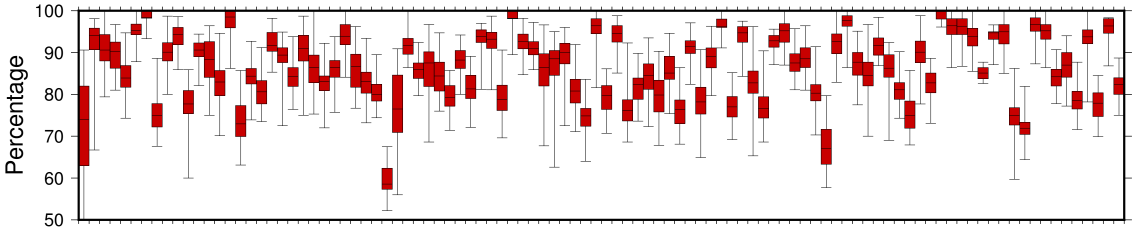

Figure 7: Percentage of resolved wide-lane ambiguities for GPS for selected stations during 100 days (day 200 to 299 of year 2018).

The stability of the phase biases is essential for a successful ambiguity resolution. From the internal PPP solution computed at AIUB (including more than 300 IGS stations each day) the success rate of the wide-lane ambiguity resolution is analysed per receiver type in Figure 6. Even if the number of stations is very different, also a dependency on the receiver type for the ambiguity resolution rate seems to exist. When comparing for instance the statistics for the LEICA GR50 and LEICA GRX1200+GNSS, both receiver groups have approximately the same number of stations/days, where the second one has a much bigger variation in the success rate. It seem that this receiver is more sensitive to environmental effects depending on the station where it is used. Looking at the statistic per station in Figure 7, there are many stations with a similar success rate for each day. The overall rate varies from station to station. The assumption that this effect depends on the stability of the biases at the sites should be investigated in future.

The positive impact of the introduced ambiguity resolution scheme on the CODE contribution (red line) can be seen in Figure 8. It shows the clock standard deviations as they are computed in the clock combination procedure by the analysis center coordinator (ACC, `http://acc.igs.org`). The zoomed part is related to the epoch in June 2018 when the single-receiver ambiguity resolution was enabled.

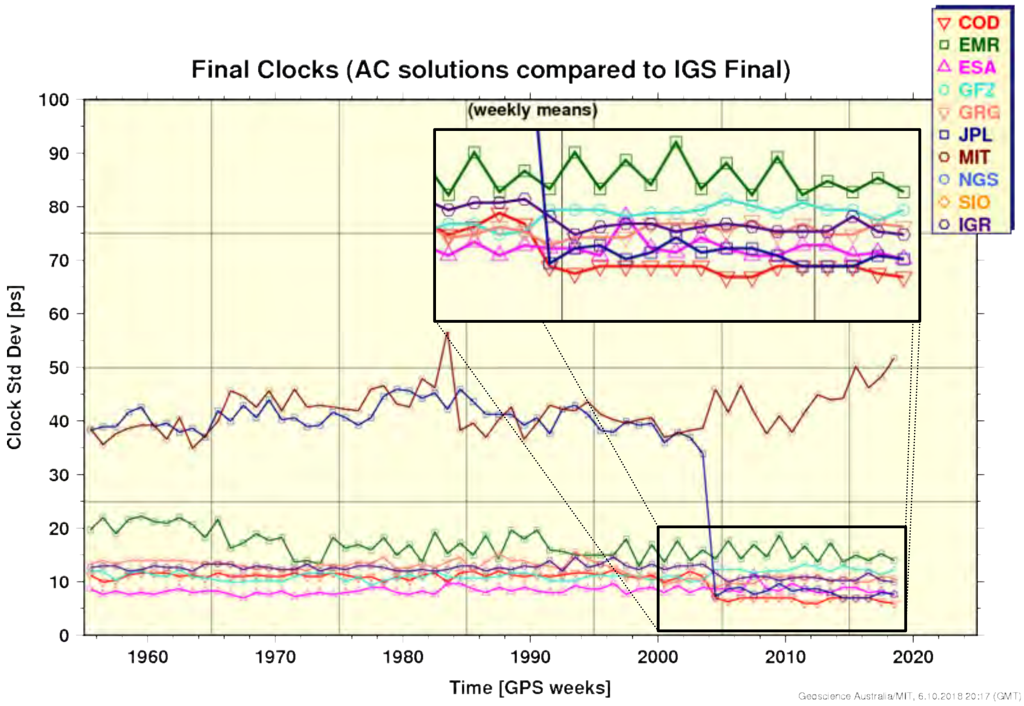

Figure 8: Impact of introducing undifferenced ambiguitiy resolution at CODE on the IGS final clock combination as provided by http://acc.igs.org.

4 CODE contribution to the IGS–MGEX campaign

In the frame of the IGS MGEX (Multi-GNSS Extension), CODE continues to provide a five-system orbit and clock solution in a FINAL-like mode. It includes GPS, GLONASS, Galileo, BDS2 MEO and IGSO, as well as QZSS. Apart from bugfixes and smaller software updates, the main changes concern the introduction of the ambiguity fixing in the MGEX clock solution (as described in Sect. 3.2) and the activation of an empirical solar radiation pressure (SRP) model for BDS2 and QZSS satellites switching to the orbit normal (ON) attitude mode if the Sun is close to the orbital plane. Unlike the "classical" ECOM models (Arnold et al. 2015) the new ECOM-TB model (Prange et al. 2018) describes the SRP accelerations in a so-called terminator reference frame. Moreover, it takes into account that the Sun incident angle on the solar panels and the spacecraft body is changing in time during ON mode.

The new SRP model has been activated by beginning of July 2018 for BDS2 and QZSS satellites during their ON periods. For QZS-1 a significant improvement of satellite orbits and clocks (by a factor of 4) is confirmed by comparison with external MGEX products from the QZF solution (see Figure 9).

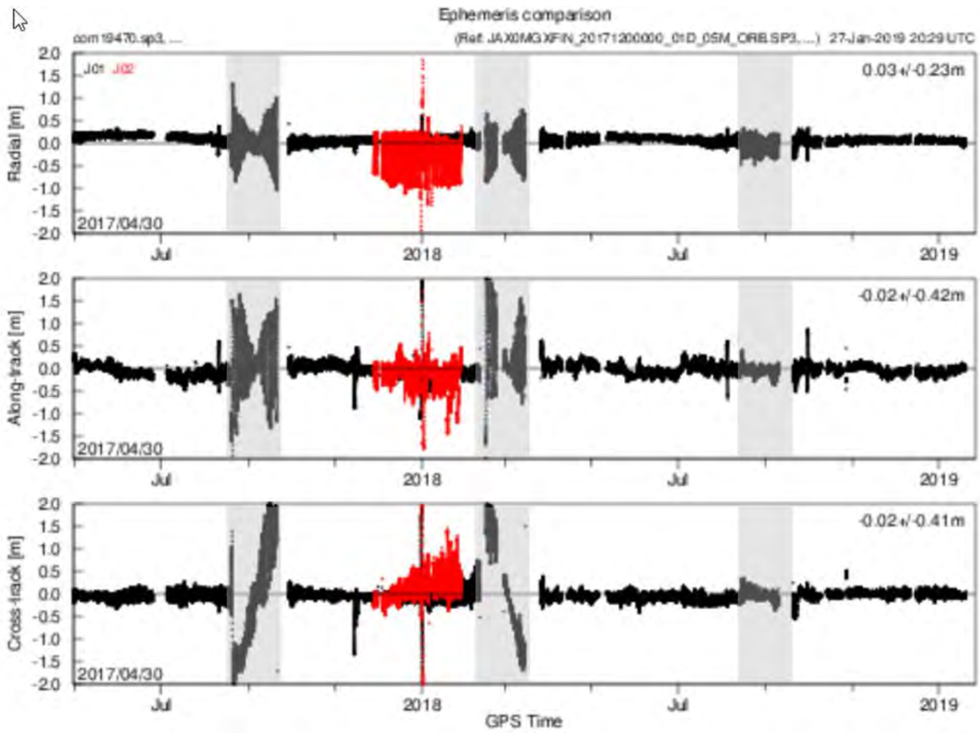

Figure 9: Orbit comparison of QZS-1 MGEX orbits from CODE and JAXA (radial, along-track and cross-track components). Grey boxes mark periods when QZS-1 is moving in ON-mode.

For BDS2 spacecrafts the improvement is less pronounced. Here we encountered moderate (in the case of MEO satellites) or significant (in the case of IGSO satellites) difficulties to properly determine the model coefficients in the case of using long arcs. We assume that different factors contribute to the limited model performance for BDS2: Heterogeneous density of tracking network, unclear antenna offsets (the published estimates for the IGSO satellite offsets differ significantly from each other), and unknown spacecraft properties. Therefore we created modified versions of the ECOM-TB for BDS2 spacecraft: For MEO satellites stochastic pulses support the SRP model (ECOM-TBP). For IGSO satellites we use a reduced version ECOM-TBMP (with 2 instead of 9 SRP parameters), supported by pulses. With these modified versions of the SRP model we are able to improve the orbit and clock accuracy of BDS2 satellites in ON-mode by about a factor of 2.

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MacMillan, D. S. Atmospheric gradients from Very Long Baseline Interferometry observations. *Geophysical Research Letters*, 22(9):1041–1044, 1995. doi: 10.1029/95GL00887.

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All publications, posters, and presentations of the *Satellite Geodesy* research group at AIUB are available at http://www.bernese.unibe.ch/publist .

NRCan Analysis Center Technical Report 2018

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1 Introduction

This report covers the major activities conducted at the NRCan Analysis Center (NRCan-AC) and product changes during the year 2018 (products labelled 'em*'). Additionally, changes to the stations operated by NRCan are briefly described. Readers are referred to the Analysis Coordinator web site at http://acc.igs.org for historical combination statistics of the NRCan-AC products.

2 NRCan Core Products

The Final GPS products continued to be estimated with JPL's GIPSY-OASIS software in 2018, with no major changes to the processing strategy. The GNSS Rapid and Ultra-Rapid products continued to be generated using the Bernese software version 5.2 (Dach et al. 2015).

In 2018, we implemented a new strategy to help monitor the quality of our Ultra-Rapid satellite orbits. The new strategy consists of keeping track of the number of ambiguities setup and successfully resolved over the course of the last ten 3-hr orbit sessions (i.e. 30 hours total). Too few or too many ambiguities setup, zero or a very low number of ambiguities resolved for one or several sessions will trigger special attention within our orbit process. At the very least, the accuracy code in the SP3 file header for that satellite will be increased (indicating a decrease in precision). The worst thing that can happen is an arc reset for the faulty satellite which will likely result in an exclusion from our SP3 product. In all cases for which we detect a possible problem using this strategy, the predicted orbit is shortened to 12hr and sometimes less, depending on the severity of the problem. Clock estimation will most likely be turned off for that satellite in our Ultra-Rapid process. Such drastic measures are necessary for our Ultra-Rapid products due to the automated nature of the process, i.e. running hourly without human intervention. It also minimizes problems at the user level such as PPP and RT users.

The products available from the NRCan-AC are summarized in Table 1. The Final and Rapid products are available from the following anonymous ftp site: `ftp://rtopsdata1.geod.nrcan.gc.ca/gps/products`.

3 Ionosphere and DCB monitoring

NRCan's global ionosphere maps at 1 hour intervals (emrg[ddd]0.[yy]i) which includes GPS and GLONASS DCBs continued to be available at CDDIS with a latency of less than 2 days. In addition, starting in 2018 a daily 3-constellation (GPS, GLONASS, and Galileo) global TEC mapping and differential code bias (DCB) estimation process is running internally as its performance is being assessed. Station and satellite specific GLONASS DCB estimation using about 250 IGS stations collecting GLONASS measurements continued to be monitored. Impact of instrumentation changes on GLONASS DCBs has been presented (Ghoddousi-Fard 2018). Ionospheric irregularities as sensed by 1Hz GPS and GLONASS phase rate measurements continued to be monitored in near-real-time and have been used to study geomagnetic storms (Ghoddousi-Fard et al. 2018).

4 Real-time correction service

On May 8, 2018, NRCan's product contribution to the Real-Time Working Group changed (CLK22 on products.igs-ip.net). RTCM-SSR message type 1265 (phase biases and satellite yaw information) were added to the correction stream, in addition to the current message 1060 (satellite clock and positions) and 1059 (pseudorange biases). All messages update intervals remain at 5 seconds. The satellite clock corrections are now consistent with carrier-phase observations and all communicated biases should be applied to make local observations sets consistent with the clocks. These correction sets should allow users to resolve their carrier-phase ambiguities to integer values, provided a local phase ambiguity datum is adopted, and after proper convergence of local estimates (Collins et al. 2010). Carrier-phase discontinuities for each satellite are communicated using the message 1265 mechanics.

Table 1: NRCan-AC products.

Product	Description
Repro2:	
em2wwwwd.sp3 em2wwwwd.clk em2wwwwd.snx em2wwww7.erp	GPS only • Time Span 1994-Nov-02 to 2014-Mar-29 • Use of JPL's GIPSY-OASIS II v6.3 • Daily orbits, ERP and SINEX • 5-min clocks • Submission for IGS repro2 combination
Final (weekly):	
emrwwwwd.sp3 emrwwwwd.clk emrwwwwd.snx emrwwww7.erp emrwwww7.sum	GPS only • Since 1994 and ongoing • Use of JPL's GIPSY-OASIS II v6.4 from 2016-Feb-01 • Daily orbits, ERP and SINEX • 30-sec clocks • Weekly submission for IGS Final combination
	GPS+GLONASS • Since 2011-Sep-11 and ongoing • Use of Bernese 5.0 until 2015-Jan-31 • Use of Bernese 5.2 since 2015-Feb-01 • Daily orbits and ERP • 30-sec clocks • Weekly submission for IGLOS Final combination • Station XYZ are constrained, similar to our Rapid solutions
Rapid (daily):	
emrwwwwd.sp3 emrwwwwd.clk emrwwwwd.erp	GPS only • From July 1996 to 2011-05-21 • Use of JPL's GIPSY-OASIS (various versions) • Orbits, 5-min clocks and ERP (30-sec clocks from 2006-Aug-27) • Daily submission for IGR combination
	GPS+GLONASS • Since 2011-Sep-06 and ongoing • Use of Bernese 5.0 until 2015-Feb-11 • Use of Bernese 5.2 from 2015-Feb-12 • Daily orbits and ERP • 30-sec GNSS clocks

Table 1: NRCan-AC products (continued).

Product	Description
Ultra-Rapid (hourly):	

`emuwwwwd_hh.sp3`
`emuwwwwd_hh.clk`
`emuwwwwd_hh.erp`
	GPS only
	• From early 2000 to 2013-09-13, hour 06
	• Use of Bernese 5.0
	• Orbits, 30-sec clocks and ERP (hourly)
	• Submission for IGU combination (4 times daily)
	
	GPS+GLONASS
	• Since 2013-09-13, hour 12
	• Use of Bernese 5.0 until 2015-Feb-12
	• Use of Bernese 5.2 since 2015-Feb-13
	• Orbits and ERP (hourly)
	• 30-sec GNSS clocks (every 3 hours)
	• 30-sec GPS-only clocks (every other hours)
	• Submission for IGU/IGV combination (4 times daily)

Real-Time:	
	GPS only • Since 2011-11-10 • In-house software (HPGPS.C) • RTCM messages: – orbits and clocks:1060 positions at Antenna Reference Point float ambiguity clocks – pseudorange biases: 1059 • Interval: 5 sec GPS only • Since 2018-05-08 • In-house software (HPGPS.C) • RTCM messages: – orbits and clocks:1060 positions at Antenna Reference Point phase clocks – pseudorange biases: 1059 – phase biases: 1265 • Interval: 5 sec

5 CSRS-PPP service

Since the launch of NRCan's CSRS-PPP online positioning service in 2003, GPSPACE had been running as the GNSS PPP software. The various iterations of this software proved to be very reliable having processed over 3 million jobs since 2003. However, in order to fully support multi-GNSS data, generate ambiguity resolved PPP (PPP-AR) solutions, and move towards faster convergence, NRCan transitioned to a modern GNSS processing engine called SPARK on August 16, 2018.

The advantages of the SPARK software are:

- Height bias correction (4-5 mm);
- Improved single frequency positioning (code & phase) solution;
- Support for RINEX v3;
- Machine-readable summary text file format allowing for easier automation;
- Capable of processing all GNSS constellations and signals (once IGS or NRCan precise products become available);
- Improved integration with existing NRCan transformation tools;

This software upgrade was the first step towards PPP-AR and co-operative PPP solutions allowing for faster convergence and shorter observation requirements in the future.

6 Operational NRCan stations

In addition to routinely generating all core IGS products, NRCan is also providing public access to GPS/GNSS data for more than 100 Canadian stations. This includes 38 stations currently contributing to the IGS network through the Canadian Geodetic Survey's Canadian Active Control System (CGS-CACS), the CGS Regional Active Control System (CGS-RACS), and the Geological Survey of Canada's Western Canada Deformation Array (GSC-WCDA). The NRCan contribution to the IGS network includes 26 GNSS plus 12 GPS only stations. CGS-CACS network contributes 30 GNSS stations in RINEX 3.03 and RINEX 2.11 format. 20 of these stations are IGS stations. High-rate data for 9 additional stations are being contributed as of 2018-08-09. Several upgrades/changes to the CGS-CACS were completed in 2018 and these are listed in Table 2. Figure 1 shows a map of the NRCan GPS/GNSS network as of January 2019.

Table 2: NRCan Station Upgrades in 2018.

Station	Date	Remarks
alg2	2018-01-24	Station receiver upgraded to TPS NET-G5
alg3	2018-01-24	Station receiver upgraded to TPS NET-G5
baie	2018-03-14	Station receiver upgraded to TPS NET-G5
bake	2018-07-26	New antenna cable
chu2	2018-01-30	Station receiver upgraded to TPS NET-G5
prds	2018-05-24	Station receiver upgraded to JAVAD TRE_3N
sask	2018-05-27	Station receiver upgraded to JAVAD TRE_3N
stj2	2018-01-22	Station receiver upgraded to TPS NET-G5
vald	2018-03-12	Station receiver upgraded to TPS NET-G5
yel3	2018-02-01	Station receiver upgraded to TPS NET-G5

Further details about NRCan stations and access to NRCan public GPS/GNSS data and site logs can be found at:

https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php

or from the following anonymous ftp site:

ftp://rtopsdata1.geod.nrcan.gc.ca/gps/.

7 Acknowledgement

NRCan Contribution number / Numéro de contribution de RNCan: 20180369

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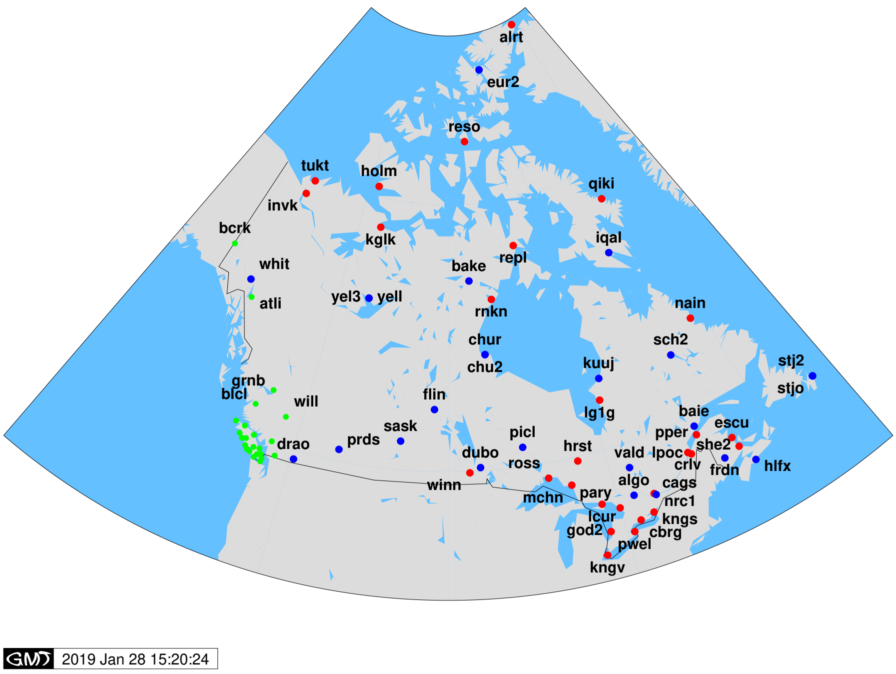

Figure 1: NRCan Public GPS/GNSS Stations (CGS-CACS in blue, CGS-RACS in red and GSC-WCDA in green).

GFZ Analysis Center Technical Report 2018

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1 Summary

During 2018, the standard IGS product generation was continued with minor changes in the processing software EPOS.P8. The GNSS observation modeling still conforms to the GFZ repro-2 (2nd IGS Reprocessing campaign) settings for the IGS Final product generation. The multi-GNSS processing was continued routinely during 2018 including GPS, GLONASS, BeiDou, Galileo, and QZSS with only few exceptions from a regular submission.

2 Products

The list of products provided to the IGS by GFZ is summarized in Table 1.

3 Operational Data Processing and Latest Changes

Our EPOS.P8 processing software is following the IERS Conventions 2010 (Petit and Luzum 2010). For the IGS Final, Rapid and Ultra-rapid chains approximately 200, 130, and 95 sites are used, respectively. Recent changes in the processing strategy are listed in Table 2. Only minor changes have been applied for the observation modeling in order to keep the consistency with respect to the repro-2 processing strategy. The most important change was the switch from ECOM1 to ECOM2 parametrization in terms of solar radiation pressure (Arnold et al. 2015).

Table 1: List of products provided by GFZ AC to IGS and MGEX

IGS Final	(GLONASS since week 1579)
gfzWWWWD.sp3	Daily orbits for GPS/GLONASS satellites
gfzWWWWD.sp3	Daily orbits for GPS/GLONASS satellites
gfzWWWWD.clk	5-min clocks for stations and 30-sec clocks for GPS/GLONASS satellites
gfzWWWWD.snx	Daily SINEX files
gfzWWWW7.erp	Earth rotation parameters
gfzWWWW7.sum	Summary file including Inter-Frequency Code Biases (IFB) for GLONASS
gfzWWWWD.tro	1-hour tropospheric Zenith Path Delay (ZPD) estimates
IGS Rapid	(GLONASS since week 1579)
gfzWWWWD.sp3	Daily orbits for GPS/GLONASS satellites
gfzWWWWD.clk	5-min clocks for stations and GPS/GLONASS satellites
gfzWWWWD.erp	Daily Earth rotation parameters
IGS Ultra-Rapid	(every 3 hours; provided to IGS every 6 hours; GLONASS since week 1603)
gfuWWWWD_HH.sp3	Adjusted and predicted orbits for GPS/GLONASS satellites
gfzWWWWD_HH.erp	Earth rotation parameters
MGEX Rapid	
gbmWWWWD.sp3	Daily satellite orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
gbmWWWWD.clk	30 sec (since GPS-week 1843) receiver and satellite clocks
gbmWWWWD.erp	Daily Earth rotation parameters
MGEX Ultra-Rapid	(since week 1869)
gbuWWWWD_HH.sp3	Adjusted and predicted orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
gbuWWWWD_HH.erp	Earth rotation parameters

Table 2: Recent processing changes

Date	**IGS**	**IGR/IGU**	Change
2018-11-26	w2028	w2029.2	Switch from ECOM1 to ECOM2 (D4B1, Arnold et al. (2015))

Table 3: Used observation types and number of satellites (averaged) in the multi-GNSS data processing (gbm)

Satellite System	# Satellites	Observation Types
GPS	32	L1/L2
GLONASS	22	L1/L2
Galileo	24	E1/E5a
BeiDou II	15	B1/B2
QZSS	4	L1/L2

4 Multi-GNSS data processing

The IGS rapid/ultra-rapid like style multi-GNSS processing was continued in 2018 (Deng et al. 2016). The GFZ multi-GNSS solution covers five different systems, namely GPS, GLONASS, Galileo, BeiDou and QZSS. Figure 1 shows the total number of satellites per GNSS included in the `gbm` MGEX solution in 2018. The maximum number of GNSS satellites in `gbm` is 97. The number of used multi-GNSS stations in `gbm` and `gbu` is about 150 and 100, respectively. Currently the consumed data processing time is about 4 and 1 hour for the `gbm` and `gbu` analysis, respectively. Table 3 shows the corresponding observation type selection made for the individual GNSS. The `gbm` and `gbu` product are available at ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

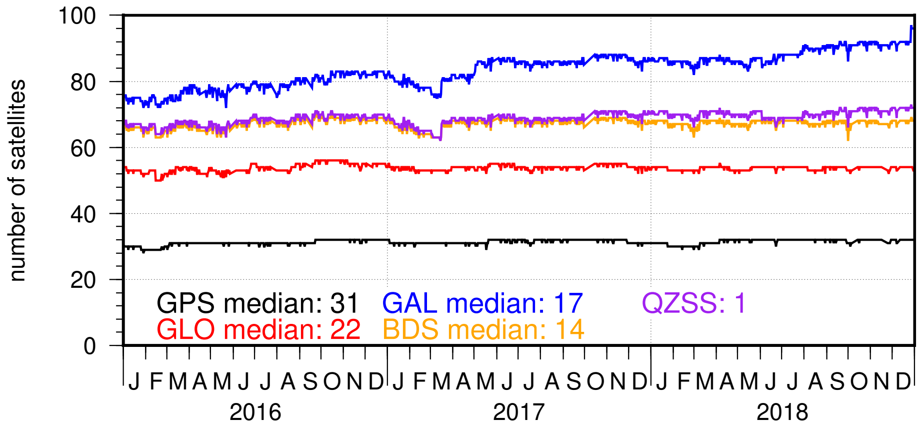


Figure 1: Total number of satellite per GNSS included in the daily multi-GNSS data processing (gbm)

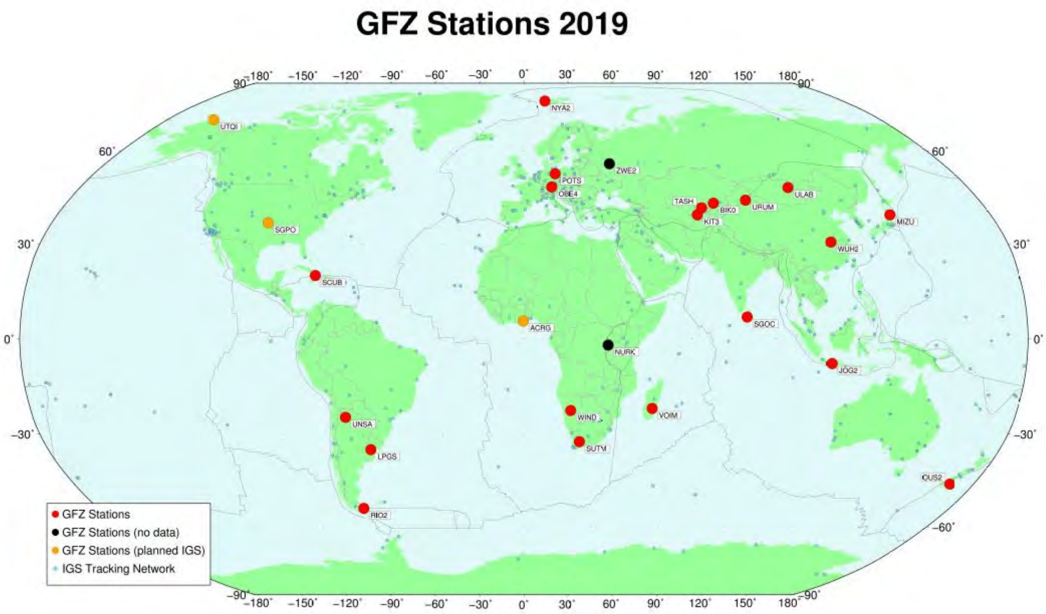


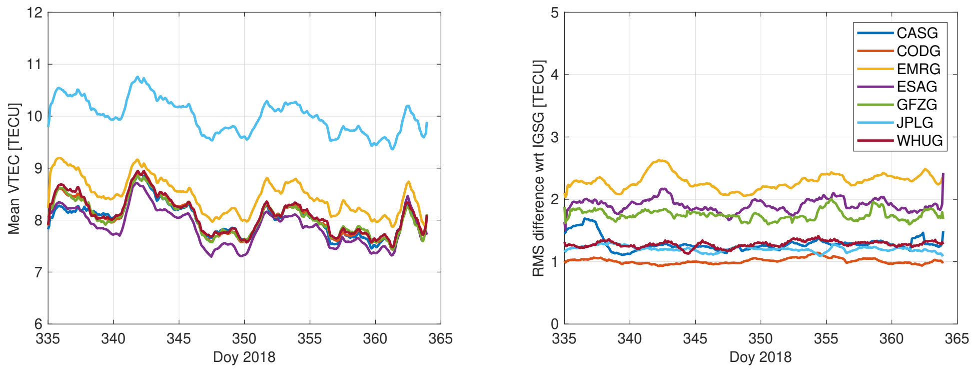
Figure 2: GNSS stations operated by GFZ (as of December 2018)

5 Operational GFZ Stations

The GFZ operated global GNSS station network comprises currently 23 GNSS stations participating in the IGS tracking network. Figure 2 shows the globally distribution of these stations.

In 2018, the stations Potsdam/Germany (POTS), Colombo/Sri Lanka (SGOC), Ulaan Bataar/Mongolia (ULAB) and Wuhan/China (WUH2) were upgrade by changing their receivers to a JAVAD TRE 3 and the antennas to a JAVRINGANT G5T NONE. The station are now capable to track all available satellite systems, including GPS, GLONASS,Galileo, BeiDou and QZSS. The problems for our stations NURK (Kigali, Rwanda) and ZWE2 (Zwenigorod/Russia) could not be resolved yet.

Together with our colleagues of the seismic netork (GEOFON) we installed a station in Accra/Ghana (ACRG). The station is equipped with a JAVAD TR G3TH receiver and a JAV GRANT-G3T NONE antenna. ACRG is capable to track GPS, GLONASS, and Galileo. After a successful monitoring of the station's behaviour it is planned to propose ACRG as IGS tracking station during summer 2019.



(a) mean VTEC

(b) RMS VTEC differences

Figure 3: Smoothed mean VTEC values and RMS VTEC differences for December 2018

6 Ionosphere Monitoring

The GFZ EPOS.P8 analysis software is currently being extended with the capability to provide estimates of the ionospheric activity in form of vertical TEC maps in the IONEX format. At present, the associated software is undergoing extensive internal testing, and the products are not published yet. Global ionospheric solutions with a temporal resolution of 2 h as specified by the IGS are generated from daily GNSS observations, with the option to combine the solutions from adjacent days on the normal equation level. The processing is based on dual-frequency undifferenced and uncombined GNSS data. Multi-GNSS solutions are supported. A standard single layer model in which the spatial distribution of the vertical TEC is described by spherical harmonics is currently employed, but will be the subject of future investigations. For an initial assessment of the GFZ solution (GFZG) in comparison with the IAACs' solutions, the mean vertical TEC and the RMS difference with respect to the IGS Final solution are presented in Figure 3 for December 2018 (UPCG was not available). GFZG is computed from GPS and GLONASS data from a network with a comparably small number of approximately 180 stations. The results show an excellent agreement of the mean vertical TEC of GFZG with the other solutions, while the RMS difference to IGSG, which is a combination of CODG and JPLG, is at a similar level.

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CNES-CLS
Technical Report 2018

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1 Introduction

In 2018, the CNES-CLS Analysis Center continued its contribution through the weekly delivery of combined final GPS-GLONASS-Galileo products using the GINS software package. The formal "GRG" GPS-GLONASS products can be downloaded from the "gps/products/wwww" directory of any IGS archiving center while experimental "GRM" GPS-GLONASS-Galileo products are accessible from the "gps/products/mgex/wwww" directory. The main evolutions of our processing strategy are summarized in section 2 while section 3 focuses on its impact on station coordinates and section 4 is dedicated to Galileo ambiguity resolution results. More information can be found in the given references as well as at:https://igsac-cnes.cls.fr/.

2 Data processing strategy changes

The data weighting strategy was suspected to be one of the reason of the higher noise in the stations positions residuals relatively of our solutions compared to other Analysis Centers in particular in the up direction. These errors were dominated by an anomalous

Table 1: Processing parameters changes in 2018.

Parameter	Old	New
Data Cut-off	10°	8°
Data sampling	900s	300s
Data weighting-law	Constant	Elevation dependent

Table 2: Processing parameters changes in 2018.

Constellation	σ_0 (meter)	a	p
GPS phase	0.0035	0.15	1.0
GPS code	0.6000	0.15	1.0
GLONASS phase	0.0350	0.15	1.0
GLONASS code	2.0000	0.15	1.0
Galileo phase	0.0350	0.15	1.0
Galileo code	1.0000	0.15	1.0

spectral signature around 3.7 days (Ray et al. 2013). We decided to increase the number of observations considered in the processing using a sampling of 300 seconds, lower the elevation cut-off to 8 degrees and simultaneously adopt an elevation dependent weighting law for phase measurements (table 1).

The form of the weighting law was provided by Mercier (2019):

$$\sigma(\sigma_0, a, p, \theta) = \frac{\sigma_0}{a + (1-a)sin^p\theta} \tag{1}$$

In which θ represents the elevation angle and σ_0 , a and p were adjusted and averaged on one day of GPS-only observations from the entire MGEX network. Starting from the values estimated for GPS code and phase measurements down-weighting factors have been applied to GLONASS and Galileo corresponding parameters (table 2).

3 Impact of the new strategy on station coordinates

Starting April 15th (week 1997), the new processing strategy have been applied to the official GRG products. They had a significative positive impact on the estimated station coordinates. Figure 1 provided by Paul Rebischung (IGN, France) shows a daily comparison to the IGS combined solution in terms of global RMS on the North, East and Up components from week 1984 to 2018. The improvement is clear on the Up and East directions.

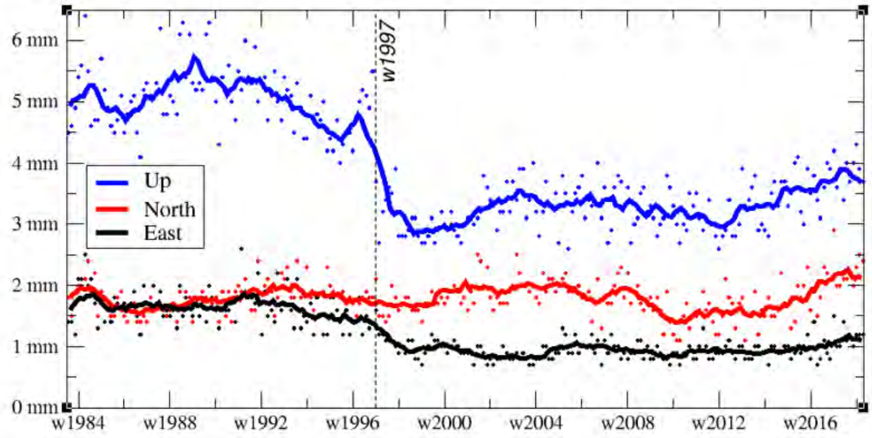

Figure 1: Station daily comparison: GRG vs IGS combined solution. The change of processing strategy during week 1997 has a clear positive impact on the GRG solution (Courtesy Paul Rebischung, IGN, France.

Even more satisfactory is the disappearance of the 3.7 periodic signal. Figure 2 compares the lomb-scargle normalized periodogram of the "new" series of daily station residuals with both a GPS-only and a GPS+GLONASS "old" series.

4 Galileo ambiguity resolution

Since October 7th (week 2022), Galileo un-differenced phase observations are fixed to integer values within the multi-GNSS (GRM) products delivered to MGEX. The applied algorithm is similar to the one described in Katsigianni et al. (2018a, b). Figure 3 shows the statistic of daily fixing rates for GPS and Galileo constellations.

As a consequence, Galileo phase clock products like the historical GPS one's, became compatible with PPP with ambiguity resolution processing. In addition, the impact on the Galileo satellite orbit solution precision is clear. Successive 36 hours orbit solution overlap during 12 hours. Figure 4 shows the 3D-RMS orbit overlapping values per satellite and per day (during a test period of 1 month in September 2018).

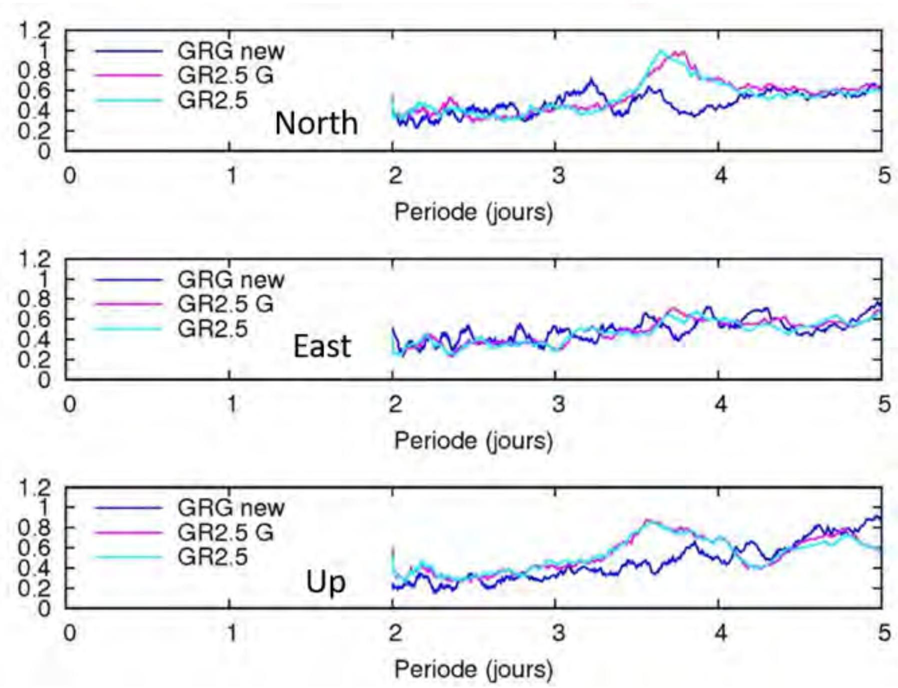

Figure 2: Lomb-scargle normalized periodogram of new GRG and old GRG2.5G (GPS only) and old GR2.5 (GPS+GLONASS) solutions. The spurious 3.7 day period signal affecting the Up and North components seems to disappear when using the new strategy.

Figure 3: GPS and Galileo ambiguity fixing daily success rates.

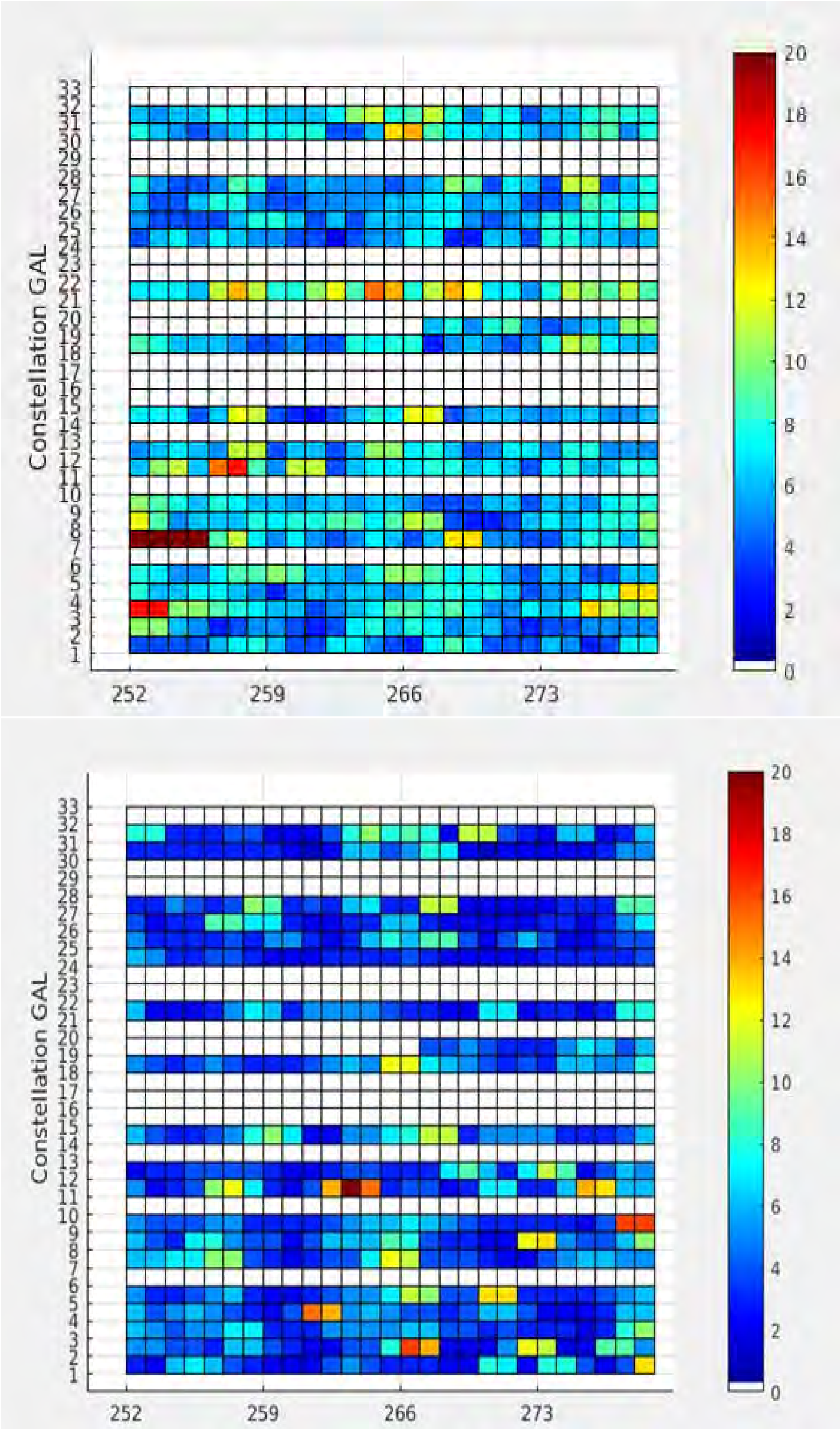

Figure 4: Galileo orbit comparison between successive 36 hours arcs overlapping on 12 hours. 3D-RMS values in centimeters per DOY 2018 and per available satellite. Top figure: float ambiguities. Bottom figure: fixed ambiguities.

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JPL IGS Analysis Center Technical Report 2018

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1 Introduction

In 2018, the Jet Propulsion Laboratory (JPL) continued to serve as an Analysis Center (AC) for the International GNSS Service (IGS). We contributed operational orbit and clock solutions for the GPS satellites; position, clock and troposphere solutions for the ground stations used to determine the satellite orbit and clock states; and estimates of Earth rotation parameters (length-of-day, polar motion, and polar motion rates). This report summarizes the activities at the JPL IGS AC in 2018.

Table 1 summarizes our contributions to the IGS Rapid and Final products. All of our contributions are based upon daily solutions centered at noon and spanning 30-hours. Each of our daily solutions is determined independently from neighboring solutions, namely

Table 1: JPL AC Contributions to IGS Rapid and Final Products.

Product	Description	Rapid/Final
jplWWWWd.sp3	GPS orbits and clocks	Rapid & Final
jplWWWWd.clk	GPS and station clocks	Rapid & Final
jplWWWWd.tro	Tropospheric estimates	Rapid & Final
jplWWWWd.erp	Earth rotation parameters	Rapid(d=0-6), Final(d=7)
jplWWWWd.yaw	GPS yaw rate estimates	Rapid & Final
jplWWWWd.snx	Daily SINEX file	Final
jplWWWW7.sum	Weekly solution summary	Final

without applying any constraints between solutions. High-rate (30-second) Final GPS clock products are available from 2001 onwards.

The JPL IGS AC also generates Ultra-Rapid orbit and clock products for the GPS constellation. These products are generated with a latency of less than 2.5 hours and are updated hourly (Weiss et al. 2010). Although not submitted to the IGS, our Ultra-Rapid products are available in native GIPSY and GipsyX formats at:

- https://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Ultra
- https://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/Ultra

Note: These files will no longer be available via ftp after June 2019 since the sideshow ftp site is being completely superseded by the sideshow https site on this date.

2 Processing Software and Standards

On 29 Jan 2017 (start of GPS week 1934) we switched from using GIPSY (version 6.4) to the GipsyX to create all our orbit and clock products. At the switch we also started to produce rapid products in IGS14 while continuing to produce final products in IGb08.

In our operations, we have adopted the data processing approach used for our repro2 reprocessing which had the following improvements from our previous data processing strategy:

1. Application of second order ionospheric corrections (Garcia-Fernandez et al. 2013).
2. Revised empirical solar radiation pressure model named GSPM13 (Sibois et al. 2014).
3. Antenna thrust models per IGS recommendations.
4. Modern ocean tide loading, using GOT4.8 (Ray 2013) (appendix) instead of FES2004 (Lyard et al. 2006).
5. GPT2 troposphere models and mapping functions (Lagler et al. 2013).
6. Elevation-dependent data weighting.

A complete description of our current operational processing approach, also used for repro2, can be found at:

https://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/readme.txt

We continue to use empirical GPS solar radiation pressure models developed at JPL instead of the DYB-based strategies that are commonly used by other IGS analysis centers.

This choice is based upon an extensive evaluation of various internal and external metrics after testing both approaches with the GIPSY/OASIS software (Sibthorpe et al. 2011).

3 GipsyX Overview

For several years we have been developing a replacement to GIPSY called GipsyX which has the following features:

1. GipsyX is the C++/Python3 replacement for both GIPSY and Real-Time GIPSY (RTG).
2. Driven by need to support both post-processing and real-time processing of multiple GNSS constellations.
3. Can already process data from GPS, GLONASS, Beidou, and Galileo.
4. Supports DORIS and SLR data processing.
5. Multi-processor and multi-threaded capability.
6. Single executable replaces multiple GIPSY executables: model/oi, filter. smoother, ambiguity resolution.
7. Versatile PPP tool (gd2e) to replace GIPSY's gd2p.
8. Similar but not identical file formats to current GIPSY.
9. Runs under Linux and Mac OS.
10. First GipsyX beta-version released to the GIPSY user community in December 2016
11. Available under similar license to GIPSY license (see `https://gipsy-oasis.jpl.nasa.gov/index.php?page=software` for more details)

In parallel with the GipsyX development we have also developed new Python3 operational software that uses GipsyX to generate the rapid and final products that we deliver to the IGS as well as generating our ultra-rapid products that are available on our https site.

4 Recent Activities

Recent activities are well summarized by presentations at the 2018 IGS workshop in Wuhan, 2018 ILRS workshop in Canberra, and 2018 Fall AGU meeting in Washington, DC. These include:

- Reprocessing of GPS Products in the IGS14 Frame (Dietrich et al. 2018)

- Observing geocenter motion from LEO POD using onboard GPS tracking data(Kuang et al. 2018)
- Status of IGS14 reprocessing at the JPL IGS Analysis Center (Ries et al. 2018a)
- Multi-technique capabilities in GipsyX (Ries et al. 2018b)
- Point positioning with modern GPS signals with GipsyX (Ries et al. 2018c)
- A multi-year reanalysis of GPS Block II/IIA and IIF satellite yaw maneuvers by means of reverse kinematic point positioning technique (Sibois et al. 2018)
- Multi-GNSS Ultras (>= 4 constellations) (Sibthorpe et al. 2018)

As of week 2003 (2018-05-27), all IGS Finals were submitted in the IGS14 frame, and furthermore a reprocessing was released back through week 1147 (2002-01-01). We also plan to release a reprocessing of earlier years in 2019.

5 Future Work

We are currently testing the multi-GNSS capability of GipsyX and our longer term goal is to generate multi-GNSS constellation orbit and clock products. Furthermore, processing of non-GNSS SLR and DORIS geodetic data has been added to GipsyX and VLBI is under development.

6 Acknowledgments

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NGS Analysis Center Technical Report 2018

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1 Introduction

In 2018, NGS continued to serve as an IGS analysis center and a regional data center. This report summarizes the routine analysis and data center activities conducted at the National Geodetic Survey (NGS), and all significant changes that occurred during the year 2018.

2 Core Analysis Center Products

There were no changes in the NGS analysis center products (see Table **??**) for 2018. Please refer to the Analysis Coordinator website (http://acc.igs.org) for combination statistics of the NGS analysis center products.

3 Analysis Center Processing Software and Strategies

For details about the models and strategies used, please refer to the NOAA/NGS Analysis Strategy Summary (ftp://igs.org/pub/center/analysis/noaa.acn).

Changes in the models and strategies to the processing software include:

- A bug has been fixed in reading an external ocean loading file. This is effective from 2018-225 for rapid products and from GPS Week 2018 for final products. Thanks to Bob King at MIT who reported the bug.

Table 1: NGS Analysis Center Products

Product	Description
Final (weekly)	
`ngswwwwd.sp3`	GPS only
`ngswwwwd.snx`	PAGES software suite (5.102 – 5.103)
`ngswwww7.erp`	Orbits, ERP and SINEX
Rapid (daily)	
`ngrwwwwd.sp3`	GPS only
`ngrwwwwd.erp`	PAGES software suite (5.102 - 5.103)
	Orbits, ERP and SINEX
	Daily submission for IGR combination
Ultra-Rapid (hourly)	
`nguwwwwd.sp3`	GPS only
`nguwwwwd.erp`	PAGES software suite (5.102 - 5.103)
	Orbits and ERP
	4 times a day submission for IGU combination

Changes in staff include:

- Bryan Stressler came on-board in December 2017
- Phillip McFarland came on-board in November 2018

4 Regional Data Center Core Products

During 2018, NGS contributed data from the sites listed in Table 2 to the IGS Network.

As a Regional Data Center, NGS also facilitated data flow for the sites given in Table 3 .

Please refer to the IGS Network website (http://igs.org/network) for site logs, photos, and data statistics for the sites serviced by the NGS regional data center.

Table 2: Site contributed by the NGS to the IGS network during 2018.

Site	Location	Lat.	Long.	Receiver Type	System
ASPA	Pago Pago, American Samoa	-14.33	-170.72	TRIMBLE NETR5	GPS+GLO
BARH	Bar Harbor, ME, USA	44.39	-68.22	LEICA GRX1200GGPRO	GPS+GLO
BRFT	Eusebio, Brazil	-3.88	-38.43	LEICA GRX1200PRO	GPS
BRMU	Bermuda, United Kingdom	32.37	-64.70	LEICA GRX1200GGPRO	GPS+GLO
CNMR	Saipan, CNMI, USA	15.23	145.74	TRIMBLE NETR5	GPS+GLO
GUUG	Mangilao, Guam, USA	13.43	144.80	TRIMBLE NETR5	GPS+GLO
HNPT	Cambridge, MD, USA	38.59	-76.13	LEICA GRX1200GGPRO	GPS+GLO
WES2	Westford, MA, USA	42.61	-71.49	LEICA GR50	GPS+GLO+GAL

Table 3: Sites where NGS is facilitating data flow as a Regional Data Center.

Site	Location	Lat.	Long.	Receiver Type	System
BJCO	Cotonou, Benin	6.38	2.45	TRIMBLE NETR5	GPS+GLO
GUAT	Guatemala City, Guatemala	14.59	-90.52	LEICA GRX1200GGPRO	GPS+GLO
ISBA	Baghdad, Iraq	33.34	44.44	TRIMBLE NETR5	GPS+GLO
MANA	Managua, Nicaragua	12.15	-86.25	TRIMBLE NETR9	GPS

5 Acknowledgments

The analysis and data center teams wish to express our gratitude to NGS management: Director Juliana Blackwell, Deputy Director Brad Kearse, Division Chief Steve Hilla, Division Chief Srinivas Reddy and Division Chief Dr. Theresa Damiani, for their support of this work as fundamental activities of NGS. For information about how these activities fit into NGS plans, see the National Geodetic Survey Strategic Plan 2019–2023 (https://geodesy.noaa.gov/web/about_ngs/info/documents/ngs-strategic-plan-2019-2023.pdf).

USNO Analysis Center Technical Report 2018

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1 Introduction

The United States Naval Observatory (USNO), located in Washington, DC, USA has served as an IGS Analysis Center (AC) since 1997, contributing to the IGS Rapid and Ultra-rapid Combinations since 1997 and 2000, respectively. USNO contributes a full suite of rapid products (orbit and clock estimates for the GPS satellites, earth rotation parameters (ERPs), and receiver clock estimates) once per day to the IGS by the 1600 UTC deadline, and contributes the full suite of Ultra-rapid products (post-processed and predicted orbit/clock estimates for the GPS satellites; ERPs) four times per day by the pertinent IGS deadlines.

USNO has also coordinated IGS troposphere activities since 2011, producing the IGS Final Troposphere Estimates and chairing the IGS Troposphere Working Group (IGS TWG).

The USNO AC is hosted in the GPS Analysis Division (GPSAD) of the USNO Earth Orientation Department. USNO AC activities, chairing the IGS TWG, and serving on the IGS Governing Board are overseen by Dr. Sharyl Byram who also oversees production of the IGS Final Troposphere Estimates. All GPSAD members, including Dr. Victor Slabinski, Mr. Jeffrey Tracey, and contractor Mr. James Rohde, participate in AC efforts.

USNO AC products are computed using Bernese GNSS Software (Dach et al. 2015). Rapid products are generated using a combination of network solutions and precise point positioning (PPP; Zumberge et al. (1997)). Ultra-rapid products are generated using network solutions. IGS Final Troposphere Estimates are generated using PPP.

GPSAD also generates a UT1-UTC-like value, UTGPS, five times per day. UTGPS is a GPS-based extrapolation of VLBI-based UT1-UTC measurements. The IERS (International Earth Rotation and Reference Systems Service) Rapid Combination/Prediction

Service uses UTGPS to improve post-processed and predicted estimates of UT1-UTC. Mr. Tracey oversees UTGPS.

USNO rapid, Ultra-rapid and UTGPS products can be downloaded immediately after computation from http://www.usno.navy.mil/USNO/earth-orientation/gps-products. IGS Final Troposphere Estimates can be downloaded at ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd.

2 Product Performance, 2018

Figures 1-4 show the 2018 performance of USNO rapid and Ultra-rapid GPS products, with summary statistics given in Table 1. USNO rapid orbits had a median weighted RMS (WRMS) of 15 mm with respect to (wrt) the IGS rapid combined orbits. The USNO Ultra-rapid orbits had median WRMSs of 20 mm (24-h post-processed segment) and 37 mm (6-h predict) wrt the IGS rapid combined orbits. These values are slightly improved compared to the 2017 values (16, 21 and 38 mm).

USNO rapid (post-processed) and Ultra-rapid 6-h predicted clocks had median 179 ps and 992 ps RMSs wrt IGS combined rapid clocks. Both show slight degradation from the 2017 values of 142 ps and 967 ps respectively.

USNO rapid polar motion estimates had (x, y) 40 and 28 microarcsec RMS differences wrt IGS rapid combined values. USNO Ultra-rapid polar motion estimates differed (RMS of x, y) from IGS rapid combined values by 423 and 277 microarcsec for the 24-h post-processed segment. The USNO Ultra-rapid 24-h predict-segment values differed (RMS of x, y) from the IGS rapid combined values by 565 and 383 microarcsec.

The USNO AC began using measurements from the Russian GLONASS satellites into processing in 2011 (Byram and Hackman 2012a, b) and has been computing a full set of test rapid and Ultra-rapid combined GPS+GLONASS products since 2012.

In 2018, seven-parameter Helmert transformations computed between USNO and IGS Ultra-rapid GPS+GLONASS orbits had median RMSs of 34 and 63 mm for the 24-h post-processed and 6-h predict portions, respectively. Meanwhile, the USNO GPS+GLONASS Ultra-rapid 24-h post-processed polar motion x and y values differed from the IGS rapid combined values, RMS, by 456 and 258 microarcsec, respectively. USNO GPS+GLONASS Ultra-rapid 24-h predicted polar motion x and y values differed from the IGR values, RMS, by 531 and 339 microarcsec, respectively. These data are shown in Table 2/Figs. 5-6.

All USNO AC official products were generated with the Bernese 5.2 GNSS Software in 2018.

Table 1: Precision of USNO Rapid and Ultra-Rapid Products, 2018. All statistics computed with respect to IGS Combined Rapid Products.

USNO GPS satellite orbits				USNO GPS–based polar motion estimates						USNO GPS–based clock estimates	
Statistic: median weighted RMS difference units: mm				Statistic: RMS difference units: 10^{-6} arc sec						Statistic: median RMS difference units: ps	
dates	rapid	ultra–rapid		rapid		ultra–rapid				rapid	ultra–rapid
		past 24 h	6-h predict			past 24 4		24-h predict		past 24 h	6-h predict
				x	y	x	y	x	y		
1/1/2018– 12/31/2018	15	20	37	40	28	423	277	565	383	179	992

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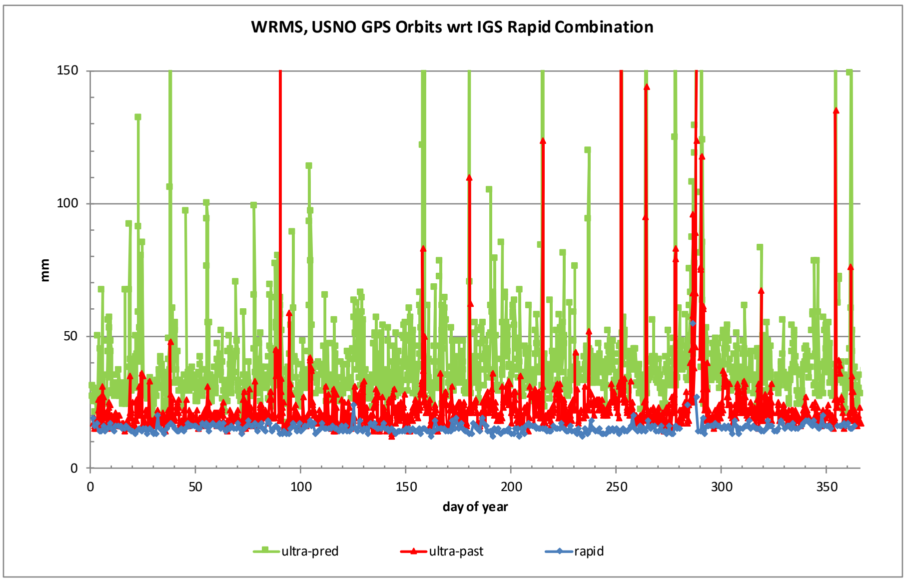

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2018. "Ultra-past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra-pred" refers to first six hours of Ultra-rapid orbit prediction.

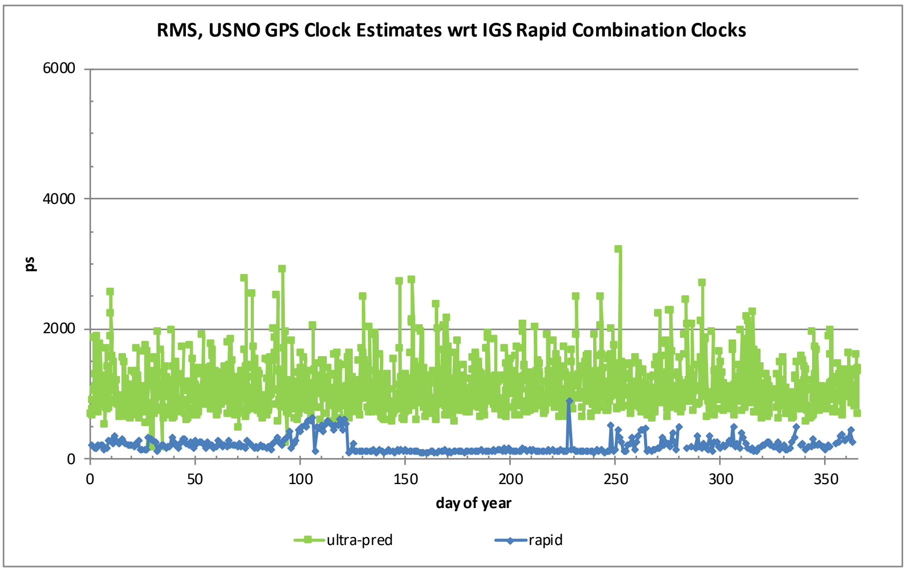

Figure 2: RMS of USNO GPS rapid clock estimates and Ultra-rapid clock predictions with respect to IGS Rapid Combination, 2018.

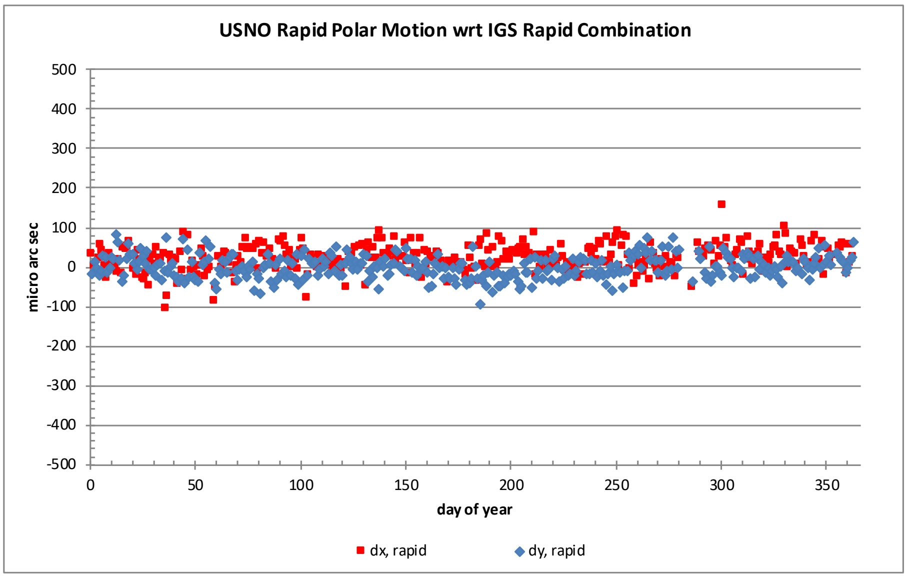

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2018. Note, scale kept same as in previous reports.

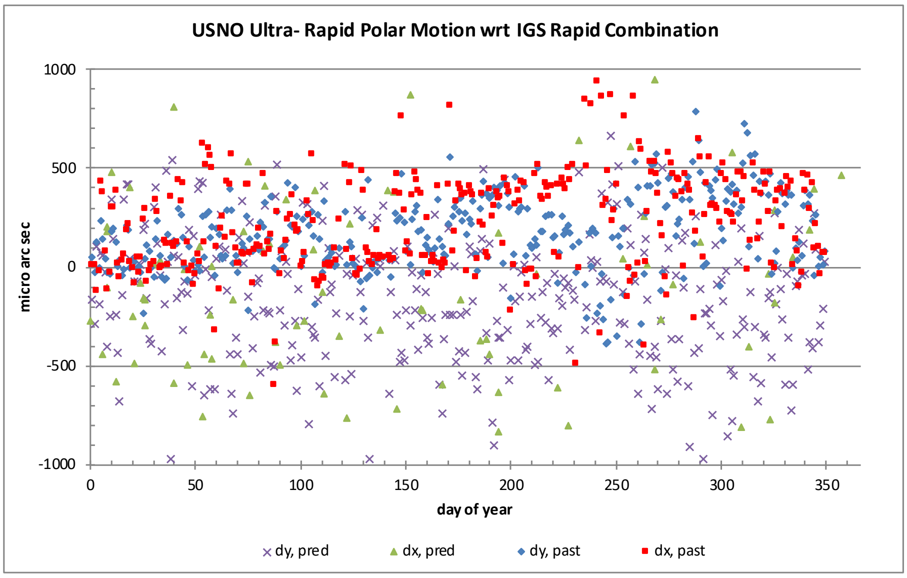

Figure 4: USNO Ultra-rapid polar motion estimates minus IGS Rapid Combination values, 2018

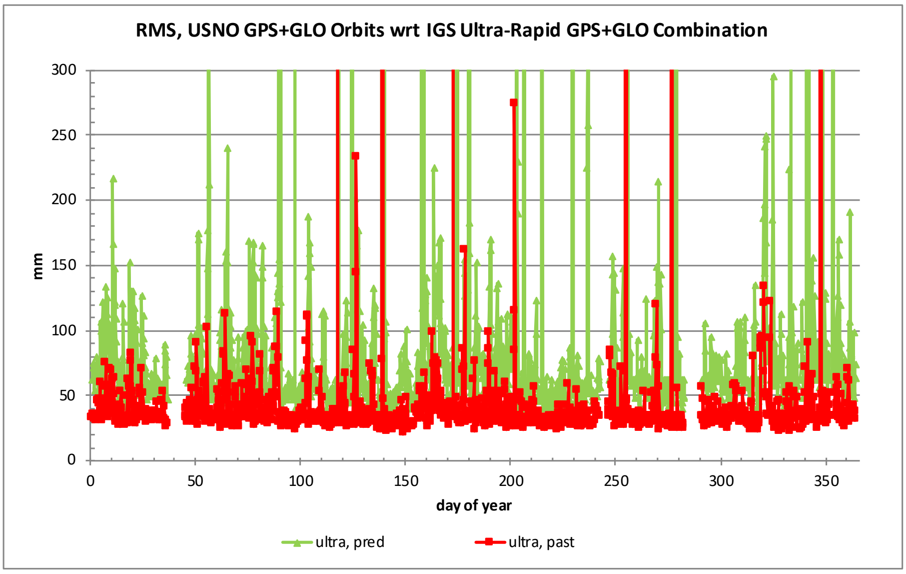

Figure 5: RMS of USNO Ultra-rapid GLONASS orbit estimates with respect to IGS Combined Ultra-rapid GLONASS orbits, 2018. "Ultra, past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra, pred" refers to first six hours of Ultra-rapid orbit prediction.

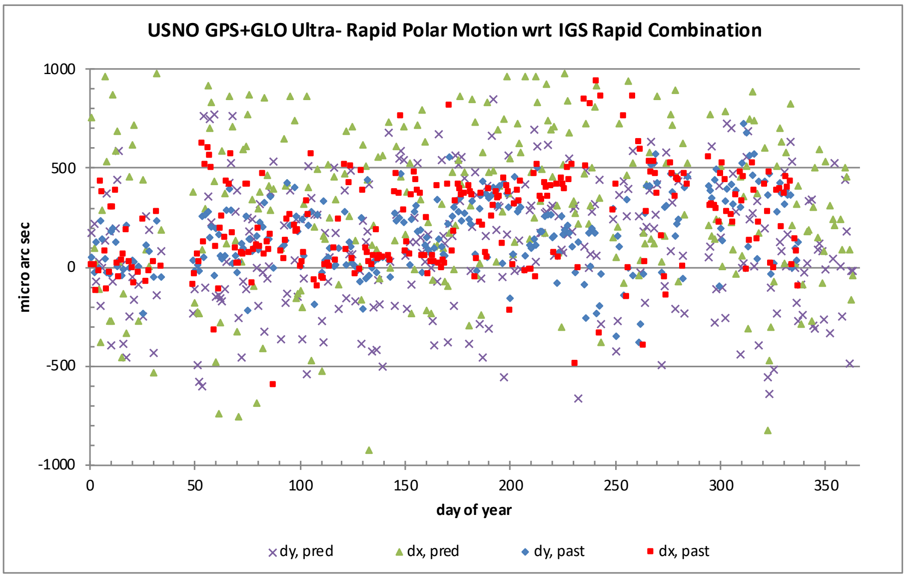

Figure 6: Difference between 24-h post-processed polar motion estimates in USNO test Ultra-rapid GPS+GLONASS solution and IGS "IGR" GPS-only rapid solution, 2018.

Table 2: Precision of USNO Ultra-Rapid GPS+GLONASS Test Products, 2018. Orbit statistics computed with respect to IGV Combined Ultra-Rapid GPS+GLONASS Products. Polar motion statistics computed with respect to IGS Rapid combined values.

USNO GLONASS satellite orbits			USNO GPS+GLONASS polar motion estimates	
Median RMS of 7-parameter Helmert transformation units: mm			RMS difference units: 10^{-6} arc sec	
dates	past 24 h	6-h predict	past 24 h	pred 6 h
1/1/2018–12/31/2018	24	63	x: 456 y: 258	x: 531 y: 339

WHU Analysis Center Technical Report 2018

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1 Introduction

The IGS Analysis Center of Wuhan University (WHU) has contributed to the International GNSS Service (IGS) since 2012 with a regular determination of the precise GPS+GLONASS ultra–rapid and rapid products. All the products are generated with the latest developed version of the Positioning And Navigation Data Analyst (PANDA) Software (Liu and Ge 2003; Shi et al. 2008).

During 2018, the precise orbit determination (POD) of BDS-3 has been carried out, and a new GNSS Ionosphere Monitoring and Analysis Software (GIMAS) integrated with the OpenMP parallel algorithm was developed at the GNSS Research Center of Wuhan University, and the capability of producing phase clock/bias products routinely has been implemented. In this report we give a summary of the IGS related activities at WHU during the year 2018.

2 WHU Analysis Products

The list of products provided by WHU is summarized in Table 1.

3 3. Multi-GNSS activities of BDS-3

The PANDA software has been under specific modifications to fulfil the POD for BDS-3 satellites. Some highlight modeling issues and improvements concerning the POD of BDS-3 made by WHU include a recommended yaw attitude model for BDS-3 satellites

Table 1: List of products provided by WHU.

WHU rapid GNSS products	
whuWWWD.sp3	Orbits for GPS/GLONASS satellites
whuWWWD.clk	5-min clocks for stations and GPS/GLONASS satellites
whuWWWD.erp	ERPs
WHU ultra-rapid GNSS products	
whuWWWD_HH.sp3	Orbits for GPS/GLONASS satellites provided to IGS every 6 hours
whuWWWD_HH.erp	observed and predicted ERPs provided to IGS every 6 hours
WHU Ionosphere products	
whugDDD0.YYi	Final GIM with 3-d GPS/GLONASS observations
whrgDDD0.YYi	Rapid GIM with 1-d GPS/GLONASS observations

manufactured by CAST (China Academy of Space Technology) (Wang et al. 2018a), a refined priori solar radiation model for the BDS-3 I2-S satellite (Wang et al. 2018b) and the assessment of contribution of inter-satellite data to POD (Zhao et al. 2018).

Recently, we have conducted the POD for BDS-3 satellites to obtain a consistent analysis of the orbits. The data from iGMAS (international GNSS monitoring and assessment system) and MGEX stations from August to the end of 2018 are collected. Thanks to the efforts of iGMAS and MGEX GNSS receiver providers, the amount of the receivers which have the tracking capability of BDS-3 satellites on over or equal to two signals are increasing gradually as illustrated on Figure 1. After two rapid rise phases around DOY (Day of year) 290 and 340, the number of dual-frequency capability receivers of BDS-3 satellites reaches nearly 130 in which the iGMAS network contributes over 25 receivers tracking BDS-3 satellites on five frequencies.

As at the beginning of selected period (i.e. DOY before 270, 2018) the ground stations are not sufficient enough, a three-day POD solutions are calculated. As normally does, a two-step POD strategy is applied. Thanks to the measurement kindly provided by ILRS, which contributes to a global collaboration for the 4 (i.e. PRN C20, C21, C29 and C30) BDS-3 satellites starting from August 2018, that makes an external orbit accuracy evaluation possible. The SLR residuals series of two of them are plotted in Figure 2. The beginning phase suffers accuracy reduction slightly due to fewer ground stations used though, a three-day POD arc can somewhat smooth this effect. In general, the orbit accuracy revealed by SLR validation reaches around 5 cm for the BDS-3 satellites.

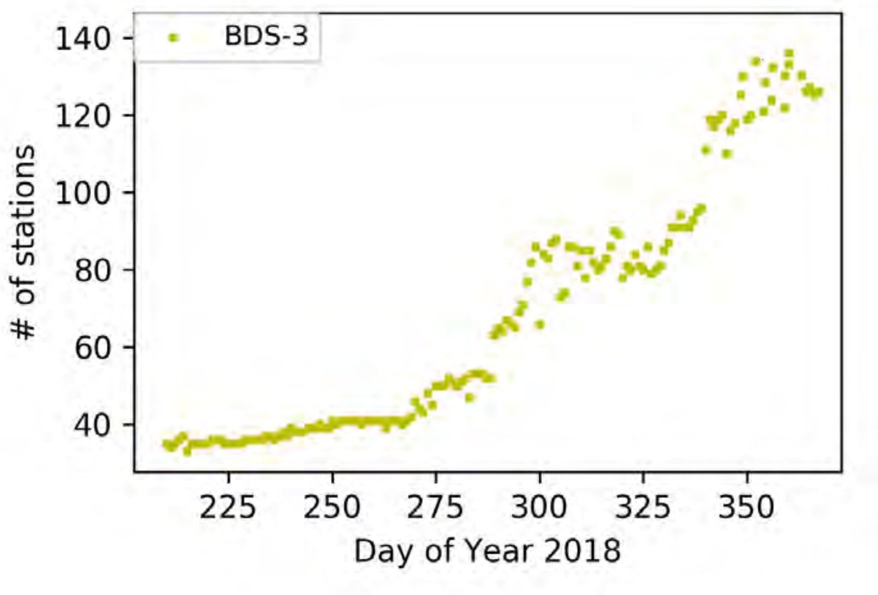

Figure 1: Time series of stations which can track BDS-3 satellites on dual-frequencies.

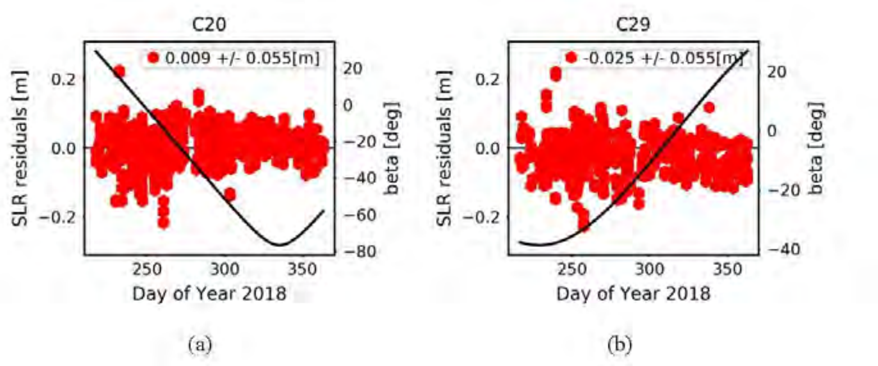

Figure 2: The SLR residuals series of (a) C20 and (b) C29.

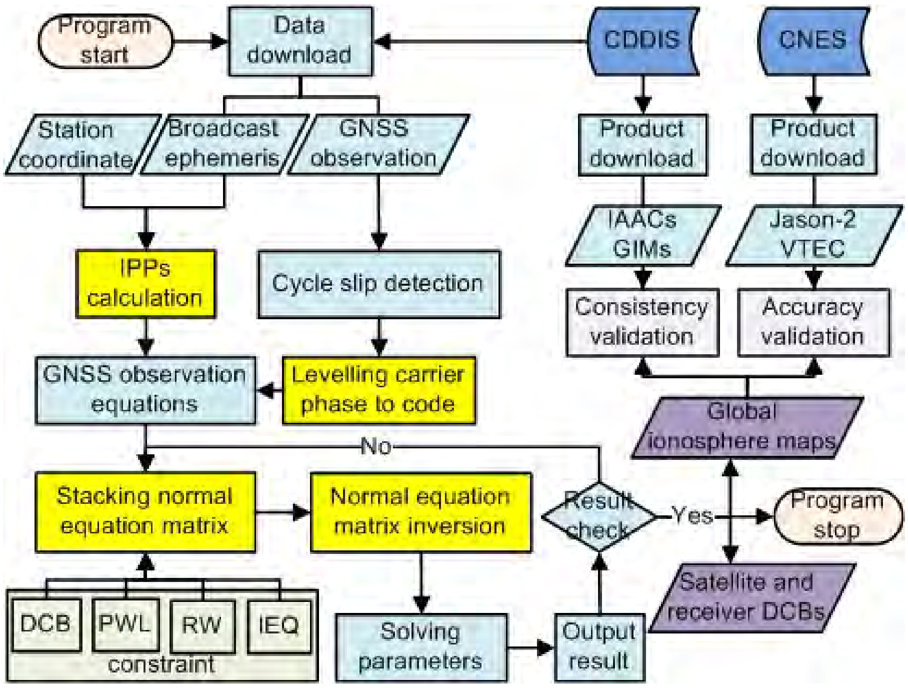

Figure 3: The GIMAS software flowchart.

4 Ionosphere Activities

In February 2016, the GNSS Research Center of Wuhan University was recognized as a new member of the IGS IAACs. WHU uses the spherical harmonic (SH) expansion model to map the global ionosphere in a solar-geomagnetic reference frame.

Currently, both the GPS and the GLONASS data are used with the data sampling rate of 300s. The maximum degree and order are 15, and the time resolution is 2h. Considering the continuity of the SH expansion coefficients between consecutive days, 28-h (one day and two hours before and after the current day) observations are used. An inequality-constrained least squares method was proposed to eliminate the non-physical negative values in the VTEC maps (Zhang et al. 2013). The global ionosphere mapping methodology was implemented by the GIMAS software that was developed at the GNSS Research Center of Wuhan University (Zhang and Zhan 2018).

The core modules of the GIMAS software were programmed by the C++ language and the automatic scripts were written by the Shell language. Figure 3 shows the flowchart of the software. The yellow rectangles represent the parallel computing with the OpenMP techniques.

For preprocessing, matrix stacking and matrix inversion stages, the computing time with different numbers of threads are shown in Figure 4. The total time for the daily GIM

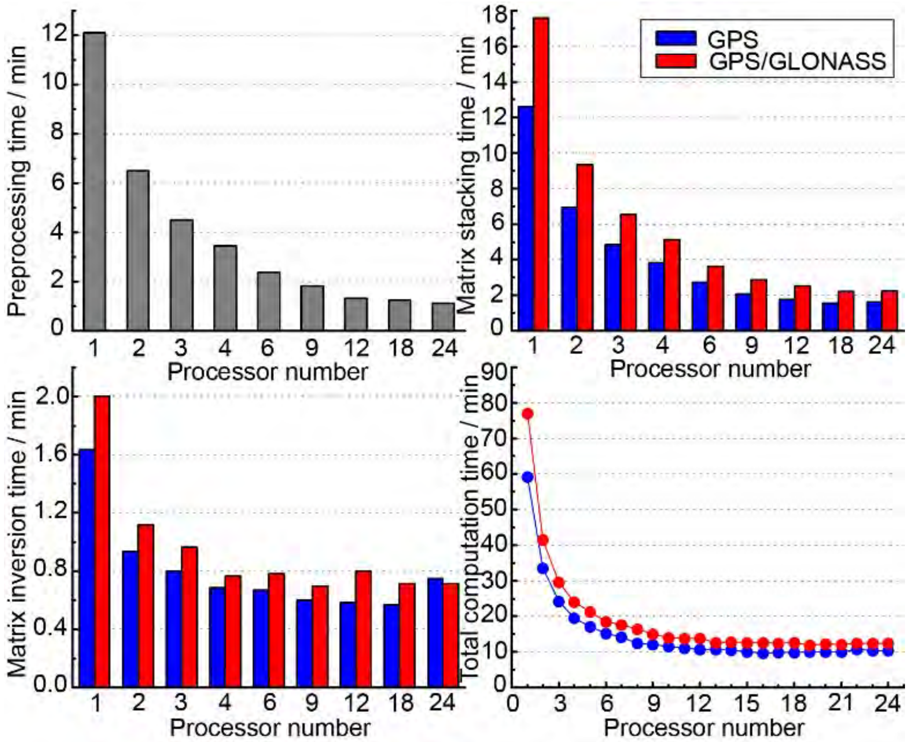

Figure 4: Parallel computing time for preprocessing, matrix stacking, and matrix inversion stages.

generation was only 10 to 13 minutes with 24 processors in our experiment.

With this new high-performance software, we preprocessed the GIM products from 1998 to 2018 within about two solar cycles. The root mean square of WHU GIMs relative to the IGS final GIMs were computed and compared with that of the other six IAACs GIMs, as shown in Figure 5. This assessment demonstrates that the GIM products at WHU are consistent with other IAACs GIMs and have high accuracy and reliability for the global ionosphere monitoring and analysis.

In addition, we specifically performed comprehensive analysis in terms of the data sampling rate, the time resolution, the spherical harmonic degree, and the relative constraint in the data processing methods of the SH expansion model on the global ionosphere mapping (Zhang and Zhan 2019). The results showed that the global VTEC map could be better represented in temporal and spatial domains with higher time resolution and higher spherical harmonic degree, especially at low latitude bands and in the southern hemisphere. The GIM precision improvement was about 10.91% for 1-h and about 15.15% for 0.5-h compared with the commonly used 2-h time resolution. The use of spherical harmonic degree 17 or 20 instead of 15 could improve the precision by 3.19% or 6.06%.

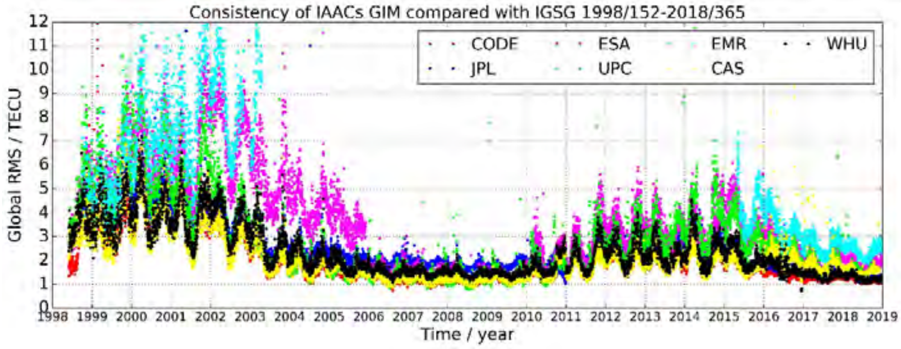

Figure 5: Parallel computing time for preprocessing, matrix stacking, and matrix inversion stages.

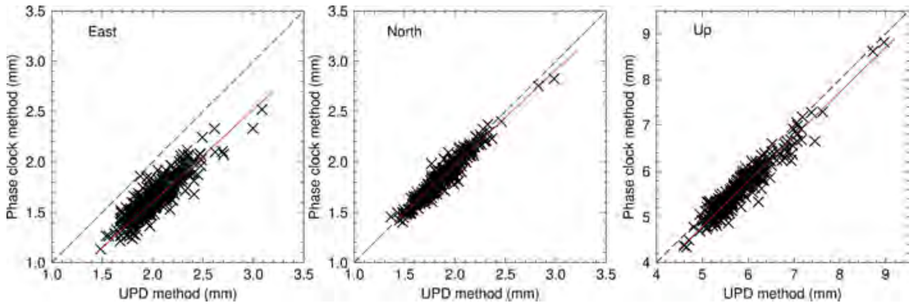

Figure 6: IGS station coordinates' RMS comparison of two types of PPP-AR solutions, i.e. the widely used UPD (uncalibrated phase delay) model and our newly developed phase clock/bias model (i.e. with our phase clock/bias products), with respect to the IGS weekly solutions in the year of 2016.

5 Phase Clock/Bias Activities

We have implemented the capability of producing phase clock/bias products routinely, which is intended to facilitate precise point positioning ambiguity resolution (PPP-AR) applications. The products will be provided with two components: 1) Bias-SINEX formatted GPS phase biases; 2) Ambiguity-fixed GPS satellite phase clocks. Along with those products, a companion software, called "PRIDE PPP-AR", will be released together. With our phase clock/bias products and software, users can conduct PPP-AR easily and focus on the result analysis. One example of data processing results is provided in Figure 6.

The products generation strategies are listed as follows:

1. Phase biases are obtained from the globally distributed IGS network stations;
2. PPP-AR is accomplished with the same network using the above phase biases;
3. Satellite clocks are re-estimated while keeping integer ambiguities plus phase biases

fixed to pre-determined values.

At the moment, these phase clock/bias products and the software package are under final validation. After the validation which is expected to be finished before April, 2019, the products from 2006 onwards will be publicly accessible from the WHU ftp (ftp://igs.gnsswhu.cn) and the software package can be downloaded from the homepage of PRIDELAB Group (`http://pride.whu.edu.cn`).

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EUREF Permanent Network Technical Report 2018

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1 Introduction

The International Association of Geodesy Regional Reference Frame sub-commission for Europe, EUREF, defines, maintains, and provides access to the European Terrestrial Reference System (ETRS89). This is done through the EUREF Permanent GNSS Network (EPN). EPN observation data as well as the precise coordinates and the zenith total delay (ZTD) parameters of all EPN stations are publicly available. The EPN cooperates closely with the International GNSS Service (IGS); EUREF members are e.g. involved in the IGS Governing Board, the IGS Reference Frame Working Group, the RINEX Working Group, the IGS Real-Time Working Group, the IGS Antenna Working Group, the IGS Troposphere Working Group, the IGS Infrastructure Committee, and the IGS Multi-GNSS Working Group and Multi-GNSS Extension Pilot Project (MGEX).

This paper provides an overview of the main changes in the EPN during the year 2018.

2 EPN Central Bureau

The EPN Central Bureau (CB, located at the Royal Observatory of Belgium - ROB) continued to monitor operationally EPN station performance in terms of data availability,

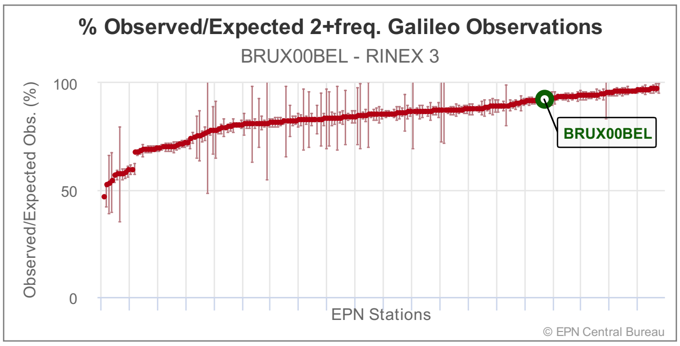

Figure 1: : Comparison of the completeness of dual frequency Galileo tracking (mean and standard deviation over the last 28 days) for each EPN station. More plots are available from http://epncb.eu/_networkdata/data_quality/comparison.php

correctness of metadata, and data quality. The data quality checks are partly based on G-Nut/Anubis developed by the Geodetic observatory Pecný, Czech Republic (Václavovic and Dousa, 2016), and complemented with in-house developed software. Based on a new reprocessing of all EPN data since 1996 using the latest version of Anubis, a first set of the metrics assessing the data quality important for EUREF applications has been derived. However, due to the increased complexity of the tracked satellite constellations and signals, the interpretation of the temporal variations in these data quality metrics, and the generation of operational alarms, remains challenging. A first analysis of the results showed already: a) the importance of using RINEX v3 (above RINEX v2), even if only processing GPS and GLONASS, b) the need to keep receiver firmware up to date, and c) the necessity to carefully select the tracked satellite constellations for receivers with a limited number of channels.

In addition, in order to easily detect stations that behave worse than other stations, new plots comparing the performance of the EPN stations have been issued. The example in Figure 1 shows a cluster of EPN stations with poorer Galileo tracking performance compared to the other EPN stations. All these results are available from the EPN CB web site, http://epncb.eu/ (Bruyninx et al. 2018).

The new "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^3G, available from https://gnss-metadata.eu) has reached in 2018 the level of maturity required for operational use in EUREF and consequently all EPN and EPN densification metadata were migrated to M^3G. To be compliant with the EU General Data Protection Regulation (GDPR), M^3G was extended in 2018 to request from where each person whose personal data is stored in M^3G (e.g. in the station site logs) a confirmation if his/her personal data can be made publicly available or not. If the person refuses, then his/her contact information is removed from all concerned site logs. Consequently, station managers are asked to manually revise and confirm all the contact information in all their site logs when updating a site log for the first time in M^3G. Together with the metadata of

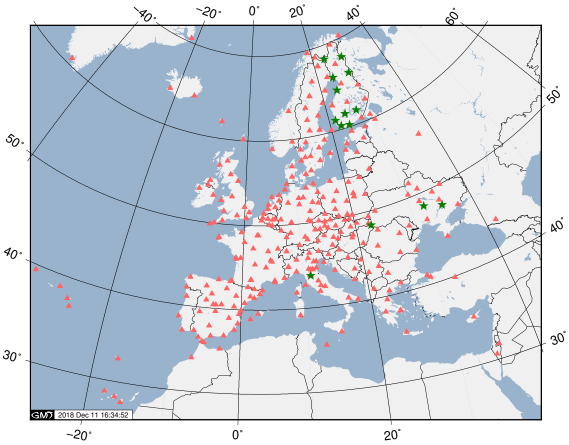

Figure 2: EPN tracking stations (status Dec. 2018). * indicates new stations included in the network in 2018.

the EPN densification network (see http://epncb.eu/_densification/), the EPN CB now maintains and distributes centrally the metadata of 1831 GNSS stations contributing to the EPN or EPN densification network.

3 Multi-GNSS Tracking Network

15 new stations were integrated in the EPN in 2018: ten in Finland, three in Ukraine, one in Italy, and one in Norway (see Figure 2). The total number of EPN stations is now 333. Twelve of the new stations are tracking GPS, GLONASS, and Galileo satellites (Table 1). Ten stations also have individual antenna calibrations. From nine of them, these individual antenna calibrations are for GPS and GLONASS signals only.

End of 2018, an impressive 48% of the EPN stations were providing BeiDou data and 63% Galileo data, which is an increase of 16% wrt to 2017 (Figure 3). About 208 (159 end of 2017) stations provided their data in the RINEX v3 format and 187 (135 end of 2017) of them were using the new RINEX v3 file naming conventions.

4 Data Products

4.1 Positions

The EPN Analysis Centres (ACs) operationally process GNSS observations collected at EPN stations. In 2018, all 16 ACs (Table 2) were providing final weekly and daily coordinate solutions of their subnetworks. Ten ACs were providing also rapid daily solutions,

Table 1: New stations included in the EPN in 2018 (stations indicated with * also contribute to the IGS) – G=GPS, R=GLONASS, E=Galileo, C=BeiDou, J=QZSS

9–char ID	Location	Tracked Satellite Systems	Real–time	Antenna Calibration
HETT00FIN	Hetta	GREC	Y	Indiv. robot (GR)
IGM200ITA	Firenze	GREC		Type
KRRS00UKR	Kropyvnytsky	GR		Type
KUU200FIN	Kuusamo	GREC	Y	Indiv. robot (GR)
METG00FIN*	Metsahovi	GREC	Y	Type
MIK300FIN	Mikkeli	GREC	Y	Indiv. robot (GR)
MKRS00UKR	Mukachevo	GR		Type
NYA200NOR*	Ny Alesund	GREJ	Y	Indiv. chamber (GRE)
OLK200FIN	Rauma	GREC	Y	Indiv. robot (GR)
ORIV00FIN	Orivesi	GREC	Y	Indiv. robot (GR)
PYHA00FIN	Pyhajoki	GREC	Y	Indiv. robot (GR)
SAVU00FIN	Savukoski	GREC	Y	Indiv. robot (GR)
TORN00FIN	Tornio	GREC	Y	Indiv. robot (GR)
TUO200FIN	Kaarina	GREC	Y	Indiv. robot (GR)
ZPRS00UKR	Zaporizhzhia	GR		Type

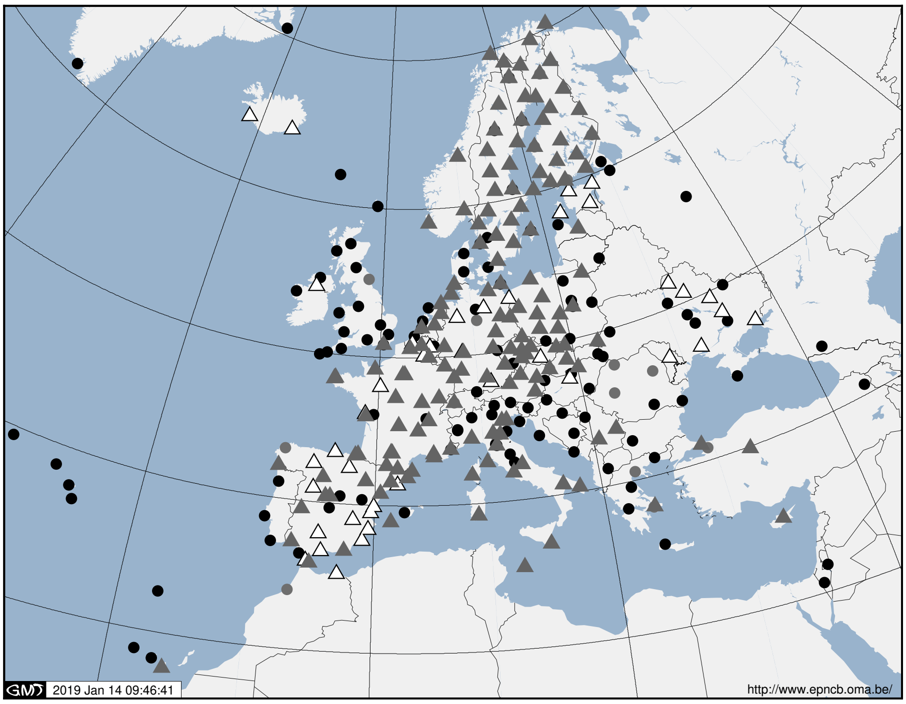

Figure 3: EPN tracking stations (status Dec. 2018). : ● tracking only GPS, ●: tracking GPS+GLONASS, △: tracking GPS+GLONASS+Galileo, and ▲: tracking GPS+GLONASS+Galileo+BeiDou.

and three ACs were providing ultra-rapid solutions. Details of the various combinations done by the analysis center coordinator (ACC) are given on http://www.epnacc.wat.edu.pl.

In 2018, the guidelines for the EPN Analysis Centres were reviewed and updated (the updated document is available at http://www.epncb.eu/_documentation/guidelines/guidelines_analysis_centres.pdf). Main changes concerned the troposphere modelling (the use of the Vienna Mapping Functions and the submission of troposphere horizontal gradients became mandatory) and the combination strategy of the AC solutions (moving from weekly to daily combinations). The description of the combination strategy was updated as well (http://www.epncb.eu/_productsservices/analysiscentres/CombinationStrategy.pdf).

LPT (swisstopo) is currently the only AC submitting a full multi-GNSS solution for the above mentioned solution types. Within the LPT analysis, 64% of the stations deliver daily RINEX v3, 60% hourly RINEX v3 (yearly increase since mid-2016 is about 7-10%). About 50% of the stations deliver Galileo observations.

Several ACs (BEK, BKG, IGE, NKG, ROB, UPA, WUT) submitted in 2018 a GPS-GLONASS-Galileo solution in addition to their operational product based only on GPS and GLONASS observations (see Table 2). In order to quantify the effect of the additional Galileo observations, the ACC combined one year of operational daily solutions and daily solutions where Galileo observations were used. The mean position differences between these solutions over weeks 2000-2027 (NKG GPS-GLONASS-Galileo solutions were only available from week 2023 on) did not exceed 1 mm in the horizontal components (for one station, NYA200NOR, the position difference was 3 mm), and 2 mm for the vertical component (for several stations the differences were between 2.0 and 3.5 mm). The operational daily combined EPN solutions were also compared to the daily combined solutions which are based on all GPS-GLONASS-Galileo AC solutions (BEK, BKG, IGE, LPT, NKG, ROB, UPA, WUT). Considering that not all the ACs participated in the Galileo analysis, the combined solution including Galileo covers only 95% of the EPN and many stations were processed by less than three ACs. The mean position differences over 12 weeks (2016-2027) between operational and the GPS-GLONASS-Galileo combined solutions for stations observing Galileo satellites (about 55% of EPN stations) are presented in Figure 4. The largest difference in the north component was noticed for station NYA200NOR (+3.2 mm), in the east component for station POTS00DEU (+2.1 mm), and for the vertical component for station LEON00ESP (+5.9 mm). Due to the (in comparison to GPS and GLONASS) smaller number of available satellites, the not yet completed enhancement to multi-GNSS on the stations and the small number of ACs using Galileo, the influence is rather small, especially when comparing it to the introduction of GLONASS in addition to GPS several years ago.

Following resolution 2 of the 2018 symposium in Amsterdam "ACs are encouraged to build their capabilities for processing Galileo observations". In parallel, the problems concerning

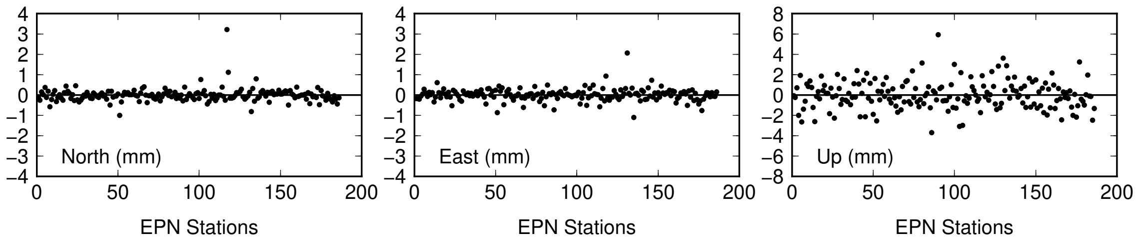

Figure 4: Mean position differences between operational EPN daily combined solutions and combined solutions created on the GPS-GLONASS-Galileo solutions of 8 ACs. Position differences are presented only for stations observing Galileo satellites.

antenna calibrations for multi-GNSS signals need to be tackled.

An evaluation of the impact of adding global stations to EPN solutions on station positions and on the reference frame alignment has also been started. Two EPN ACs (IGN, WUT) provided their solutions with global stations to the ACC (IGN includes global stations in its operational EPN solutions). IGE AC also provided a global solution, but did not include all EPN stations from its operational EPN subnetwork in the global solution. These solutions, together with CODE IGS global solution, and the remaining regional EPN AC solutions (excluding WUT operational solution), were combined for a period of eight weeks. In general, a good position agreement between the combined solution with global stations and the operational EPN solution (regional) was obtained, and the differences between them mostly came from the reference frame alignment. A more detailed analysis on this topic will be done in 2019.

4.2 Troposphere

Besides station coordinates, the 16 ACs also submit operationally Zenith Total Delay (ZTD) parameters and horizontal gradients in the SINEX_TRO format. The ZTDs and horizontal gradients are delivered with a sampling rate of one hour, on a weekly basis, but in daily files. As regard to the troposphere mapping function, from GPS week 1980 onwards all the ACs modelled the tropospheric delay using the VMF1 mapping function together with a priori hydrostatic delays from VMF1 grids (based on atmospheric pressure data from ECMWF[1]). The EUREF combined solution provides only ZTD estimates for stations processed by more than 3 ACs. Therefore in 2018, the ZTD combined estimates are available for 316 stations (compared to 310 in 2017).

Starting from GPS week 2002, three ACs namely BEK, BKG, and ROB started delivering, in addition to the legacy one, a multi-GNSS solution processing Galileo data along with GPS and GLONASS. Following the example of these three ACs, UPA started delivering multi-GNSS solutions in GPS week 2014, IGE in GPS week 2022 and NKG in GPS week

[1] European Centre for Medium-range Weather Forecasting

Table 2: EPN Analysis Centres characteristics: provided solutions (W – final weekly, D – final daily, R – rapid daily, U – ultra-rapid), the number of analyzed GNSS stations (in brackets: stations added in 2017), used software (GOA – GIPSY-OASIS, BSW – Bernese GNSS Software), used GNSS observations (G – GPS, R – GLONASS, E – Galileo, C – BeiDou)

AC	Analysis Centre Description	Solutions	# sites	Software	GNSS
ASI	Centro di Geodesia Spaziale G. Colombo, Italy	WDRU	66(13)	GOA 6.4	G
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	98(1)	BSW 5.2	GR
BEV	Federal Office of Metrology and Surveying, Austria	WD	111(10)	BSW 5.2	GR
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRU	118(1)	BSW 5.2	GR
COE	Center for Orbit Determination in Europe, Switzerland	WD	42(0)	BSW 5.3	GR
IGE	Instituto Geografico Nacional, Spain	WDR	88(2)	BSW 5.2	GR
IGN	Institut Gé'ographique National de L'information Geographique et Forestié're, France	WDR	63(0)	BSW 5.2	G
LPT	Federal Office of Topography swisstopo, Switzerland	WDRU	60(0)	BSW 5.3	GREC
MUT	Military University of Technology, Poland	WD	146(3)	GG 10.61	GR
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WD	98(11)	BSW 5.2	GR
RGA	Republic Geodetic Authority, Serbia	WD	55(0)	BSW 5.2	GR
ROB	Royal Observatory of Belgium, Belgium	WDR	100(3)	BSW 5.2	GR
SGO	BFKH Satellite Geodetic Observatory, Hungary	WDR	42(0)	BSW 5.2	GR
SUT	Slovak University of Technology, Slovakia	WD	59(3)	BSW 5.2	GR
UPA	University of Padova, Italy	WDR	61(4)	BSW 5.2	GR
WUT	Warsaw University of Technology, Poland	WDR	128(11)	BSW 5.2	GR

2023. These multi-GNSS solutions allowed the EPN tropospheric coordinator to assess the impact Galileo data have on the combination level. On weekly basis, the estimated impact of Galileo data in bias and standard deviation is at sub-millimeter level (average value computed considering all the EPN stations).

http://epncb.eu/_productsservices/sitezenithpathdelays/ shows the weekly mean bias (top) and the related standard deviation (bottom). They give insight into the agreement of the individual solutions with respect to the combined solution. The time series are based on EPN-Repro2 solutions (GPS week 834 until 1824) and on operational solutions afterwards. The EPN-Repro2 time series is a climate quality tropospheric dataset over Europe. This independent dataset, converted into Integrated Water Vapour, has been used by climate researchers to validate the regional distribution of water vapour from climate models.

The EPN multi-year tropospheric solution has been updated in March 2018 till GPS week 1981. For each EPN station, ZTD time series, ZTD monthly mean and comparison with radiosonde data (if collocated) plots are available at the EPN CB.

4.3 Reference Frame

To maintain the ETRS89, EUREF provides, each 15 weeks, an update of multi-year coordinates/velocities of the EPN stations in the latest ITRS/ETRS89 realizations. The coordinates/velocities of this 'EPN multi-year solution' (or EUREF Reference Frame product) are used as the reference coordinates/velocities for densifying the IGS14, ETRF2000 or ETRF2014 in Europe.

The consistency of the EPN multi-year solution wrt to the IGS14 and the weekly updates of the IGS multi-year solution is monitored at each update by comparing the position and velocity discontinuities applied and position/velocity estimates. For example, for GPS Week 2025, 522 position and velocities estimates are common to both solutions (C2025 for EPN and IGS18P44 for the IGS solution). 80% of the position differences are below 0.9, 1.2, and 3.7 mm on resp. the east, north and up components. In addition, there are no systematic and significant biases between both as the mean position differences are 0.1, -0.3, 0.4 mm on east, north and up components. For the velocities, 80% of the differences are below 0.2, 0.2, and 0.5 mm/yr on the east, north and up components. The mean differences are 0.01, -0.06, and 0.08 mm/yr on the east, north and up velocity components. Larger differences can mostly be explained by a significantly lower data availability in the IGS solution compared to the EPN.

The EPN multi-year product files (including the discontinuity list and associated residual position time series) are available from ftp://epncb.eu/pub/station/coord/EPN/. More details can be found in http://epncb.eu/_productsservices/coordinates/. The residual daily position time series and position time series in IGS14 and ETRF2014 are available online at http://epncb.eu/_productsservices/timeseries/. In addition, extended time series are updated every day by completing the EPN multi-year solution with the more recent EPN final and rapid daily combined solutions (Figure 5). Together with the quality check monitoring performed by the EPN CB, these quick updates allow to monitor the behavior of the EPN stations and to react promptly in case of problems.

4.4 Official National Coordinates

Since 2009, EUREF is collecting official national coordinates for the EPN sites as they are used in the countries for national reference frame densifications, mainly done using real-time positioning services. Those coordinates are routinely compared with those provided by the reference frame coordinator. Differences between the before mentioned coordinate sets at epoch of the national densification are published under http://epncb.eu/_productsservices/coordinates/img/ETRF_EPN_HOR.JPG (horizontal differences). In August, 2018, SGC Spain (Superior Geographical Commission of Spain) published a new realization of the ETRS89 for Spain using ETRF2000 (Epoch 1.1.2017). The results are based on the combination of almost 6 years of permanent network analysis including velocity estimation and are stemming from four different Spanish groups (Sobrino et al.

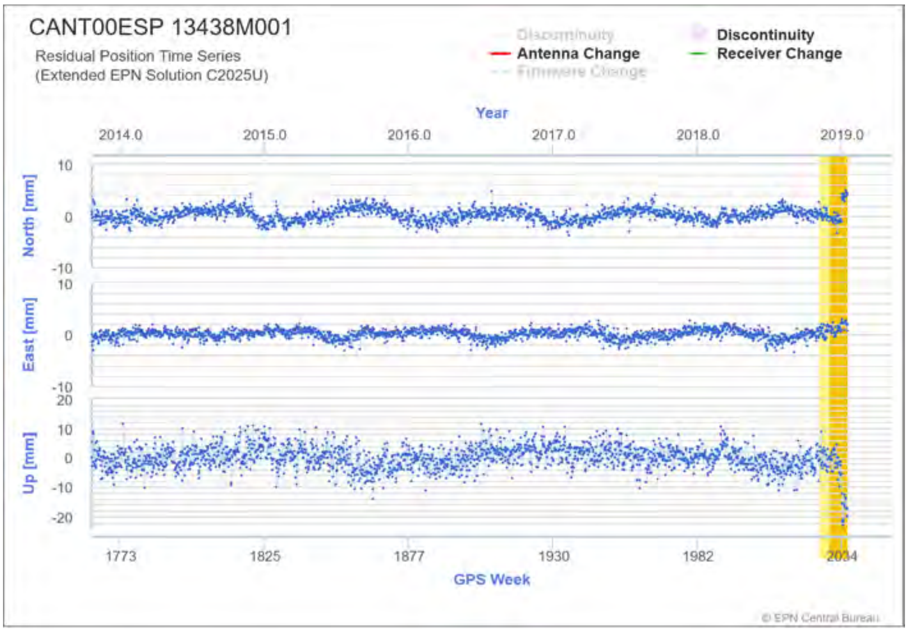

Figure 5: Extended residual position time series of the station CANT00ESP, the period highlighted in yellow shows the recent operational daily combined solutions. The period highlighted in orange, shows the rapid daily combined solutions.

2017). The differences of 31 Spanish EPN stations to the EPN cumulative solution C1995 (published on July 25, 2018) are on the 1-mm level for the horizontal components and 1-2 mm vertically. This excellent agreement proves impressively that national and European densifications can be realized on an extremely high consistency level.

5 Working Groups

5.1 EPN Densification

EPN Densification is a collaborative effort of 26 European GNSS Analysis Centres providing series of daily or weekly station position estimates of dense national and regional GNSS networks in SINEX format (Kenyeres et al. 2018). These are combined into one homogenized set of station positions and velocities using the CATREF software. Such a set is extremely valuable for cross-border and large-scale geodetic and geophysical applications. Prior to the combination of the solutions, the station meta-data, including station names, DOMES numbers, and position offset definitions were carefully cleaned and homogenized. During the combination, position outliers were identified and eliminated iteratively and the results were cross-checked for any remaining inconsistencies.

The state-of-the-art results cover the period from March 1999 to January 2017 (GPSweek

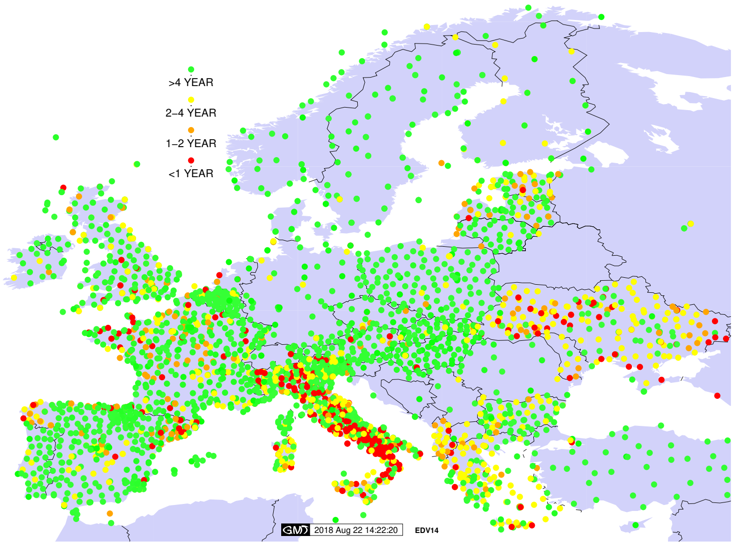

Figure 6: The distribution and length of the position SINEX series available for EPN Densification.

1000-1933) exclusively using inputs expressed in IGb08. The solution includes 31 networks with positions and velocities for 3192 stations, well covering Europe. The length of the individual station position time series is shown in Figure 6. The positions and velocities are expressed in ITRF2014 and ETRF2014 reference frames based on the Minimum Constraint approach using a selected set of ITRF2014 reference stations. The position alignment with the ITRF2014 is at the level of 1.5, 1.2, and 3.2 mm RMS for the East, North, Up components, respectively, while the velocity RMS values are 0.17, 0.14 and 0.38 mm/year for the east, north, up components, respectively. The high quality of the combined solution is also reflected by the 1.1, 1.1 and 3.5 mm weighted RMS values for the east, north, up components, respectively. Description of EPN Densification, station metadata and results are available in the EPN CB Densification webpages (`http://epncb.eu/_densification/`).

5.2 European Dense Velocities

The velocity estimates in ETRF2000, derived by currently 25 contributors, are the direct input to the generation process of a dense velocity field for Europe. In addition to results from GNSS permanent networks, densified solutions stemming from GNSS campaigns, InSAR or levelling are also included. In some countries, as e.g. in the Nordic countries, velocity models are already in use. They can also be integrated to indicate

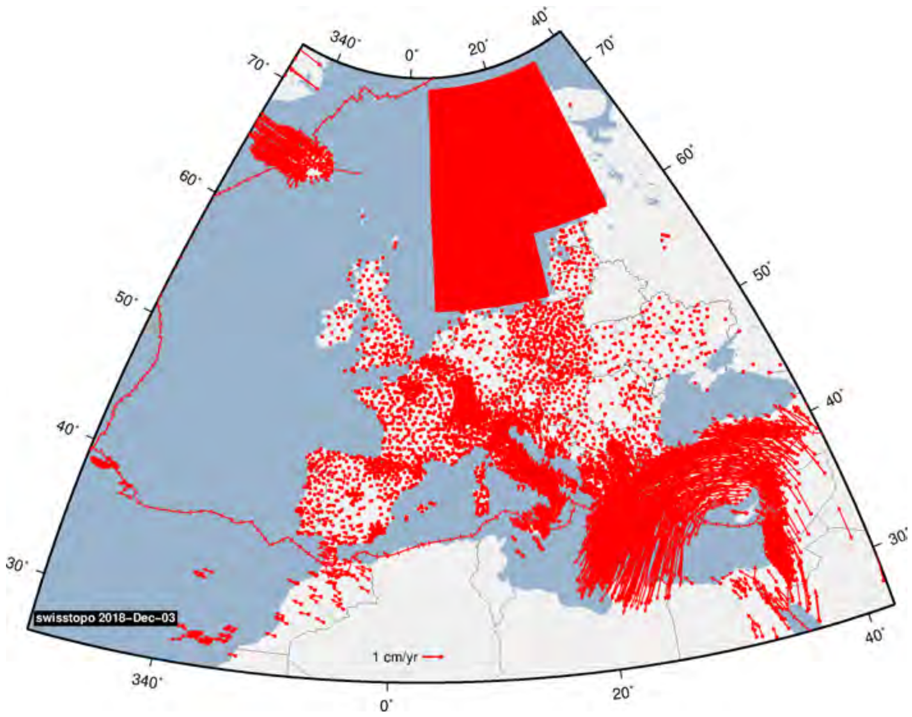

Figure 7: Horizontal velocities derived by the "European Dense Velocity" Working Group.

possible differences between modeled and observed velocities. Also the results of the EPN Densification Working Group are included. The alignment of the geodetic datum of each input is controlled by overlapping stations. About 5000 individual station velocities are available for Europe and more than 2000 sites are determined at least by two independent contributions. Several IGS/EPN stations are part of the majority of solutions. In average, the velocities agree for the horizontal component on a level of 0.2-0.3 mm/yr (standard deviation).

The web site (http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html) provides feedback to the contributors and shows differences with estimates of other contributors. Fig. 7 shows the horizontal velocity field in its current status. Whereas the horizontal velocities are on a level of clearly below 1 mm/yr for the stable part of the European plate, the velocities reach 3-4 mm/yr in Italy and 3-4 cm/yr in Greece and Turkey. The polygon covering the Nordic countries Norway, Sweden and Finland shows the NKG velocity grid.

6 Stream and Product Dissemination

End of 2018, 55% of the EPN stations provided real-time data with 183 mountpoints. The introduction of long mount-point names on the three EPN broadcasters has been almost completed. Some stations like IGEO00MDA and WSRT00NLD resumed real-time data streaming after a longer absence. Almost all varieties of RTCM messages (2.x to 3.3) are available from the EPN broadcasters. The number of streams supporting the RTCM 3.3 Multi Signal Messages (MSM) has been growing. However, the majority of the data streams (approx. 95) are providing the "legacy" messages 1004 (GPS) and 1012 (GLONASS). It should be noted that one third of the data streams providing MSM message are delivering MSM4 (message type 1074 etc.) or MSM5 (message type 1075 etc.), the other 2 thirds MSM7 (1077 etc.).

The monitoring of the three EPN broadcasters at the EPN CB covers mainly two sections: the availability of data and product streams (http://epncb.eu/_networkdata/data_access/real_time/status.php) and the meta-data monitoring (http://epncb.eu/_networkdata/data_access/real_time/metadata_monitoring.php). The latter examines a large variety of parameters, from latency over equipment to message types and satellite constellations. There are stations-dependent as well as broadcaster-dependent outputs implemented. Following the discussion within the EPN GB on how to overcome the discrepancies between the actual content of the data streams and the information given in the source-table, the NtripChecker tool provided by André Hauschild from DLR (Hauschild 2018) has been tested at the EPN broadcasters. A usage on a regular basis, however, has not been finally decided.

Real-time network processing for satellite orbits and clocks suffers very much from reliable and continuous data availability, i.e. low latency, no interruptions etc. Figure 8 shows an example of the drastically improvement for EPN station BRST00FRA after changing the receiver.

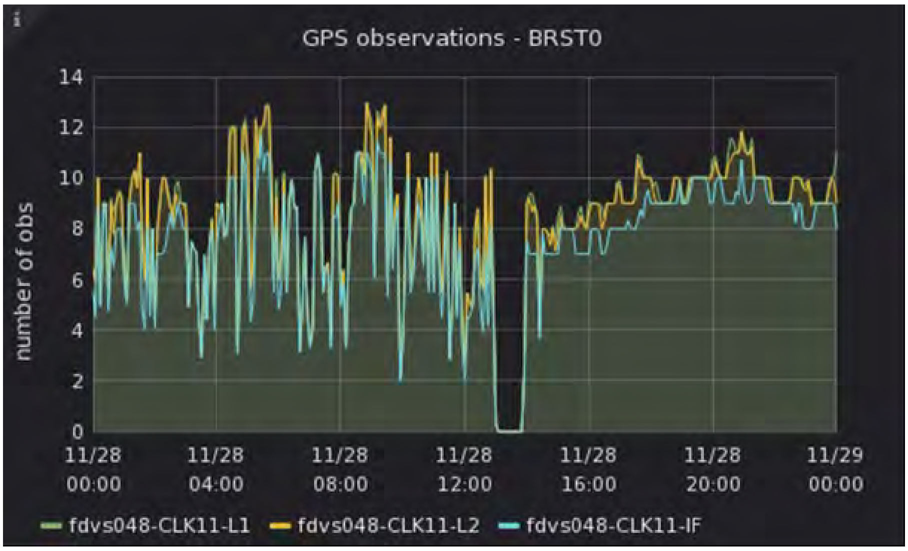

Figure 8: Improvement of real-time data performance of EPN station BRST00FRA after receiver change on 28-Nov-2018. The number of used observation for processing correction stream CLK11 of BKG became much more stable.

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SIRGAS Regional Network Associate Analysis Centre Technical Report 2018

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1 Introduction

A network of continuously operating GNSS stations distributed over Latin America gives the present realisation of SIRGAS (Cioce et al. 2018). This network is processed on a weekly basis to generate instantaneous weekly station positions aligned to the ITRF and multi-year (cumulative) reference frame solutions (Bruini et al. 2012). The instantaneous weekly positions are especially useful when strong earthquakes cause co-seismic displacements or strong relaxation motions at the SIRGAS stations disabling the use of previous coordinates (e.g. Sánchez et al. 2013; Sánchez and Drewes 2016; Montecino et al. 2017). The multi-year solutions provide the most accurate and up-to-date SIRGAS station positions and velocities. They are used for the realisation and maintenance of the SIRGAS reference frame between two releases of the ITRF. While a new ITRF release is published more or less every five years, the SIRGAS reference frame multi-year solutions are updated every one or two years (see e.g. Sánchez 2017; Sánchez and Drewes 2016; Sánchez et al. 2016; Sánchez and Seitz 2011).

2 SIRGAS reference network

The SIRGAS continuously operating network is at present composed of 407 stations (Fig. 1), 22 of which were integrated in 2018. 83% of the SIRGAS stations tracks GLONASS, 22% Galileo and 14% Beidou. The operational performance of the SIRGAS network is based on the contribution of more than 50 organisations, which install and operate the permanent stations and voluntarily provide the tracking data for the weekly processing of the network. Since the national reference frames in Latin America are based on GNSS continuously operating stations and these stations should be consistently integrated into the continental reference frame, the SIRGAS reference network comprises (Fig. 2):

- One core network (SIRGAS-C), primary densification of ITRF in Latin America, with a good continental coverage and stabile site locations to ensure high long-term stability of the reference frame.
- National reference networks (SIRGAS-N) improving the densification of the core network and providing accessibility to the reference frame at national and local levels. Both, the core network and the national networks satisfy the same characteristics and quality; and each station is processed by three analysis centres.

3 SIRGAS processing centres

The SIRGAS-C network is processed by DGFI-TUM as IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS, see e.g. Sánchez (2018a)). The SIRGAS-N networks are computed by the SIRGAS Local Processing Centres, which operate under the responsibility of national Latin American organisations. At present, the SIRGAS Local Processing Centres are:

- CEPGE: Centro de Procesamiento de Datos GNSS del Ecuador, Instituto Geográfico Militar (Ecuador)
- CNPDG-UNA: Centro Nacional de Procesamiento de Datos GNSS, Universidad Nacional (Costa Rica), see Moya-Zamora et al. (2018).
- CPAGS-LUZ: Centro de Procesamiento y Análisis GNSS SIRGAS de la Universidad del Zulia (Venezuela), see Cioce et al. (2018).
- IBGE: Instituto Brasileiro de Geografia e Estatistica (Brazil), see Costa et al. (2018).
- IGAC: Instituto Geográfico Agustín Codazzi (Colombia)
- IGM-Cl: Instituto Geográfico Militar (Chile), see Parra (2017).
- IGN-Ar: Instituto Geográfico Nacional (Argentina), see Gómez et al. (2018).
- INEGI: Instituto Nacional de Estadística y Geografía (México), see Gasca (2018).
- SGM: Servicio Geográfico Militar (Uruguay), see Caubarrère (2018).

These processing centres deliver loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. The individual solutions are combined

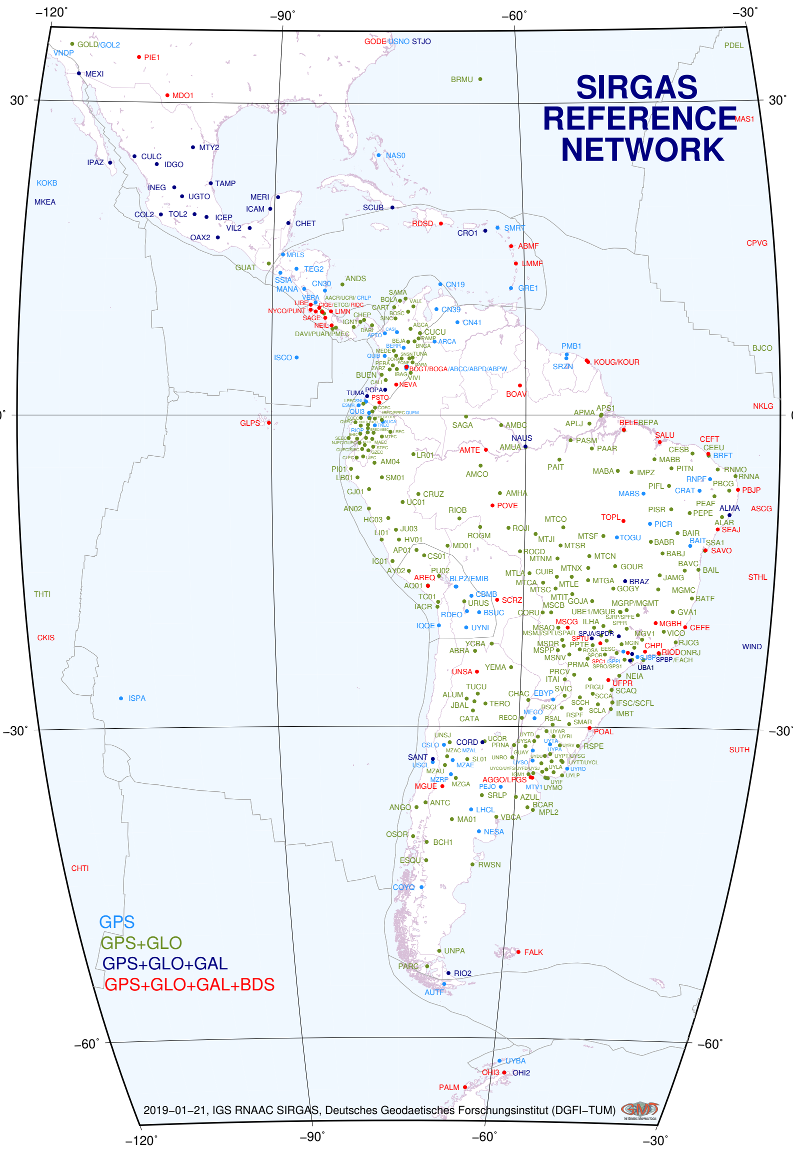

Figure 1: SIRGAS reference network as of Jan 2019 (source www.sirgas.org).

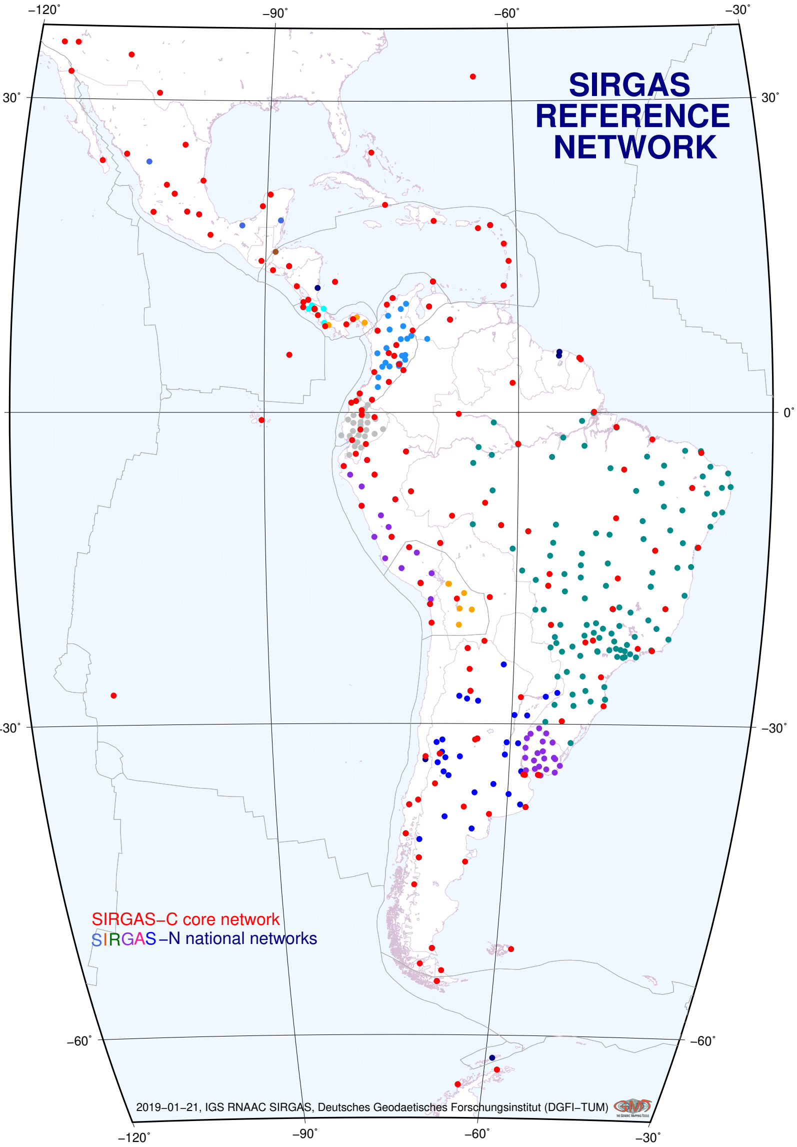

Figure 2: SIRGAS-C core and SIRGAS-N national reference networks (as of Jan 2019, source www.sirgas.org).

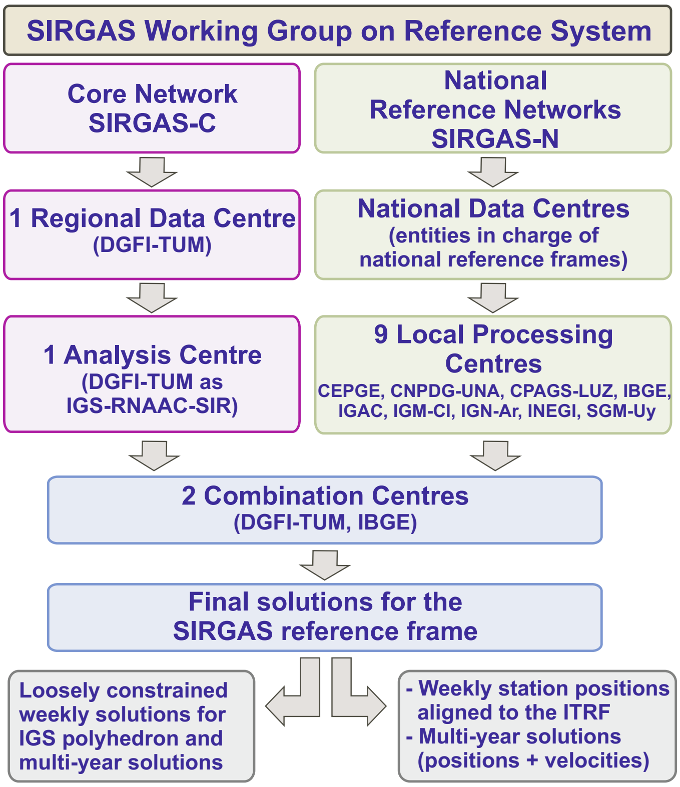

Figure 3: Data flow within the SIRGAS reference frame analysis (source `www.sirgas.org`).

by the SIRGAS Combination Centres currently operated by DGFI-TUM (Sánchez et al. 2012) and IBGE (Costa et al. 2012). Data flow and relationship between national operational/data centres, processing centres, and combination centres is coordinated by the SIRGAS Working Group I (SIRGAS-WGI: Reference System), see Fig. 3.

4 Routine processing of the SIRGAS reference frame

The SIRGAS processing centres follow unified standards for the computation of the loosely constrained solutions. These standards are generally based on the conventions outlined by the IERS (International Earth Rotation and Reference Systems Service, Petit and Luzum (2010)) and the GNSS-specific guidelines defined by the IGS (Johnston et al. 2017); with the exception that in the individual SIRGAS solutions the satellite orbits and clocks as well as the Earth orientation parameters (EOP) are fixed to the final weekly IGS values (SIRGAS does not compute these parameters), and positions for all stations are constrained to ±1 m (to generate the loosely constrained solutions in SINEX format). INEGI (Mexico) and IGN-Ar (Argentina) employ the software GAMIT/GLOBK (Herring

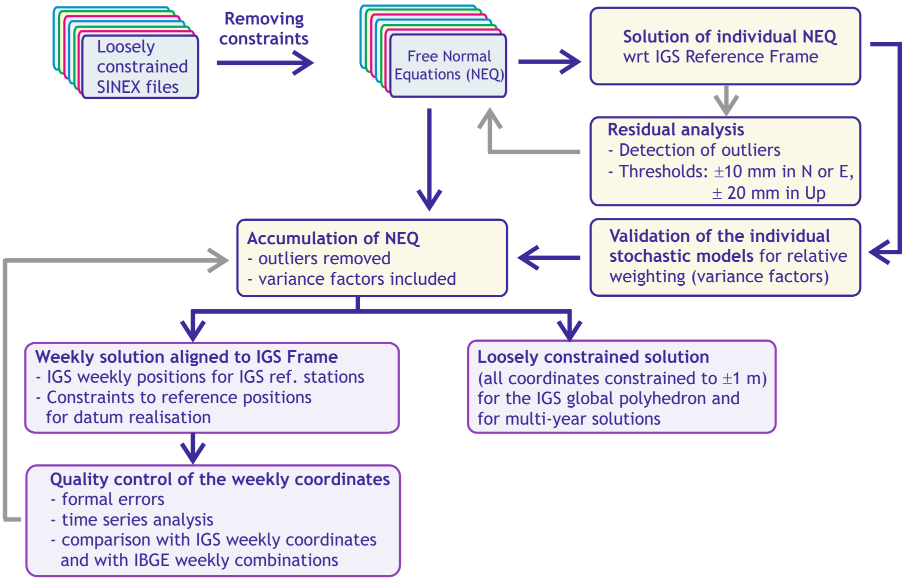

Figure 4: DGFI-TUM analysis strategy for the combination of the individual solutions delivered by the SIRGAS processing centres (grey arrows represent iterative cycles).

et al. 2010); the other local processing centres use the Bernese GNSS Software V. 5.2 (Dach et al. 2015).

For the combination, the constraints included in the individual solutions are removed and the sub-networks are individually aligned to the IGS reference frame using a set of 24 IGS14 reference stations. Station positions obtained for each sub-network are compared to each other to identify possible outliers. Stations with large residuals (more than ±10 mm in the N-E component, and more than ±20 mm in the Up component) are removed from the normal equations. Scaling factors for relative weighting of the individual solutions are inferred from the variances obtained after the alignment of the individual sub-networks to the IGS14. The datum realisation in the final SIRGAS combination is achieved through the IGS weekly coordinates (igsyyPwwww.snx) of the IGS14 reference stations. Fig. 4 summarises the DGFI-TUM analysis strategy for the combination of the individual solutions (Sánchez et al. 2012). Normal equations are added and solved using the Bernese GNSS software Version 5.2 (Dach et al. 2015).

5 SIRGAS coordinates

Following products are generated within the routine processing of the SIRGAS-CON network:

- Loosely constrained weekly solutions in SINEX format (or normal equations) for later computations, i.e. combination within the IGS polyhedron, determination of multi-year solutions, etc.

- Weekly station positions aligned to the IGS reference frame, as the GNSS satellite orbits used in the SIRGAS processing refer to that frame. These coordinates serve as reference values for surveying in Latin America.
- Multi-year solutions (coordinates + velocities) for those applications requiring time depending positioning.

The SIRGAS-CON products are made available by the IGS RNAAC SIRGAS (DGFI-TUM) at www.sirgas.org and ftp.sirgas.org (Sánchez 2018b).

6 Reprocessing of the SIRGAS reference frame in ITRF2014

The SIRGAS products refer to the IGS reference frame valid at the time when the GNSS data are routinely processed. A first reprocessing campaign of the SIRGAS reference network was performed in 2010 in order to make available SIRGAS coordinates based on absolute corrections for the GPS antenna phase centre variations and referring to IGS05 reference frame (Seemüller et al. 2010). A reprocessing referring to the IGS08/IGb08 frame was not undertaken. In this way, the SIRGAS weekly solutions presently refer to:

- IGS05: from the GPS week 1042 (Jan 2, 2000) until week 1631 (Apr 16, 2011)
- IGS08: from week 1632 (Apr 17, 2011) to week 1708 (Oct 6, 2012)
- IGb08: from week 1709 (Oct 7, 2012) to week 1933 (Jan 28, 2017)
- IGS14: since the GPS week 1934 (Jan 29, 2017).

In order to increase the reliability and long-term stability of the SIRGAS reference frame, the SIRGAS efforts concentrate on a new reprocessing of the reference network based on the ITRF2014 (IGS14). The SIRGAS-WGI performed an inventory of availability and quality of the existing RINEX files and updated or corrected the station log files according to the IGS standards for old GPS antennas and receivers. Based on the existing SIRGAS time series, the performance of each station was evaluated to decide if it should be included in the reprocessing. In fact, since the establishment of SIRGAS in 1993, 533 continuously operating GNSS stations have been used for the realisation of SIRGAS, being 126 of them presently decommissioned. From the 126 decommissioned stations, 40 offer less than two years of observations. Consequently, they were removed from the reference frame and will not be included in the reprocessing.

In November 2018, DGFI-TUM (as IGS RNAAC SIRGAS) started a pilot reprocessing of the SIRGAS reference network using the IGS14-based orbits and clocks published by JPL at ftp://sideshow.jpl.nasa.gov/pub/jpligsac (see IGSMAIL 7637). This reprocessing does not include SIRGAS regional stations only, but also a global distribution of IGS

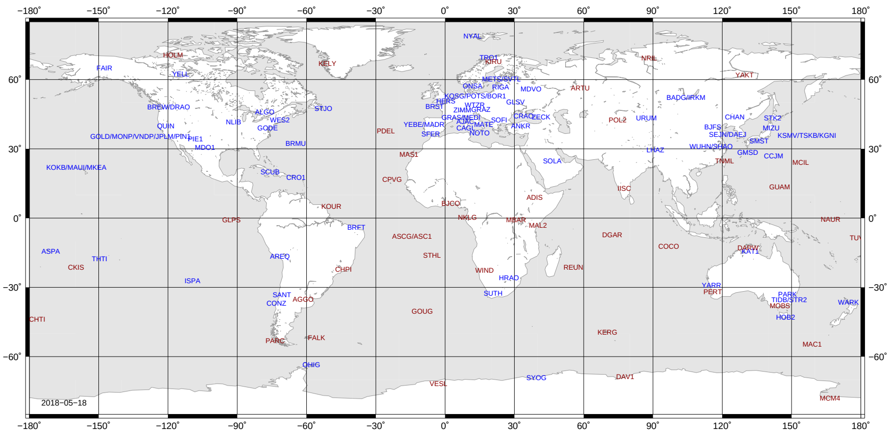

Figure 5: IGS stations included in the IGS14-based reprocessing of the SIRGAS reference network. Blue labels represent GNSS stations co-located with VLBI or SLR stations. Red labels represent additional IGS14 reference stations to improve the station distribution.

stations co-located with VLBI and SLR (Fig. 5). The main objective of this experiment is to increase the reliability of the realisation of the geocentric datum in the regional network by combining the SIRGAS GNSS solutions with VLBI- and SLR-based global solutions. First results are expected by middle 2019.

7 Twenty-five years of SIRGAS

SIRGAS was created in 1993 during the International Conference for the Definition of a South American Geocentric Reference System held in Asuncion, Paraguay. This conference was promoted and supported by the International Association of Geodesy (IAG), the Pan-American Institute for Geography and History (PAIGH), and the US Defence Mapping Agency (DMA), today National Geospatial-Intelligence Agency (NGA). The original acronym of SIRGAS (Geocentric Reference System for South America) was changed in 2001 to Geocentric Reference System for the Americas, since the United Nations Organisation, through its 7th Cartographic Conference for The Americas (New York, January 22 – 27, 2001), recommend to adopt SIRGAS as official reference system in all American countries. Today, SIRGAS forms part of the Sub-commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of IAG and corresponds to a Working Group of the Cartography Commission of PAIGH. The administrative issues (Fig. 6) are managed by an Executive Committee, which depends on the Directing Council, main body of the organisation. The official policies and recommendations of SIRGAS are approved and given by the Directing Council. Since this Council is composed by one representative of each member country, one of IAG and one of PAIGH, it is also in charge of communicating the SIRGAS recommendations to the national bodies responsible for the local geodetic reference systems. The scientific and technical activities are coordinated by three Working Groups in close cooperation with the Scientific Council and the representatives of IAG and PAIGH. This section summarizes the milestones related to the geocentric reference frame SIRGAS in these 25 years.

- 1993: International Conference for the Definition of a South American Geocentric Reference System, foundation of SIRGAS, and establishment of the SIRGAS Working Groups I (Reference System) and II (Geocentric Datum).
- 1995: First GPS campaign for the realisation of SIRGAS (58 stations over South America, continuous GPS positioning along ten days, see Fig. 7), SIRGAS (1997).
- 1996: Establishment of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS) at DGFI (Deutsches Geodätisches Forschungsinstitut, Munich, Germany), Drewes et al. (1997); Seemueller and Drewes (1998).
- 1997: Release of the first SIRGAS reference frame solution: SIRGAS95 (ITRF94, epoch 1995.4), SIRGAS (1997).
- 2000: Second GPS campaign for SIRGAS. The SIRGAS95 reference network was re-measured and extended to the Caribbean and Central and North America. SIRGAS2000 included 184 GPS stations (Fig. 7) and was continuously measured during ten days (Luz et al. 2002; Drewes et al. 2005).
- 2001: Recommendation of the 7th UN regional cartographic conference for the Americas to adopt SIRGAS as official reference system in all American countries.
- 2001: Change of the SIRGAS acronym from "Geocentric Reference System for South America" to "Geocentric Reference System for the Americas".
- 2002: Release of the SIRGAS reference frame solution SIRGAS2000 (ITRF2000, epoch 2000.4), Drewes et al. (2005).
- 2002: Release of the first SIRGAS multi-year solution (31 stations, ITRF97, epoch 2000.4, Seemüller et al. (2002). Until now, 17 SIRGAS multi-year solutions have been released (Fig. 8); see Sánchez et al. (2018).
- 2003: Release of the first deformation model for SIRGAS: VEMOS (Velocity Model for SIRGAS, Drewes et al. (2005). VEMOS is used to predict station position changes through time, when the station velocities are unknown. Until now, four VEMOS solutions have been released (Fig. 9).
- 2004: Extension of the SIRGAS technical and organisational activities to Central America and Mexico (Sánchez and Brunini 2009).
- 2008: Establishment of the first SIRGAS processing centres under the responsibility of South American organisations (IBGE-Brazil, Da Silva et al. (2008); IGAC-

Colombia, De La Rosa et al. (2008); UNLP/CIMA-Argentina, Natali et al. (2009); Mateo et al. (2010)). Until August 2008, DGFI-TUM (as IGS RNAAC SIRGAS) processed the entire SIRGAS reference network in one block. With the establishment of processing centres in South America, DGFI-TUM became responsible for (i) processing the SIRGAS-C core network, (ii) combining the core network with the national reference networks, (iii) ensuring that the SIRGAS processing strategy meets the IERS standards and IGS guidelines, and (iv) developing strategies to guarantee the reliability of the reference frame over time (this includes estimation of the reference frame kinematics, evaluation of the seismic impacts on the reference frame, and modelling crustal deformation in the SIRGAS region).

- 2008: Routine generation of regional ionospheric maps (vTEC) based on the SIRGAS GNSS reference stations (Bruini et al. 2018).
- 2010: Establishment of five new processing centres in Latin America: CEPGE-Ecuador (Cisneros et al. 2010), CPAGS-LUZ-Venezuela (Cioce et al. 2010), SGM-Uruguay (Suárez 2011), IGN-Argentina (Cimbaro and Piñón 2010) and INEGI-Mexico (González 2010).
- 2013: Establishment of a new SIRGAS processing centre: IGM-Chile (Parra 2013).
- 2014: Establishment of a new SIRGAS processing centre: CNPDG-UNA-Costa Rica (Moya et al. 2014).
- 2014: Establishment of real-time GNSS positioning services in different SIRGAS countries.
- 2014: Routine processing of GLONASS observations.

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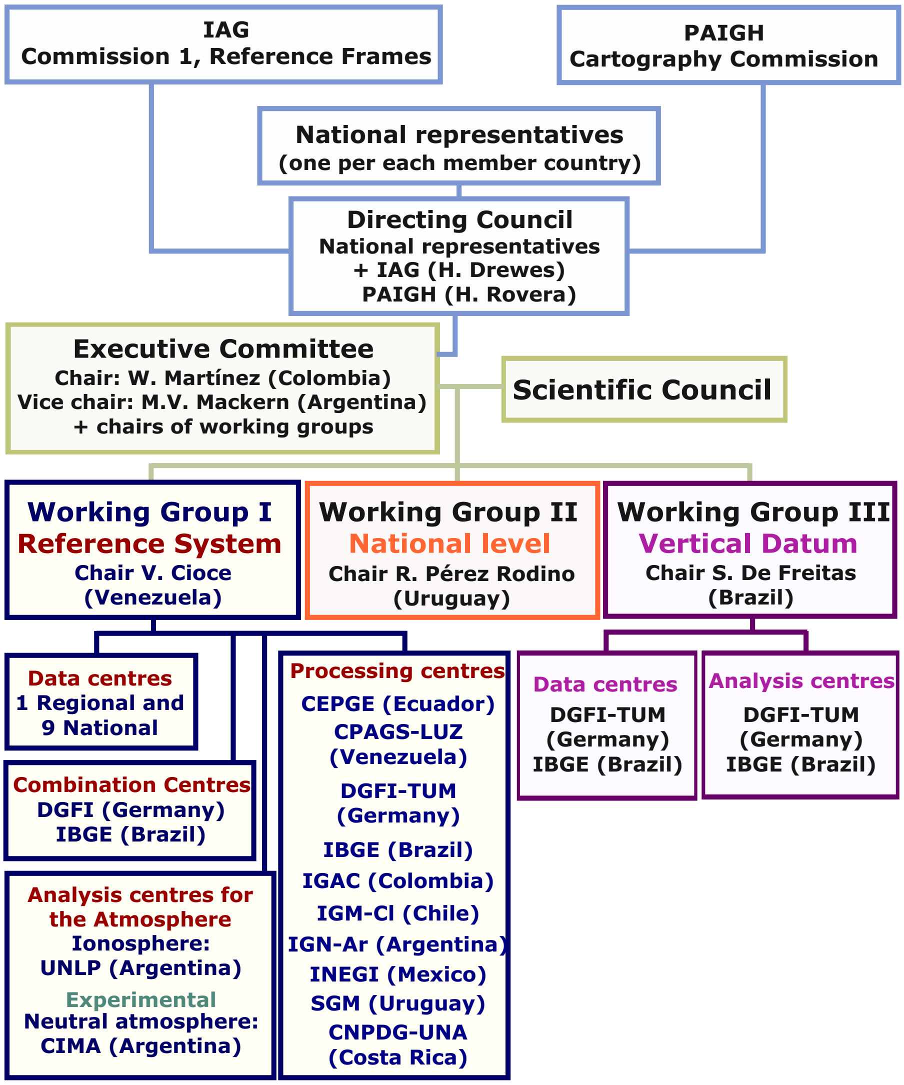

Figure 6: Operational structure of SIRGAS (source www.sirgas.org).

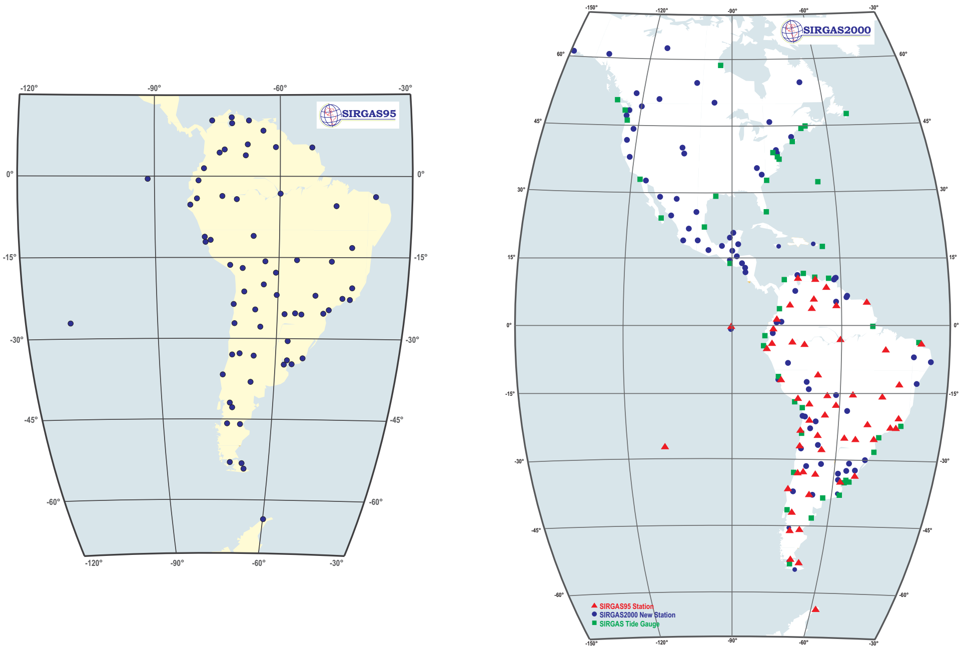

Figure 7: SIRGAS realisations based on episodic GPS campaigns: SIRGAS95 (left, SIRGAS (1997)) and SIRGAS2000 (right, Drewes et al. (2005)).

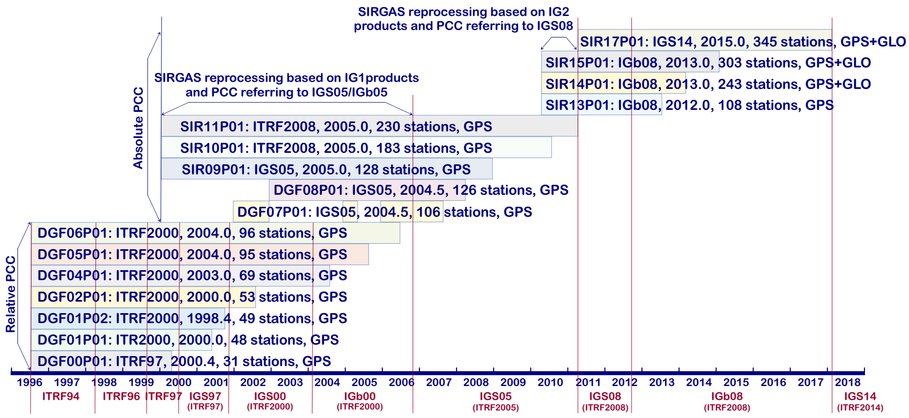

Figure 8: Multi-year solutions computed for the SIRGAS reference frame since 2002. Coloured bars represent the time-span covered by each solution. The reference epoch for the station positions, the number of stations, the considered observations (GPS and GLONASS (GLO)) as well as the reference frame (ITRFyy/IGSyy) are shown. The figure also displays when relative or absolute corrections to the antenna phase centre variations (PCC) were applied, and which weekly solutions were reprocessed following the IGS reprocessing campaigns IG1 and IG2 (Sánchez et al. 2018).

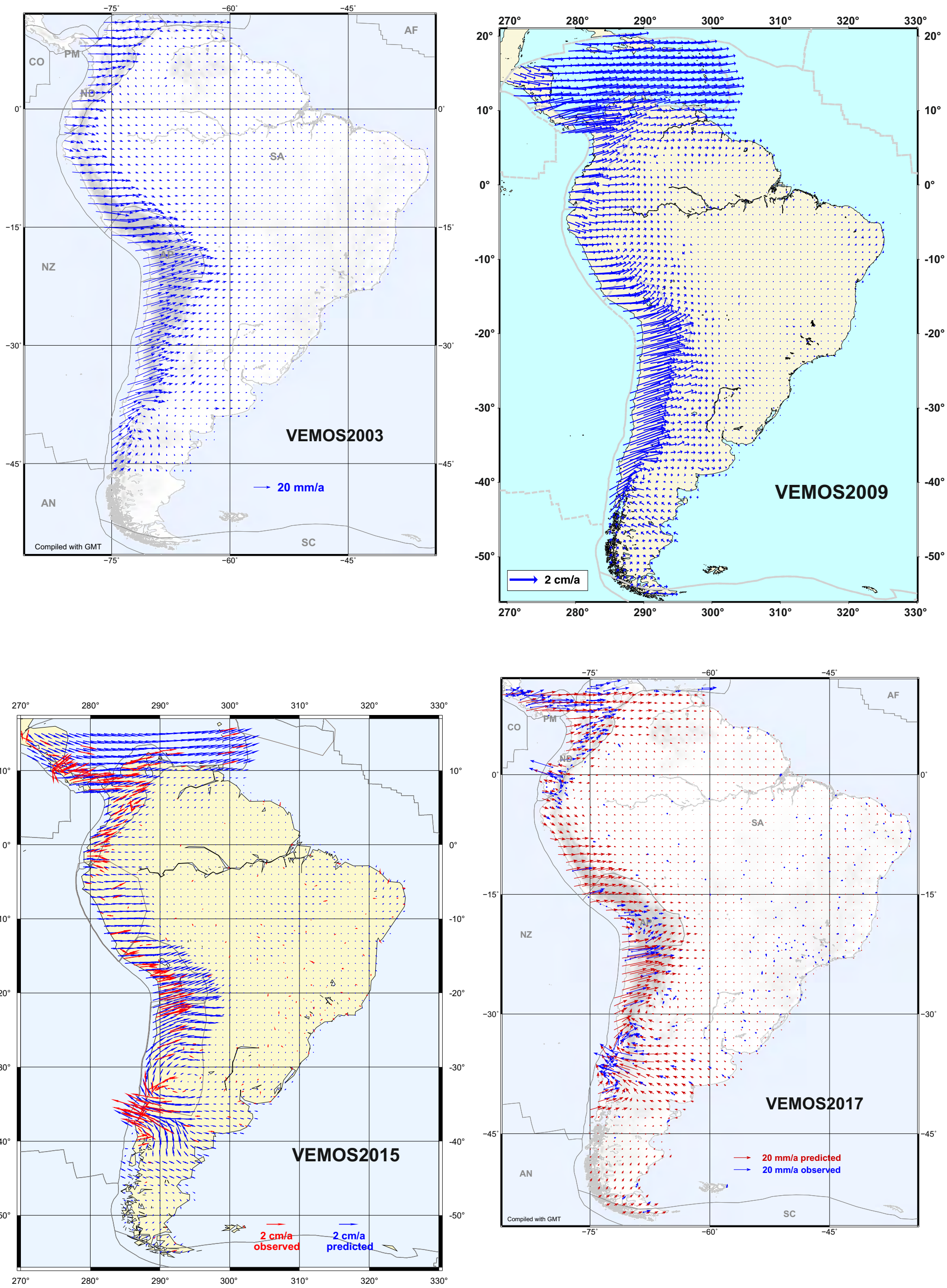

Figure 9: VEMOS surface deformation models relative to the South American plate: VEMOS2003 valid from 1995.4 to 2002.0 (Drewes and Heidbach, 2005), VEMOS2009 valid from 2000.0 to 2009.6 (Drewes and Heidbach, 2012); VEMOS2015 valid from 2012.2 to 2015.2 (Sánchez and Drewes, 2016); VEMOS2017 valid from 2014.0 to 2017.1 (Drewes and Sánchez, 2017).

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Part III

Data Centers

Infrastructure Committee Technical Report 2018

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1 Introduction

The IGS Infrastructure Committee (IC) is a permanent body established to ensure that the data requirements for the highest quality GNSS products are fully satisfied while also anticipating future needs and evolving circumstances. Its principal objective is to assure that the IGS infrastructure components that collect and distribute the IGS tracking data and information are sustained to meet the needs of principal users, in particular the IGS analysis centers, fundamental product coordinators, pilot projects, and working groups.

The IC fulfills this objective by coordinating and overseeing facets of the IGS organization involved in the collection and distribution of GNSS observational data and information, including network stations and their configurations (instrumentation, monumentation, communications, etc), and data flow.

The IC establishes policies and guidelines, where appropriate, working in close collaboration with all IGS components, as well as with the various agencies that operate GNSS tracking networks. The IC interacts with International Association of Geodesy (IAG) sister services and projects – including the International Earth Rotation and Reference Systems Service (IERS) and the Global Geodetic Observing System (GGOS) – and with other external groups (such as the RTCM) to synchronize with the global, multi-technique geodetic infrastructure.

- Carine Bruyninx (ROB)
- Lou Estey (UNAVCO)
- Nicholas Brown (GA)
- Nacho Romero – Chairman – (ESOC)
- Brian Donahue (NRCan)

- Wolfgang Soehne (BKG)

Ex–officio Members:

- Steve Fisher – Central Bureau
- David Maggert – Network Coordinator
- Michael Moore – Analysis Coordinator
- Tom Herring – Analysis Coordinator
- Axel Ruelke – Real time Working Group Chair
- Bruno Garayt – Reference Frame Coordinator
- Carey Noll – Data Center Working Group Chair
- Michael Coleman – Clock Products Coordinator

2 Summary of Activities in 2018

Over 2018 the IC has supported the Network Coordinator on answering questions from IGS product and data users, plus;

- Added 14 stations to the Station Network,
- removed 12 long-standing absent stations from the network,
- continued to improve and refine the combined RINEX 3 multi-GNSS mixed navigation file at CDDIS: **BRDC00IGS**

The IC has participated in the 2018 Wuhan IGS Workshop by coordinating together with the Data Center WG and the RINEX WG one plenary session with 6 very interesting presentations and a poster session with 11 posters. Additionally the IC supported the IGS Working Groups and product coordinators as needed in terms of planning station contacts, format developments, etc.

The RINEX 3 data file integration into the IGS can be considered complete and successful at this time. Work continues in coordination with the different working groups for all the IGS products to accept the station long names into the products.

3 Planned 2019 Activities

During 2019 the IC will be concentrating on the following recommendations that came from the 2018 IGS Workshop;

1. To implement a Station product participation table for the IGS station webpage to show each station inclusion in the different IGS products
2. To create a way forward to provide at least weekly positions for ALL IGS network stations, rather than just having the stations that Final ACs have selected
3. To investigate and create a plan of what to do with parallel station installation data when upgrading antennas; whether to use the data to estimate the "antenna change" offsets, where to store the parallel data and the results.
4. To support the Antenna WG in the new test activity to check available individual antenna calibrations in the existing IGS stations
5. To request NSWE pictures from station antennas especially for those that do provide individual antenna calibrations
6. To request antenna's ground plane distance to the ground (local height) ($<$ 10cm accuracy)

The IC will also push to complete the implementation of the remaining recommendations still outstanding from the 2017 IGS Workshop;

1. To implement a Station product participation table for the IGS station webpage to show each station inclusion in the different IGS products
2. To investigate and create a plan of what to do with parallel station installation data when upgrading antennas; whether to use the data to estimate the "antenna change" offsets, where to store the parallel data and the results.
3. To support the Antenna WG in the new test activity to check available individual antenna calibrations in the existing IGS stations
4. To request antenna's ground plane distance to the ground (local height) ($<$ 10cm accuracy)

CDDIS Global Data Center Technical Report 2018

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1 Introduction

The Crustal Dynamics Data Information System (CDDIS) is NASA's data archive and information service supporting the international space geodesy community. For over 35 years, the CDDIS has provided continuous, long term, public access to the data (mainly GNSS-Global Navigation Satellite System, SLR-Satellite Laser Ranging, VLBI-Very Long Baseline Interferometry, and DORIS-Doppler Orbitography and Radiopositioning Integrated by Satellite) and products derived from these data required for a variety of scientific studies, including the determination of a global terrestrial reference frame and geodetic studies in plate tectonics, earthquake displacements, volcano monitoring, Earth orientation, and atmospheric angular momentum, among others. The specialized nature of the CDDIS lends itself well to enhancement to accommodate diverse data sets and user requirements. The CDDIS is one of NASA's Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs) (see https://earthdata.nasa.gov); EOSDIS data centers serve a diverse user community and are tasked to provide facilities to search and access science data and products. The CDDIS is also a regular member of the International Council for Science (ICSU) World Data System (WDS, https://www.icsu-wds.org) and the Earth Science Information Partners (ESIP, https://www.esipfed.org). The CDDIS serves as one of the primary data centers and core components for the geometric services established under the International Association of Geodesy (IAG), an organization that promotes scientific cooperation and research in geodesy on a global scale. The system has supported the International GNSS Service (IGS) as a global data center since 1992. The CDDIS activities within the IGS during 2018 are summarized below; this report also includes any recent changes or enhancements made to the CDDIS.

2 System Description

The CDDIS archive of IGS data and products are accessible worldwide through anonymous ftp (address: cddis.nasa.gov). The CDDIS has also implemented web-based (https://cddis.nasa.gov/archive) access to its archive. The CDDIS is located at NASA's Goddard Space Flight Center (GSFC) and is available to users 24 hours per day, seven days per week.

2.1 Hardware Configuration

The CDDIS computer facility is fully redundant with primary and secondary/failover systems utilizing a virtual machine (VM) based system, configured with 100 Tbytes of unified storage operating within the EOSDIS computer facility and network infrastructure. This system configuration provides reliable environment (power, HVAC, 24-hour on-site emergency personnel, etc.) and network connectivity; a disaster recovery system is installed in a different location on the GSFC campus for rapid failover if required. Multiple, redundant 40G network switches are available to take full advantage of a high-performance network infrastructure by utilizing fully redundant network paths for all outgoing and incoming files along with dedicated 10G network connections between its primary operations and its backup operations. The use of the virtual machine technology provides multiple instance services for a load balancing configuration and allows for VM instances to be increased or decreased due to demand. Furthermore, the VM technology allows for system maintenance (patching, upgrades, etc.) to proceed without any downtime or interruption to user access. The large, unified storage system will easily accommodate future growth of the archive and facilitate near real-time replication between its production and disaster recovery sites. The entire archive is also mirrored to traditional storage arrays for additional complete copies of the archive. This system architecture has allowed the CDDIS to achieve an uptime figure of over 99.9 in recent years; a few brief interruptions occurred in 2018 which were outside CDDIS control, due to issues with EOSDIS and NASA infrastructure. As shown in Figure 1, the providers of files for the CDDIS archive push their files (data, derived products, etc.) to the CDDIS ingest server, utilizing the Earthdata Login system for validating access. Incoming files are then handled by the processing system which performs file/content validation, quality control, and metrics extraction. Metadata and metrics (ingest/archive and distribution) information is pushed to the EOSDIS Common Metadata Repository (CMR) system. Content metadata, describing collections and granules, are available for access by a broad user community through the CMR. Valid files are then moved to the CDDIS archive for public access through the CDDIS ftp and web servers.

2.2 Data Upload System

The CDDIS file ingest processing system allows staff to check for errors in a more consistent fashion, regardless of data type or file provider; the automated system allows the staff to identify several error types, such as problems with file naming, compression, and content. Any errors are further categorized as fatal or warning errors and are tracked in the CDDIS database allowing staff to more easily monitor data processing. Fatal errors include logic errors (e.g., data with a future date), an empty file, or an unknown file name/structure. Files with fatal errors are not moved to the archive; they are placed in a “quarantine” location for further examination by operations staff. Warning errors are generally auto-corrected/handled and the file is then archived; these errors include a significantly older file, invalid compression, etc. The ingest software also performs routine checksums of and anti-virus scanning on all incoming files, extracts uniform file-level and content-level metadata, and consistently tracks file and content errors. In the last year, the number of errors detected in incoming files have been reduced significantly due to staff's outreach efforts with data suppliers to correct a large majority of errors. These efforts have resulted in an improved, more reliable CDDIS archive. Since GNSS data accounts for a majority of the incoming files to CDDIS, the staff has developed a guidelines document for data providers (https://cddis.nasa.gov/docs/2017/GNSSDataStandards.pdf).

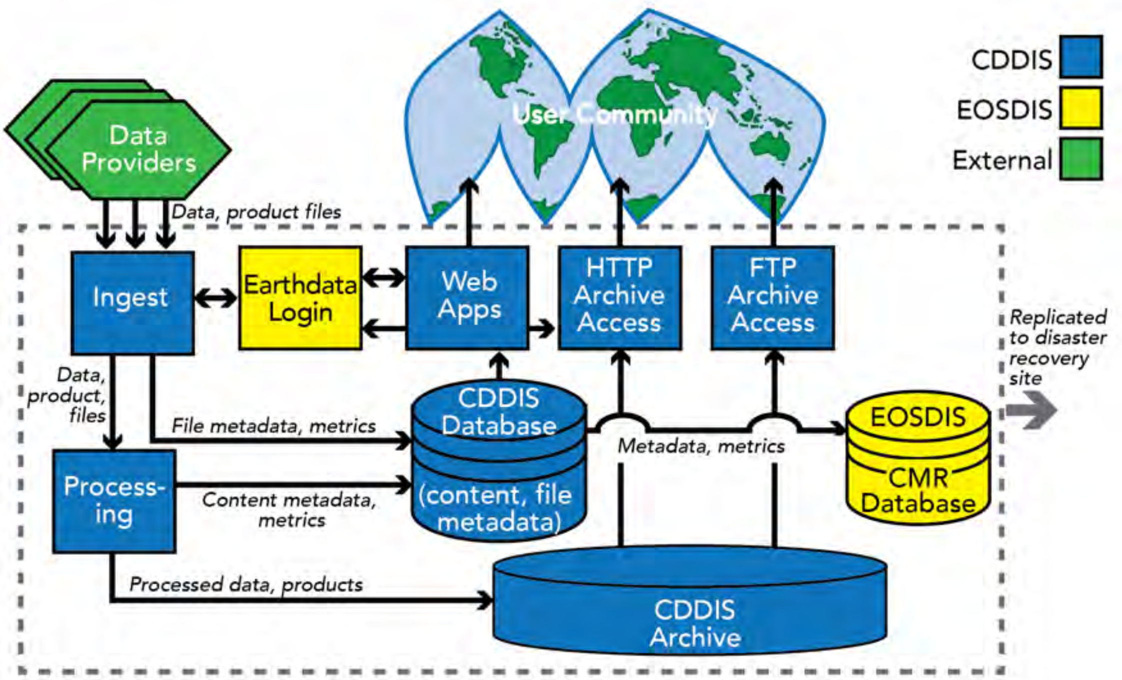

Figure 1: System architecture overview diagram for the CDDIS facility installation within the EOSDIS infrastructure.

Table 1: GNSS Data Type Summary.

Data Type	Sample Rate	Data Format	Available
Daily GNSS	30 sec.	RINEX V2	Since 1992
Daily GNSS	30 sec.	RINEX V3	Since 2016
Hourly GNSS	30 sec.	RINEX V2	Since 2005
Hourly GNSS	30 sec.	RINEX V3	Since 2016
High-rate GNSS	1 sec.	RINEX V2	Since 2001
High-rate GNSS	1 sec.	RINEX V3	Since 2016
Satellite GPS	10 sec.	RINEX V2	2002-2012

3 Archive Contents

As a global data center for the IGS, the CDDIS is responsible for archiving and providing access to GNSS data from the global IGS network as well as the products derived from the analyses of these data in support of both operational and working group/pilot project activities. The CDDIS archive is approximately 27 Tbytes in size (over 260 million files) of which over 95% is devoted to GNSS data (25 Tbytes) and GNSS products (1.5 Tbytes). All these GNSS data and products are accessible through subdirectories of https://cddis.nasa.gov/gnss and https://cddis.nasa.gov/archive/gnss.

3.1 GNSS Data

3.1.1 Main Data Archive

The user community has access to GNSS data available through the on-line global data center archives of the IGS. Over 40 operational and regional IGS data centers and station operators make data (observation, navigation, and meteorological) available in RINEX format to the CDDIS from receivers on a daily, hourly, and sub-hourly basis. The CDDIS also accesses the archives of other IGS global data centers (GDCs), the Institut Géographique National (IGN) in France, the Scripps Institution of Oceanography (SIO) in California, the Korea Astronomy and Space Science Institute (KASI), the Wuhan University data center, and the ESA GNSS Science Support Centre (GSSC) to retrieve (or receive) data holdings not routinely transmitted to the CDDIS by an operational or regional data center. Table**??** below summarizes the types of IGS GNSS data sets available in the CDDIS in the operational, non-campaign directories of the GNSS archive.

The main GNSS data archive (https://cddis.nasa.gov/gnss/data) at the CDDIS contains GPS and GPS+GLONASS data in RINEX V2 format and multi-GNSS data in RINEX V3 format. Since January 2016, RINEX V3 data, using the V3 "long" filename specification, have been made available here along with the RINEX V2 data. The avail-

Table 2: GNSS Data Archive Summary for 2018.

Data type	Number of sites V2	V3	V2&V3	Unique	Vol.	#file	Directory
Daily	282	33	284	599	710 GB	1.2 M	/gnss/data/daily
Hourly	214	4	175	393	340 GB	13.5 M	/gnss/data/hourly
High-rate	215	36	56	307	3,100 GB	16.8 M	/gnss/data/highrate

ability of RINEX V3 data into the operational, main archives at the IGS GDCs (and detailed in the "RINEX V3 Transition Plan") addressed a key recommendation from the IGS 2014 Workshop: "one network one archive" and provided for the better integration of multi-GNSS data into the entire IGS infrastructure. Starting in 2015, stations began submitting RINEX V3 data using the format's "long" filename specification. The transition plan specified that RINEX V3 data from IGS network sites using the V3 filename structure should be archived in the same directories as the RINEX V2 data. Therefore, starting on January 01, 2016, all daily, hourly, and high-rate data submitted to the CDDIS in RINEX V3 format and using the long, V3 filename specification have been archived in the same directories as the RINEX V2 data (which use the 8.3.Z filename for daily and hourly files and the 10.3.Z filename format for high-rate files). In addition, these RINEX V3 files are compressed in gzip (.gz) format; files in RINEX V2 format continue to use UNIX compression (.Z). These data in RINEX V3 format include all available multi-GNSS signals (e.g., Galileo, QZSS, SBAS, BeiDou, and IRNSS) in addition to GPS and GLONASS. Figure 2 shows the network of IGS sites providing daily data in RINEX V2 and/or V3 formats.

The CDDIS archives three major types/formats of GNSS data, daily, hourly, and high-rate sub-hourly, all in RINEX format, as described in Table 1; the network distribution of submitted files is shown in Figure 3. Over 275K daily station days from 603 distinct GNSS receivers were archived at the CDDIS during 2018; of these sites, 284 sites supplied both RINEX V2 and V3 data (see Table 2). A complete list of daily, hourly, and high-rate sites archived in the CDDIS can be found in the yearly summary reports at URL https://cddis.nasa.gov/reports/gnss/. All incoming files for the CDDIS archive are now checked for conformance to basic rules, such as valid file type, non-empty file, uses correct compression, consistency between filename and contents, uses correct file naming conventions, and other logic checks. After incoming files pass these initial checks, content metadata are extracted and the files undergo further processing based on data type and format.

Daily RINEX V2 data are quality-checked, summarized (using UNAVCO's teqc software), and archived to public disk areas in subdirectories by year, day, and file type; the summary and inventory information are also loaded into an on-line database. However, this data quality information, generated for data holdings in RINEX V2 format, is not available through the software used by CDDIS to summarize data in RINEX V3 format. CDDIS continues to investigate and evaluate software capable of providing data summary/QC information for RINEX V3 data.

Within minutes of receipt (typically less than 30 seconds), the hourly GNSS files are archived to subdirectories by year, day, and hour. Although these data are retained online, the daily files delivered at the end of the UTC day contain all data from these hourly files and thus can be used in lieu of the individual hourly files. As seen in Table 2, a total of 366 unique hourly sites (over 9.5 million files) were archived during 2018; 152 hourly sites provided data in both RINEX V2 and V3 formats.

High-rate (one-second sampling rate) GNSS data are made available in files containing fifteen minutes of data and in subdirectories by year, day, file type, and hour. Many of these data files are created from real-time streams. As shown in Table 2, data from 307 unique high-rate sites (over 16.8 million files) were archived in the CDDIS in 2018; 56 high-rate sites provided data in both RINEX V2 and V3 formats.

The CDDIS generates global RINEX V2 broadcast ephemeris files (for both GPS and GLONASS) on a daily and hourly basis. The hourly concatenated broadcast ephemeris files are derived from the site-specific ephemeris data files for each hour and are appended to a single file that contains the orbit information for all GPS and GLONASS satellites for the day up through that hour. The merged ephemeris data files, named `hourDDD0.YYn.Z`, are then copied to the day's subdirectory within the hourly data file system. Within 1-2 hours after the end of the UTC day, after sufficient station-specific navigation files have been submitted, this concatenation procedure is repeated to create the daily broadcast ephemeris files (both GPS and GLONASS), using daily site-specific navigation files as input. These daily RINEX V2 broadcast ephemeris files, named `brdcDDD0.YYn.Z` and `brdcDDD0.YYg.Z`, are then copied to the corresponding year/day nav file subdirectory as well as the yearly brdc subdirectory (`/gnss/data/daily/YYYY/brdc`).

The CDDIS also generates daily RINEX V3 concatenated broadcast ephemeris files. The files are archived in the yearly brdc subdirectory (`https://cddis.nasa.gov/gnss/data/daily/YYYY/brdc`) with a filename of the form `BRDC00IGS_R_yyyydddhhmm_01D_MN.rnx.gz`. The procedure for generating these files is similar to the V2 procedure in that site-specific, mixed V3 ephemeris data files are merged into to a single file that contains the orbit information for all GNSS satellites for the day. The chair of the IGS Infrastructure Committee provided the software that CDDIS staff uses to create these files. Users can thus download these single, daily (or hourly) files (in both RINEX V2 and V3 formats) to obtain the unique navigation messages rather than downloading multiple broadcast ephemeris files from the individual stations.

The CDDIS generates and updates "status" files, (`/gnss/data/daily/YYYY/DDD/YYDDD.status` for RINEX V2 data and YYDDD.V3status for RINEX V3 data) that summarize the holdings of daily GNSS data. These status files of CDDIS GNSS data holdings reflect timeliness of the data delivered as well as statistics on number of data points, cycle slips, and multipath (for RINEX V2 data). The user community can thus view a snapshot of

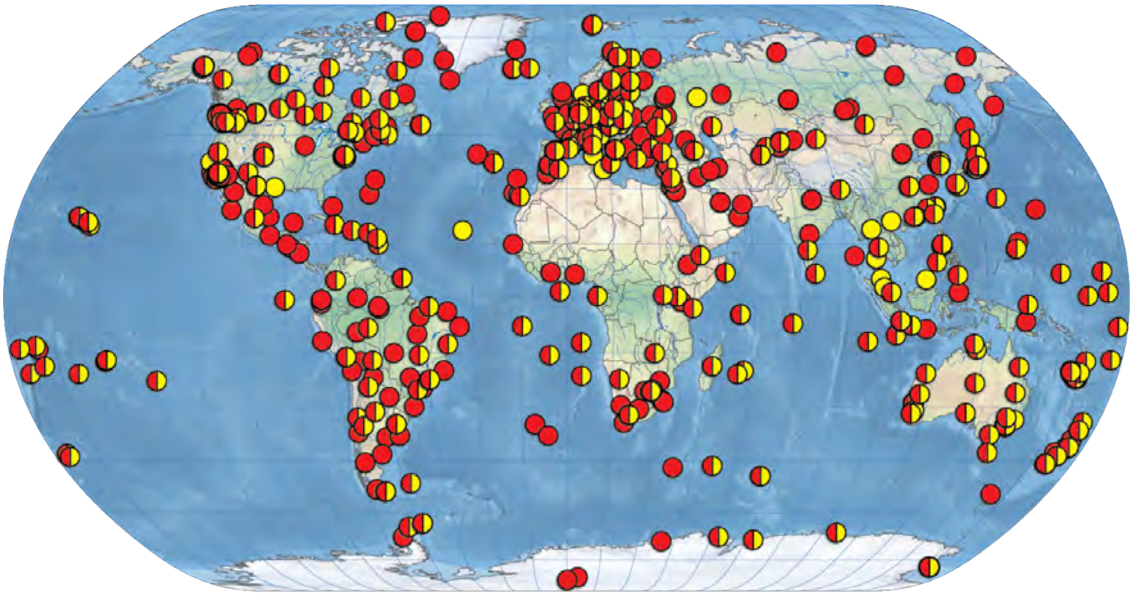

Figure 2: The main, operational archive at CDDIS now includes data in RINEX V2 format using the 8.3.Z filename specification (red) and RINEX V3 format using the V3 filename specification (yellow); sites providing both RINEX V2 and V3 formatted data are shown with the red+yellow icon.

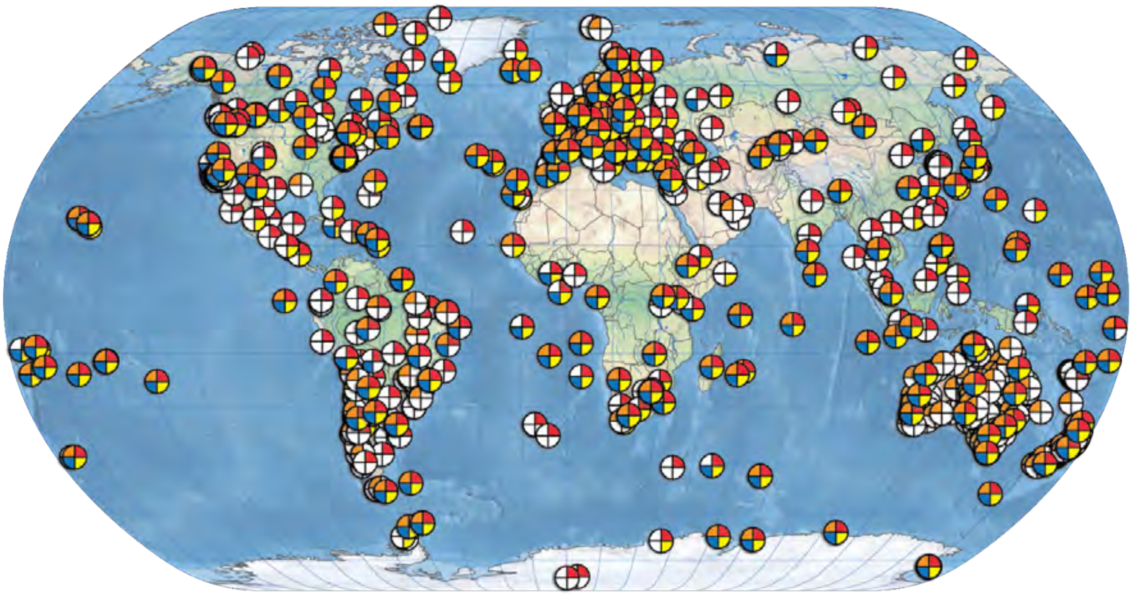

Figure 3: CDDIS GNSS archive includes data in daily (red), hourly (yellow), sub-hourly (blue), and/or real-time (orange) increments. Hourly, sub-hourly, and real-time data allow analysts to generate products for applications needing more frequent updates.

data availability and quality by checking the contents of such a summary file.

3.1.2 RINEX V3 (MGEX) Campaign Archive

During 2018, very little data in RINEX V3 format using the 8.3.Z filename specification were archived in the Multi-GNSS Experiment (MGEX) campaign directory structure at CDDIS (`/gnss/campaign/mgex/data`). The majority of data in RINEX V3 format utilize the "long" RINEX V3 naming convention with gzip compression and are integrated in the operational directory structure (`/gnss/data/daily`, `/gnss/data/hourly`, `/gnss/data/highrate`).

The CDDIS continues to archive a merged, multi-GNSS broadcast ephemeris file containing GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS ephemerides. This file, generate by colleagues at the Technical University in Munich (TUM) and Deutsches Zentrum für Luft- und Raumfahrt (DLR), is similar to the daily and hourly concatenated broadcast message files in RINEX V2 format provided by the CDDIS for the operational GPS+GLONASS data sets; it contains all the unique broadcast navigation messages for the day. The file, named `brdmDDD0.YYp.Z`, is stored in daily subdirectories within the MGEX campaign archive at CDDIS (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/DDD/YYp`) and in a yearly top level subdirectory (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/brdm`).

Colleagues at TUM and DLR are also providing GPS and QZSS CNAV (civilian navigation) data on an operational basis within MGEX. These messages are collected from a sub-network of MGEX stations and are provided in a merged daily file in a format similar to RINEX. These files are named `brdxDDD0.YYx.Z` and stored in a daily subdirectory within the MGEX archive at CDDIS (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/cnav`).

3.2 IGS Products

The CDDIS routinely archives IGS operational products (daily, rapid, and ultra-rapid orbits and clocks, ERP, and station positions) as well as products generated by IGS working groups and pilot projects (ionosphere, troposphere, real-time, MGEX). Table 3 below summarizes the GNSS products available through the CDDIS. The CDDIS currently provides on-line access to all IGS products generated since the start of the IGS Test Campaign in June 1992 in the file system /gnss/products; products from GPS+GLONASS products are available through this filesystem. Products derived from GLONASS data only continue to be archived at the CDDIS in a directory structure within the file system `/glonass/products`.

The CDDIS also continues to archive combined troposphere estimates in directories by year and day of year. Global ionosphere maps of total electron content (TEC) from the

Table 3: GNSS Product Summary for 2018.

Product Type	Number of ACs/AACs	Volume	Directory
Orbits, clocks, ERP, positions	14+Combinations	3.5 GB/week	`/gnss/products/WWWW` (GPS, GPS+GLONASS) `/glonass/products/WWWW` (GLONASS only)
Troposphere	Combination	3.2 MB/day, 1.2 GB/year	`/gnss/products/troposphere/YYYY`
Ionosphere	7+Combination	5 MB/day, 1.7 GB/year	`/gnss/products/ionosphere/YYYY`
Real–time	Combination	28 MB/week	`/gnss/products/rtpp/WWWW`
MGEX	6	225 MB/week	`/gnss/products/mgex/WWWWY`

Note: WWWW=4-digit GPS week number; YYYY=4-digit year

IONEX AACs are also archived in subdirectories by year and day of year. Real-time clock comparison products have been archived at the CDDIS in support of the IGS Real-Time Pilot Project, and current IGS Real-Time Service, since 2009.

Seven AACs (CODE, GFZ, GRGS, JAXA, TUM, SHAO, and Wuhan) generated weekly products (orbits, ERP, clocks, and others) in support of MGEX; CODE, GRGS, JAXA, and SHAO utilize the "long" filename convention for their products. These files are archived at the CDDIS in the MGEX campaign subdirectory by GPS week (`/gnss/products/mgex/WWWW`).

Colleagues at DLR and the Chinese Academy of Sciences (CAS) provide a differential code bias (DCB) products for the MGEX campaign. This product is derived from GPS, GLONASS, Galileo, and BeiDou ionosphere-corrected pseudorange differences and is available in the bias SINEX format. DLR has provided quarterly DCB files containing daily and weekly satellite and station biases since 2013 in CDDIS directory `/gnss/products/biases`; CAS provides files on a daily basis. Additional details on the DCB product are available in IGSMail message 6868 sent in February 2015 and message 7173 sent in October 2015. Both products use the RINEX V3 file naming convention.

3.3 Real-Time Activities

The CDDIS real-time caster has been operational since early 2015 in support of the IGS Real-Time Service (IGS RTS). By the end of 2018, the CDDIS caster broadcasts 37 product and 480 data streams in real-time. The caster runs the NTRIP (Network Transport of RTCM via internet Protocol) format. Figure 4 shows the distribution of stations providing

Table 4: CDDIS Caster Stream Availability.

	Agency/Country	Approximate Number of Streams
Data		
	Geoscience Australia (GA, Australia)	76
	Bundesamt für Kartographie und Geodäsie (BKG, Germany)	244*
	Land Information New Zealand (LINZ, New Zealand)	45
	Global Differential GPS, Jet Propulsion Laboratory (JPL, USA)	49
	Natural Resources Canada (NRCan, Canada)	20
	Centro Sismológico Nacional, University of Chile (CNS, Chile)	31
	Instituto Brasileiro de Geografia e Estatística (IBGE, Brazil)	15
Total Data:		480
Product	Multiple	37
Total Streams		517

Note: *Includes streams using both 5 and 10 character mount point naming convention.

real-time streams to the CDDIS caster. The CDDIS caster accesses streams from several regional casters as shown in Table 4.

The CDDIS caster serves as the third primary caster for the IGS RTS, thus providing a more robust topology with redundancy and increased reliability for the service. User registration, however, for all three casters is unique; therefore, current users of the casters located at the IGS/UCAR and BKG are required to register through the CDDIS registration process in order to use the CDDIS caster. By the end of 2018, over 265 users from 45 countries have registered to use the CDDIS caster; approximately 85 users were added in 2018. More information about the CDDIS caster is available at https://cddis.nasa.gov/Data_and_Derived_Products/Data_caster_description.html.

As stated previously, the CDDIS is one of NASA's EOSDIS DAACs and through EOSDIS, has access to a world-class user registration process, the EOSDIS Earthdata Login, with nearly 500K users in its system. Since the NTRIP-native registration/access software was not compatible with NASA policies, the CDDIS developed software to interface the caster and the Earthdata Login within a generic Lightweight Directory Access Protocol (LDAP) framework. Access to the CDDIS caster requires that new users complete two actions: 1) an Earthdata Login registration and 2) a CDDIS caster information form, providing the user's email and institution and details on their planned use of the real-time data. Following completion, the information is submitted to CDDIS staff for the final steps to authorize access to the CDDIS caster; this access is typically available to the user within 24 hours. In addition, users registering in the Earthdata Login system have access to the entire suite of EOSDIS products across all 12 EOSDIS DAACs.

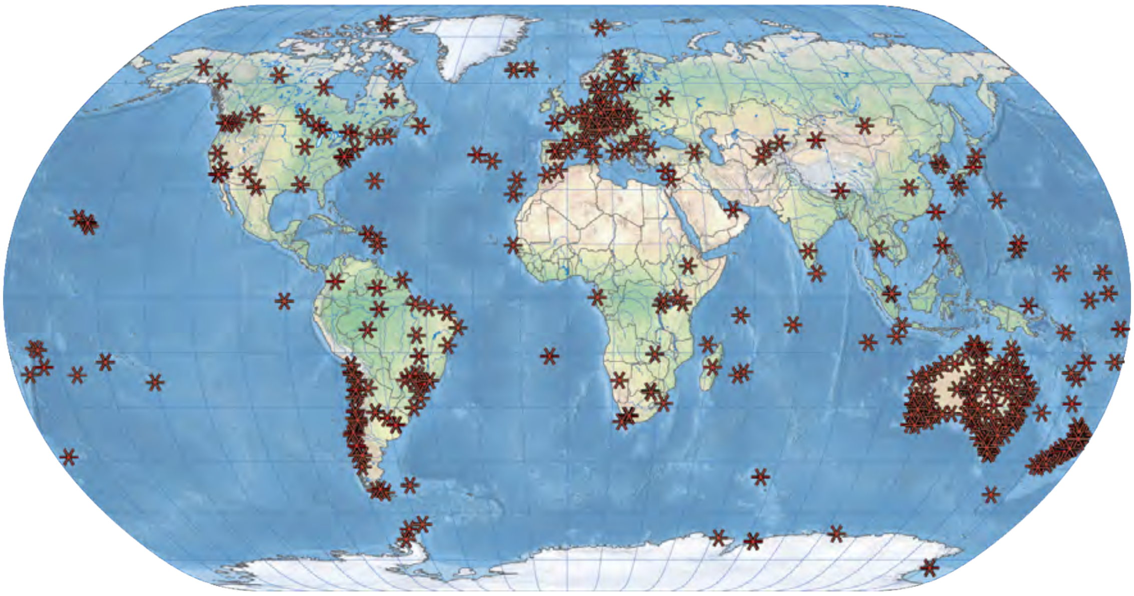

Figure 4: CDDIS is operationally supporting the dissemination of data from over 400 real-time GNSS sites as well as near real-time products derived from these data.

3.4 Supporting Information

Daily status files of GNSS data holdings, show timeliness of data receipt and statistics on number of data points, cycle slips, and multipath, continue to be generated by the CDDIS for RINEX V2 data; status files, with limited information, summarizing RINEX V3 data holdings are also available. These files are archived in the daily GNSS data directories and available through at URL `https://cddis.nasa.gov/reports/gnss/status`.

Other available ancillary information at CDDIS include daily, weekly, and yearly summaries of IGS tracking data (daily, hourly, and high-rate, in both RINEX V2 and V2 formats) archived at the CDDIS are generated on a routine basis. These summaries are accessible through the web at URL `https://cddis.nasa.gov/reports/gnss`. The CDDIS also maintains an archive of and indices to IGS Mail, Report, Station, and other IGS-related messages.

4 System Usage

Figure 5 shows the usage of the CDDIS, summarizing the retrieval of GNSS data and products from the online archive in 2018. This figure illustrates the number and volume of GNSS files retrieved by the user community during the past year, categorized by type (daily, hourly, high-rate, products). Over 1.7 billion files (nearly 170 Tbytes) were

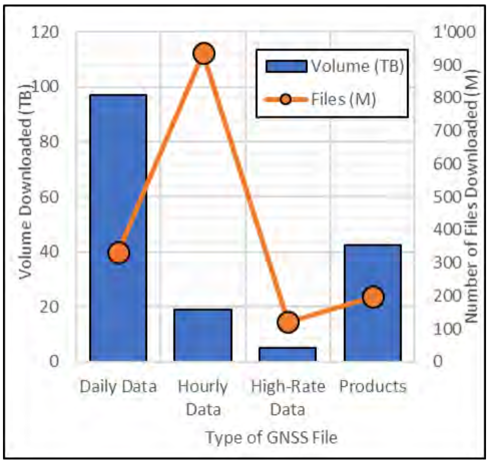

Figure 5: Number and volume of GNSS files transferred from the CDDIS in 2018.

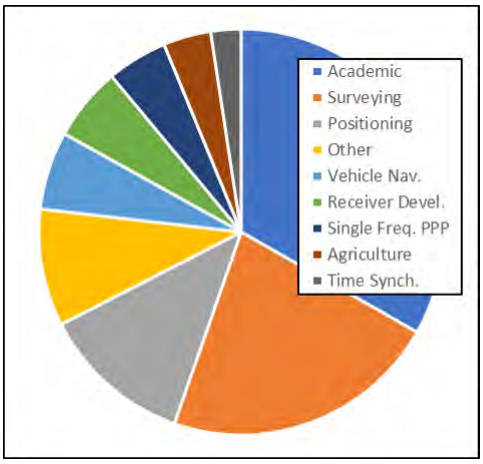

Figure 6: Primary applications supported by CDDIS real-time caster streams.

transferred in 2018, with an average of over 130 million files per month.

As for real-time system usage, an average of 15 users consistently accessed the CDDIS real-time caster on a daily basis in 2018, with on average 4500 stream connections to over 350 streams through a day. Figure 6 summarizes the primary applications the community uses from CDDIS caster streams; this information is provided by users during the caster registration process.

5 Recent Developments

5.1 Updates to Archive Access

The CDDIS has a large international user community; over 243K unique hosts accessed the system in 2018. Today, users access the CDDIS archive through anonymous ftp and https. The ftp protocol allows users to easily automate file downloads but has problems from a system/security standpoint. As per U.S. Government and NASA directives, the CDDIS has begun to move users away from reliance on anonymous ftp. Despite this requirement, the CDDIS staff is committed to ensuring continued, easy, open access to its archive. For the near-term, access to data in the CDDIS archive will continue through ftp but users are strongly encouraged to explore the https and ftp-ssl (address: gdc.cddis.eosdis.nasa.gov) capabilities as soon as possible.

The major reason for changing the archive access methods at CDDIS is system security and data integrity; ftp with its clear text username and password and lack of encryption, is just not acceptable in the current internet environment. The ftp protocol also has the disadvantage of being a two-port protocol that can result in connectivity problems (e.g., with firewall, router/switches, etc.). Unfortunately, proper network configuration is too often not the case and, in most instances, outside the control of CDDIS or the data provider to fix.

The CDDIS has configured servers to utilize protocols that allow two new methods for system access: https (browser and command line) and ftp-ssl (command line). The https protocol is as efficient as ftp transfer without the firewall/router issues of ftp; unlike ftp, https is a one-port protocol with fewer issues with downloads. The access to the CDDIS archive through both methods continues to present the same structure as that provided through anonymous ftp.

Archive access through the https protocol utilizes the same NASA single sign-on system, the EOSDIS Earthdata Login utility, as is used for the file upload and real-time caster user authentication. Before using the https protocol to access the CDDIS archive, new users must initially access the webpage, https://cddis.nasa.gov/archive, to establish an account and authorize access; this page will then redirect the user to the Earthdata Login page. Earthdata Login allows users to easily search and access the full breadth of all twelve EOSDIS DAAC archives. Earthdata Login also allows CDDIS staff to know our users better, which will then allow us to improve CDDIS capabilities.

Once an account is established, the user has all permissions required to access the CDDIS archive using the https protocol, via a web browser or via a command line interface (e.g., through cURL or Wget) to script and automate file retrieval.

In addition, ftp-ssl access, an extension of ftp using TLS (transport layer security), can be used for scripting downloads from the CDDIS archive. The ftp-ssl is the option most similar to standard anonymous ftp. As with https, ftp-ssl will satisfy U.S. Government/NASA requirements for encryption.

Examples on using these protocols, including help with the cURL and Wget commands, are available on the CDDIS website; users are encouraged to consult the available documentation at: https://cddis.nasa.gov/About/CDDIS_File_Download_Documentation.html as well as various presentations on these updates to the CDDIS archive access (see Section 7 below and https://cddis.nasa.gov/Publications/Presentations.html)

5.2 Metadata Improvements

The CDDIS continues to make modifications to the metadata extracted from incoming data and product files pushed to its archive and implemented these changes in the new file ingest software system. These enhancements have facilitated cross discipline data discovery by providing information about CDDIS archive holdings to other data portals such as the EOSDIS Earthdata search client and future integration into the GGOS portal. The staff continues work on a metadata evolution effort, re-designing the metadata extracted from incoming data and adding information that will better support EOSDIS applications such as its search client and the metrics collection effort. The CDDIS is also participating in GGOS metadata efforts within the Bureau of Networks and Observations.

The CDDIS continues to implement Digital Object Identifiers (DOIs) to select IGS data sets (GNSS data and products). DOIs can provide easier access to CDDIS data holdings and allow researchers to cite these data holdings in publications. Landing pages are available for each of the DOIs created for CDDIS data products and linked to description pages on the CDDIS website; an example of a typical DOI description (or landing) page, for daily Hatanaka-compressed GNSS data files, can be viewed at: https:/cddis.nasa.gov/Data_and_Derived_Products/GNSS/daily_gnss_d.html. DOIs will be assigned to additional GNSS data and product sets in the near future.

5.3 Real-time Caster Updates

By the end of 2018, the CDDIS real-time caster was configured to stream data from over 480 GNSS data mount points and 37 product streams. The caster added over 150 10-character mount point names as per recommendations from the IGS Real Time Working Group (RTWG). These streams, along with new product streams using the 10-character naming, will eventually replace the corresponding 5-character mount point names by the end of 2019.

6 Future Plans

6.1 Archive Access

As discussed in section 6 above, in the near future, the CDDIS cannot and will no longer support non-encrypted anonymous ftp access to its archive; access to the archive through https and ftp-ssl have already been implemented. The staff is also testing providing a WebDAV (Web Distributed Authoring and Versioning) interface to provide another method for accessing CDDIS archive. If feasible for CDDIS, this interface method would allow users to securely connect to the CDDIS archive as if it were a local drive on their computer.

6.2 RINEX V3 Data and Reprocessing Older GNSS Data

The CDDIS will continue to coordinate with the Infrastructure Committee and other IGS data centers to implement steps outlined in the RINEX V3 transition plan to complete the incorporation of RINEX V3 data into the operational GNSS data directory structure. The CDDIS began this process with multi-GNSS, RINEX V3 data from January 2016 onwards; the CDDIS will continue these efforts by integrating RINEX V3 multi-GNSS data from years prior to 2016 into the IGS operational archives. MGEX campaign directories will continue to be maintained during this transition to the operational directory archive. Furthermore, the CDDIS staff will continue to test software to copy RINEX V3 data (using the older filename format) into files with RINEX V3 filenames as well as QC RINEX V3 data and files and incorporate the software into operational procedures.

In mid-2016 CDDIS installed a new ingest processing system (see section 2.3) providing more extensive quality control on and metadata extraction of incoming files. The CDDIS staff plans to use this new software to validate the older GNSS archive (daily starting in 1992, hourly starting with 2005, and high-rate starting in 2001); this process will ensure that these historic files are valid and accurately archived for the user community. The additional metadata will also help the staff to better manage the CDDIS GNSS data holdings, provide improved metrics on data availability, and extensive data search capability for the EOSDIS Earthdata Search utility.

6.3 Real-Time Activities

The CDDIS will add real-time data and product streams to its operational caster in support of the IGS Real-Time Service. The CDDIS continues to review the implementation of software to capture real-time streams for generation of 15-minute high-rate files for archive. This capability requires further testing and coordination with the IGS Infrastructure Committee. The staff is also developing software to provide metrics on usage of the CDDIS caster.

CDDIS staff members are investigating using DLR's ntripchecker software for updating the caster source table in real-time, maintaining stream record consistency among the CDDIS and regional casters. The staff is also working on developing scripts to monitor and report interruptions and outages in broadcast streams.

6.4 High-rate Archive Modifications

CDDIS staff put forward a recommendation at the 2018 IGS Workshop to consolidate the sub-hourly high-rate data files into a tar archive, one file per site per day. At this time, each site supplies up to 96 files per day; the bundling of the files into a single daily site-specific tar file would simplify downloads for the user as well as reduce storage and streamline the directory structure at the data centers. CDDIS plans to begin these modifications to the high-rate data archive starting with 2001 and work toward the present; the data from the current year will remain in the standard, submitted 15-minute file format. The CDDIS staff will coordinate with the IGS Infrastructure Committee, users, and data centers on moving forward with this recommendation.

6.5 System Upgrades

The CDDIS has received funding to procure a system server, storage, and network hardware refresh. Staff members have begun the engineering design for this next system; plans are to have the upgraded system installed by the end 2019. The server and network hardware will remain within the same physical infrastructure as today's system, thus providing a reliable hosting environment with fully redundant networking paths and backup sites.

7 Publications

The CDDIS staff attended several conferences during 2017 and presented, or contributed to, papers on their activities within the IGS, including:

C. Noll and P. Michael. NASA CDDIS: Important Changes to User Access (poster), presented at the IDS workshop 2018, Ponta Delgada, São Miguel Island, Azores Archipelago (Portugal), September 26-28, 2018. https://cddis.nasa.gov/docs/2018/cddis_ftpPoster_201806_v5.pdf

C. Noll and P. Michael. NASA CDDIS: Important Changes to User Access (poster), presented at the IGS 2018 Workshop, Wuhan, China, October 29 - November 02, 2018. https://cddis.nasa.gov/docs/2018/cddis_ftpPoster_201810_v2a.pdf

S. Blevins, C. Noll, N. Pollack, R. Limbacher, J. Woo, J. Ash, J. Roark, P. Michael. Progress and Improvements in Real-time Services at NASA GSFC CDDIS (poster), presented at the IGS 2018 Workshop, Wuhan, China, October 29 - November 02, 2018. https://cddis.nasa.gov/docs/2018/SBlevins_IGS2018_realTime_poster_final.pdf

S. Blevins, L. Hayes, Y. Collado-Vega, P. Michael, C. Noll. Survey of Solar Flare Signatures in the Upper Ionosphere with GNSS and GOES Observations: A Case Study (poster), presented at the IGS 2018 Workshop, Wuhan, China, October 29 - November 02, 2018. https://cddis.nasa.gov/docs/2018/SBlevins_IGS2018_iono_poster_final.pdf

C. Noll, P. Michael. NASA CDDIS: Important Changes to User Access (poster), presented at the 21st International Workshop on Laser Ranging, Canberra, Australia, November 04-09, 2018. https://cddis.nasa.gov/docs/2018/cddis_ftpPoster_201811_v1b.pdf

J. Woo, E. Hoffman, M. Torrence. Station Assessment Software – Initial Results (poster), presented at the 21st International Workshop on Laser Ranging, Canberra, Australia, November 04-09, 2018. https://cddis.nasa.gov/lw21/docs/2018/posters/B3_Woo_Poster.pdf

J. Woo, P. Michael, C. Noll, R. Limbacher. Software Best Practices at Crustal Dynamics

Data Information System (CDDIS): Steps to Consider (poster), presented at the 21st International Workshop on Laser Ranging, Canberra, Australia, November 04-09, 2018. https://cddis.nasa.gov/lw21/docs/2018/posters/B20_Woo_Poster.pdf

C. Noll, P. Michael. "Important Changes to User Access at the NASA CDDIS (poster), presented at the AGU 2018 Fall meeting, Washington, DC, December 10-14, 2018, Abstract No. G31B-0675. https://cddis.nasa.gov/docs/2018/CDDIS_AGUposter_201812_v2.pdf

S. M. Blevins, C. E. Noll, N. Pollack R. Limbacher, J. Woo, J. Ash, J. Roark, P. Michael. Real-time GNSS data and product streams at NASA GSFC CDDIS (poster), presented at the AGU 2018 Fall meeting, Washington, DC, December 10-14, 2018, Abstract No. IN23B-0779. https://cddis.nasa.gov/docs/2018/SBlevins_AGU2018_final.pdf

J. Woo, P. Michael, C. Noll, R. Limbacher. Software Best Practices at Crustal Dynamics Data Information System (CDDIS): Steps to Consider (poster), presented at the AGU 2018 Fall meeting, Washington, DC, December 10-14, 2018, Abstract No. G51D-0515. https://cddis.nasa.gov/docs/2018/Coding_Best_Practices_AGU.pdf

Electronic versions of these and other publications can be accessed through the CDDIS on-line documentation page on the web at URL https:/cddis.nasa.gov/Publications/Presentations.html.

8 Contact Information

To obtain more information about the CDDIS IGS archive of data and products, contact:

Ms. Carey E. Noll	Phone:	(301) 614-6542
Manager, CDDIS	Fax:	(301) 614-6015
Code 61A	E-mail:	Carey.Noll@nasa.gov
NASA GSFC	WWW:	http://cddis.nasa.gov
Greenbelt, MD 20771		

General questions on the CDDIS, archive contents, and/or help using the system, should be directed to the user support staff at: support-cddis@earthdata.nasa.gov.

9 Acknowledgments

Funding for the CDDIS, and its support of the IAG, IGS, and other services, is provided by NASA through the Earth Science Data and Information System (ESDIS) project, which manages the EOSDIS science systems and DAACs.

The author would like to acknowledge the CDDIS deputy manager, Patrick Michael, the CDDIS contractor staff, Sandra Blevins, Rebecca Limbacher, and Nathan Pollack (Science Systems and Applications, Inc./SSAI), Lori Tyahla (Stinger Ghaffarian Technologies/KBRwyle), Justine Woo (Sigma Space Inc.), and Jennifer Ash and James Roark (ADNET Systems). The success of the CDDIS and its recognition in the many international programs supported by the system can be directly attributed to the continued dedicated, consistent, professional, and timely support of its staff.

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Noll, C. The Crustal Dynamics Data Information System: A resource to support scientific analysis using space geodesy Advances in Space Research, Volume 45, Issue 12, 15 June 2010, Pages 1421-1440, ISSN 0273-1177, DOI: 10.1016/j.asr.2010.01.018.

Noll, C., Y. Bock, H. Habrich, and A. Moore Development of data infrastructure to support scientific analysis for the International GNSS Service Journal of Geodesy, Feb 2009, pages 309-325, DOI 10.1007/s00190-008-0245-6.

IGS RINEX 3 Transition Plan v3.0 IGS website, `http://kb.igs.org/hc/en-us/article_attachments/202584007/Rinex_3_transition_plan_v3.0.pdf`.

The Receiver Independent Exchange Format. Version 3.04 IGS website, `ftp://igs.org/pub/data/format/rinex304.pdf`.

GSSC Global Data Center Technical Report 2018

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1 Introduction

The GNSS Science Support Center (GSSC) is a European Space Agency (ESA) data archive and information service in support of the IGS and the GNSS scientific community at-large hosted at the European Space Astronomy Center (ESAC) in Villanueva de la Cañada Madrid, Spain.

As an IGS Global Data Center (GDC) the GSSC makes all the lGS data and products available so as to backup and share the load from the other IGS GDC. Working closely with the other GDCs, especially with CDDIS, strong equalization routines have been established to avoid IGS data and product availability problems.

2 Description

The GSSC contains an archive of IGS data and products for the GNSS community, announced at the Galileo Colloquium 2017 in Valencia, full IGS GDC synchronization was reached in January 2018. The Data Center currently holds all the data and products available by polling hourly the contents of the other IGS Data Centers. The GSSC is also one of the original providers of the ESA/ESOC GNSS data and products. After some on-going software developments, the GSSC will aim to be the primary or secondary Data Center of choice for the IGS participants.

The GSSC also acts as a Data Center for the ESA efforts in GNSS Science by providing storage and off-site processing capabilities to a myriad of ESA projects that have used or will use GNSS data to perform science. These project data are stored in public and private areas within the GSSC to fulfill each project's requirements.

Figure 1: Data access over one week

3 2018 Developments

In 2018 the IGS Governing Board approved the GSSC as a new IGS GDC and initial operations were started immediately under the gssc.esa.int domain name. Initial data equalization with other DCs took place over a period of a month and such all IGS data and products are available in a timely fashion at the GSSC for all users via anonymous ftp and http.

In 2018 IGS GDC hosted at GSSC has experienced worldwide accesses from the GNSS community (see Fig. 1)

Additionally, as part of the GSSC development, a full portal was developed where IGS contribution was clearly acknowledged with a dedicated area in GSSC portal in addition to the data download area (see Fig. 2).

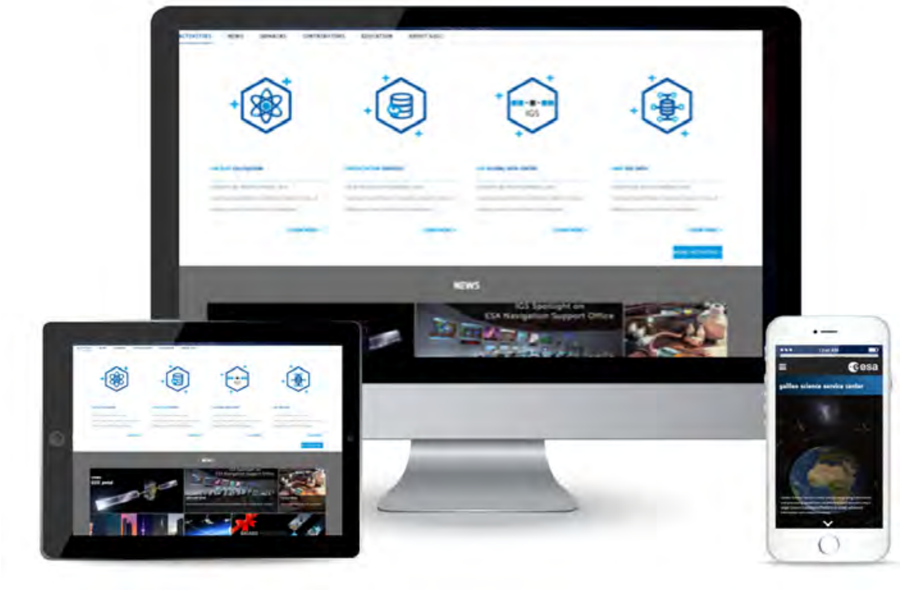

Figure 2: gssc.esa.int portal

4 Planned 2019 Activities

During 2019 the GSSC will continue to enhance and improve the access to GNSS data and product in the following areas:

- Advanced data discovery services.
- Deployment of Big Data technologies for on-the-fly analysis.
- Aggregation of outstanding GNSS assets.
- Improved monitoring of GNSS assets synchronization and utilization.
- Usability improvements for better portal ergonomics.
- Dedicated areas for GNSS science teams to share and upload their own data and products.
- Set-up of an experimental GSSC archive extension for GNSS Space Users Data.

WHU Data Center Technical Report 2018

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1 Introduction

Wuhan University has been added as an IGS Global Data Center since 2015. The IGS Data Center from WHU has been designed and implemented in answer to global and especially Chinese users, for both post–processing and real-time applications. The GNSS observations of both IGS and MGEX from all the IGS network stations, as well as the IGS products are archived and available at WHU Data Center.

The activities of WHU Data Center within the IGS during 2018 are summarized in this report, which also includes any recent changes or enhancements made to the WHU Data Center.

2 Access of WHU Data Center

So as to have a more reliable data flow and a better availability of the service, two identical configurations with the same data structure have been setup in Alibaba cloud and Data Server of Wuhan University. Each configuration has:

- FTP access to the GNSS observations and products (ftp://igs.gnsswhu.cn/).
- HTTP access to the GNSS observations and products (http://www.igs.gnsswhu.cn/).

3 GNSS Data & Products of WHU Data Center

The WHU Data Center contains all the regular GNSS data and products, such as navigational data, meteorological data, observational data, and products

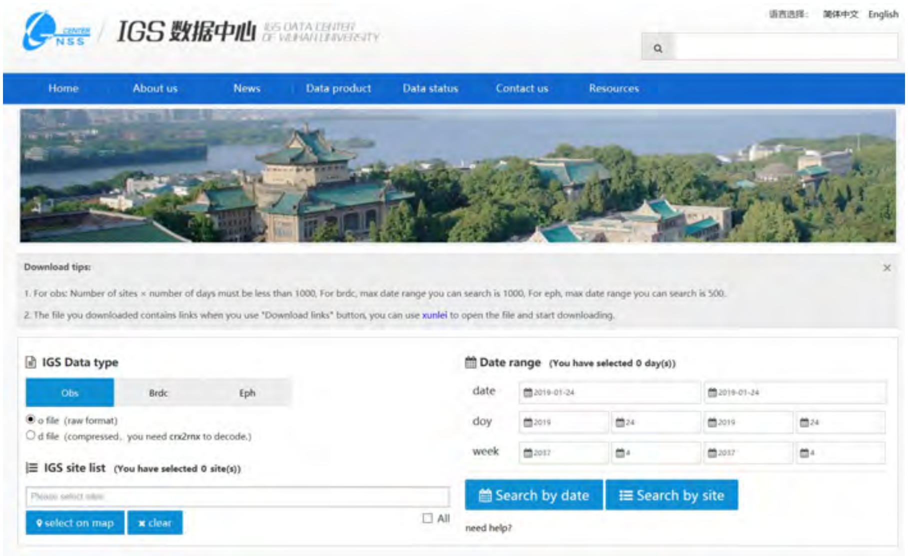

Figure 1: Download data and products from the website of WHU data center.

- Navigational data: daily and hourly data(ftp://igs.gnsswhu.cn/pub/gps/data)
- Observational data: daily and hourly data(ftp://igs.gnsswhu.cn/pub/gps/data)
- Products: rapid, and ultra–rapid orbits and clocks, Earth Rotation Parameters (ERP), and station positions, ionosphere, troposphere (ftp://igs.gnsswhu.cn/pub/gps/products)

In addition to the IGS operational products, WHU data center releases ultra-rapid products updated every 1 hour and every 3 hours (ftp://igs.gnsswhu.cn/pub/whu/MGEX/) from the beginning of June 2017. The ultra-rapid products include GPS/GLONASS/BDS/Galileo satellite orbits, satellite clocks, and ERP for a sliding 48-hr period, and the beginning/ending epochs are continuously shifted by 1 hour or 3 hours with each update. The faster updates and shorter latency should lead to significantly improved orbit predictions and reduced errors for user applications.

4 Monitoring of WHU Data Center

The data monitoring function of WHU data center is used to display log information such as online user status, the arrival status of data and products, and the status of user downloading in real time. It can display real-time data download and data analysis related products graphically and visually, with real-time information on online user status and product accuracy.

In order to ensure the integrity of the observation data and the products, we compare

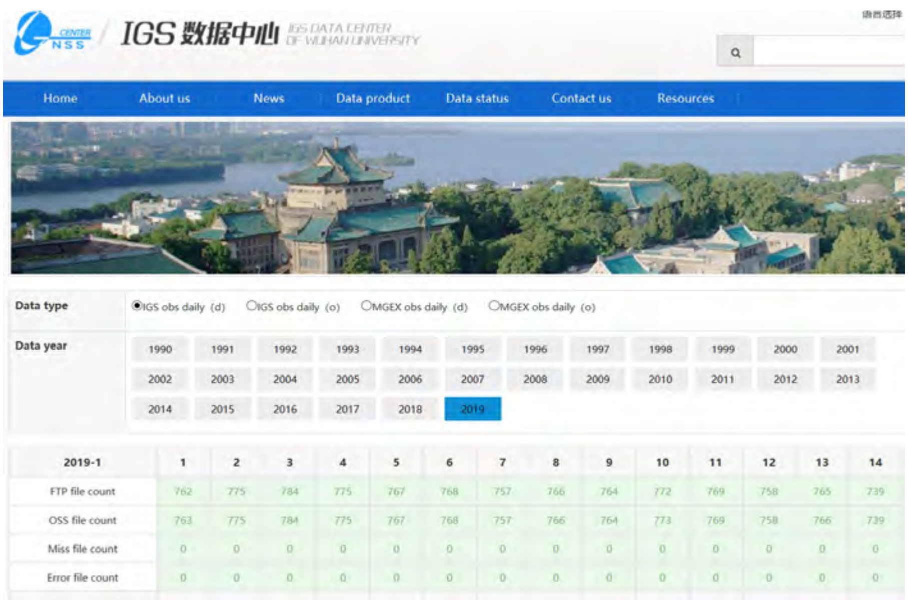

Figure 2: Data and products monitoring of WHU data center.

the daily data, hourly data and products with CDDIS. If a data file is missing, we will redownload it from CDDISs. Figure 2 shows status of daily observation.

BKG Regional Data Center Technical Report 2018

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1 Introduction

Since more than 25 years BKG is contributing to the IGS data center infrastructure operating a regional GNSS data center (GDC). BKG's GDC is also serving as a data center for the regional infrastructure of EUREF, as well as for national infrastructure or for specific projects. As a second pillar, since 2004, BKG is operating various entities for the global, regional and national real-time GNSS infrastructure. The development of the basic real-time components has been done independently from the existing file-based data center. The techniques behind, the user access etc. were completely different from the existing file-based structure. Moreover, operation of a real-time GNSS service demands a much higher level of monitoring than it is necessary in the post-processing world, where for example RINEX files can be reprocessed the next day in case of an error. However, there are several common features and interfaces like site log files, skeleton files, and high-rate files. Therefore, the goal is the public outreach as one GDC and to simplify user access to both infrastructures, e.g. via one web interface.

2 GDC Archive

2.1 Infrastructure

Currently BKG‘s GDC is running on a server integrated in a virtual machine environment placed at BKG's premises. It consist of a file server, a database server and a server dedicated to data processing and web access. All relevant parts of BKG's GDC are backed-up on a daily basis and stored on tape for at least a month before being over written. The virtualization has proved to be reliable, and downtimes due to system maintenance haven't been necessary. A disaster recovery system for the GDC is not installed and not scheduled currently.

2.2 Access

The access to the data center is possible via FTP, HTTPS and web interface. The web interface allows the following activities:

- Full 'Station List' with many filtering options and links to meta data
- File browser
- Search forms for RINEX files as well as for any file
- Availability of daily, hourly and, to a limited extent, high-rate (i.e. 1 Hz) RINEX files
- Interactive map allowing condensed information about each station

A processing monitor informs about the average time needed to process a single RINEX file and the amount of RINEX files stored daily or hourly. Changes in the processing software or system hardware are indicated as well.

The FTP commands allow easy access for anonymous download of many files and for implementation in download scripts.

2.3 GNSS Data & Products

The BKG GDC contains all the regular GNSS data, as there are navigational data, meteorological data, observational data, both RINEX v2 and RINEX v3, daily, hourly and high-rate data.

The directory structure applied by BKG is related to projects, i.e. within the "Data Access" a user will see IGS, EUREF, GREF, MGEX directories plus some other or historic projects. The main sub-directories for the projects are

- `BRDC` for the navigational data,
- `highrate` for the sub-hourly 1 Hz data,
- `nrt` for 30 seconds hourly data,
- `obs` for the daily data.

Since at the beginning of storing Rx3 files the standard short file names were identical to those containing Rx2, BKG decided to introduce parallel sub-directories with the extension _v3. It is expected that these directories will be obsolete in the near future.

For completeness, BKG is also providing some IGS products by mirroring from, e.g. CDDIS. Each project has some additional sub-directories: products, reports, and stations. For specific projects, more sub-directories might have been introduced. The detailed FTP structure of all open projects can be found on https://igs.bkg.bund.de/dataandproducts/ftpstructure.

2.4 Monitoring

Routinely, data-checks are performed for all incoming files. The files are processed through several steps, see Goltz et al. (2017) for details. An "Error Log" page on the web interface gives valuable information especially to the data providers how often and for what reasons a file was excluded from archiving.

On the "Station List" page (https://igs.bkg.bund.de/dataandproducts/stationqclist) a user or a data provider can see the completeness of the most recent data. You can also see some simple positioning time series for each station.

A new service under development is the "REST Web Service" (https://igs.bkg.bund.de/index/rest). A request for a specific file, a station or a complete GNSS network returns a compact information in either JSON or XML format.

2.5 System Usage

More than 16 million files are stored in the GDC with approx. three TByte of storage needed. We are facing with approx. 80000 uploads and 750000 downloads per day. The increase in number of downloaded files with respect to 2017 was 15 %. The full number of users may reach 24000 per hour, with approx. 110 different users. It should be mentioned that approx. 450 users per day are accessing the GDC via the http access.

3 Real-Time

3.1 Infrastructure

The development of the broadcaster technology and its usage for GNSS was mainly driven by BKG. It is originally based on the ICECAST technology and adapted for GNSS data (?). Since 2008, BKG is offering the so-called Professional Ntrip Caster which is used by various organizations and companies around the globe and which is updated and improved on a regular basis. BKG is maintaining various broadcasters for global, regional and national purposes. BKG's caster are not on own premises but hosted by an external service provider. The advantage of going this way clearly is the independency of local restrictions. Likewise for the file-based infrastructure – or even more important – is the aspect of redundancy. The redundancy concept for real-time streaming on the data center's side is realized in different ways. Firstly, the various casters are installed on different virtual machines at the service provider, so if one machine fails not all real-time streams are interrupted at the same time.

3.2 Access

The access to the broadcasters is possible with many commercial or individual tools. One software tool for easy access to the various IGS resources is the BKG Ntrip Client (BNC Weber et al. 2016). Since BNC has been developed always in parallel and close connection to the Professional broadcaster development, it is perfectly suited to the open IGS infrastructure.

3.3 GNSS Data & Products

As mentioned before, BKG is maintaining different casters (status end of 2018):

- On the mgex-ip caster (http://mgex.igs-ip.net) we are providing real-time date of approx. 93 stations. Most of the streams, 77, are received in raw data format. The streams are then converted with the EuroNet software (Horváth, 2016) into RTCM 3.2/3.3 Multiple Signal Message (MSM) format. For 19 stations the RTCM streams are coming directly from the receiver or from NRCan software: ALGO, AREG, BRST, BRUX, CHUR, DRAO, EUR2, GAMG, HARB, IQAL, KOUG, NRC1, NRMG, PRDS, PTGG, STJO, WHIT, YEL2, YELL. Only a small number of mount-points is already implemented with long mount-point names.
- On the euref-ip caster (http://www.euref-ip.net) we are providing approx. 184 data streams in RTCM3.0/1/2/3 format. There are still ten streams available in the old RTCM 2.2/3 format.
- On the igs-ip caster (http://www.igs-ip.net) we are providing approx. 216 data streams in RTCM3.0/1/2/3 format. There are still four streams available in the old RTCM 2.3 format (BOR1, DAEJ, GOPE, YEBE). All streams are provided with long mount-point names.
- On the products-ip caster (http://products.igs-ip.net) we are providing approx. 51 data streams in RTCM3.0/1/2 format. These streams divide in 43 clock & orbit correction streams from various organizations and in eight ephemeris data streams. There are various ephemeris streams available, mainly due to requests of specific user groups, e.g. constellation-specific data streams.

The information on the meta-data (e.g. format, message types, sampling rates, receiver type) can be found in the source-table of each caster. BKG also offers a source-table checker (https://igs.bkg.bund.de/ntrip/chksourcetable) allowing a user to verify his own source-table against the (official) content described at http://software.rtcm-ntrip.org/.

3.4 Monitoring

Besides the monitoring of the orbit and clock correction streams which is mainly done by the IGS Real-Time Coordinator during its combination process a qualitative analysis is carried out by using the various correction streams within the precise point positioning (PPP) in real-time (https://igs.bkg.bund.de/ntrip/ppp). On the one hand, it is done for the GREF mount-points using BKG's GPS+GLONASS correction stream CLK11. On the other hand, it is done using all individual corrections streams for GPS-only and GPS+GLONASS as well as the combined streams with the IGS station FFMJ. Moreover, global performance is monitored by using 24 different IGS real-time stations for each correction stream every day (https://igs.bkg.bund.de/ntrip/ppp#Scene15).

3.5 System Usage

While there is anonymous download for the file-based data, a registration is necessary for accessing real-time data (https://register.rtcm-ntrip.org/cgi-bin/registration.cgi). Since 2008, the demand for registration at BKG is unchanged on the level of approx. 400 requests per year (see Figure 1 for registrations per day). However, many of such registrations show up for a small amount of time only. Nevertheless, the number of so-called listeners, i.e. the requested data streams in parallel, reaches more than 2500 from approx. 100 different users during a typical day. The data volume sent to the users is roughly 10 times higher than the received data (Figure 2). Since several streams have been moved from the MGEX to the IGS caster, there is a significant increase for download for the latter one. For the IGS and the EUREF caster we have a mean upload of 12 GByte per day for each caster and a download of 170 GByte and 70 GByte per day, resp. For the MGEX caster, however, we are confronted with a mean upload of 25 GByte per day and a download of 150 GB per day. For the PRODUCTS caster, finally, we have a smaller upload of 1 GB per day and a download of 40 GB per day. This sums up to a traffic of more than 450 GByte per day for the four caster.

4 Future Plans

In the IGS Real-Time WG a discussion on changes regarding the naming of the product streams started. The running system with the five character names in the form "CLKmn" allow an easy and quick access for the experienced user. However, there is no clear scheme behind the two integers "mn" and it needs at least the additional information from the meta-data of the source-table. The fundamental IT consolidation process within the German federal government which has been described in last year's report has been delayed and, therefore, not been finalized in in 2018. The impact on almost all activities of BKG is still not fully foreseeable.

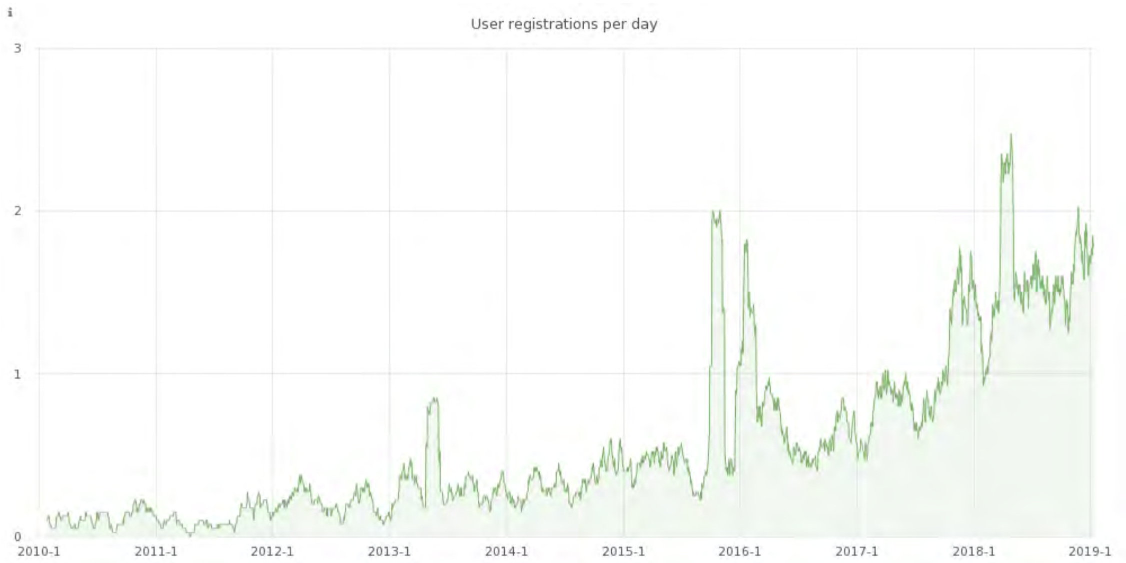

Figure 1: Number of user registrations per day for BKG Broadcasters since 2010.

References

Goltz, M. E. Wiesensarter, W. Söhne, and P. Neumaier Screening, Monitoring and Processing GNSS Data and Products at BKG Poster presented at the IGS Workshop 2017 in Paris (http://www.igs.org/assets/pdf/W2017-PS05-08%20-%20Goltz.pdf)

Weber, G., D. Dettmering, H. Gebhard, and R. Kalafus Networked Transport of RTCM via Internet Protocol (Ntrip) – IP-Streaming for Real-Time GNSS Applications ION GNSS, 2005, pp. 2243-2247

Weber, G., L. Mervart, A. Stürze, A. Rülke, and D. Stöcker BKG Ntrip Client (BNC) Version 2.12 Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Band 49, 2016, ISBN 978-3-86482-083-0

RTCM Standard 10410.1 Networked Transport of RTCM via Internet Protocol (Ntrip) – Version 2.0 RTCM Paper 111-2009-SC-STD

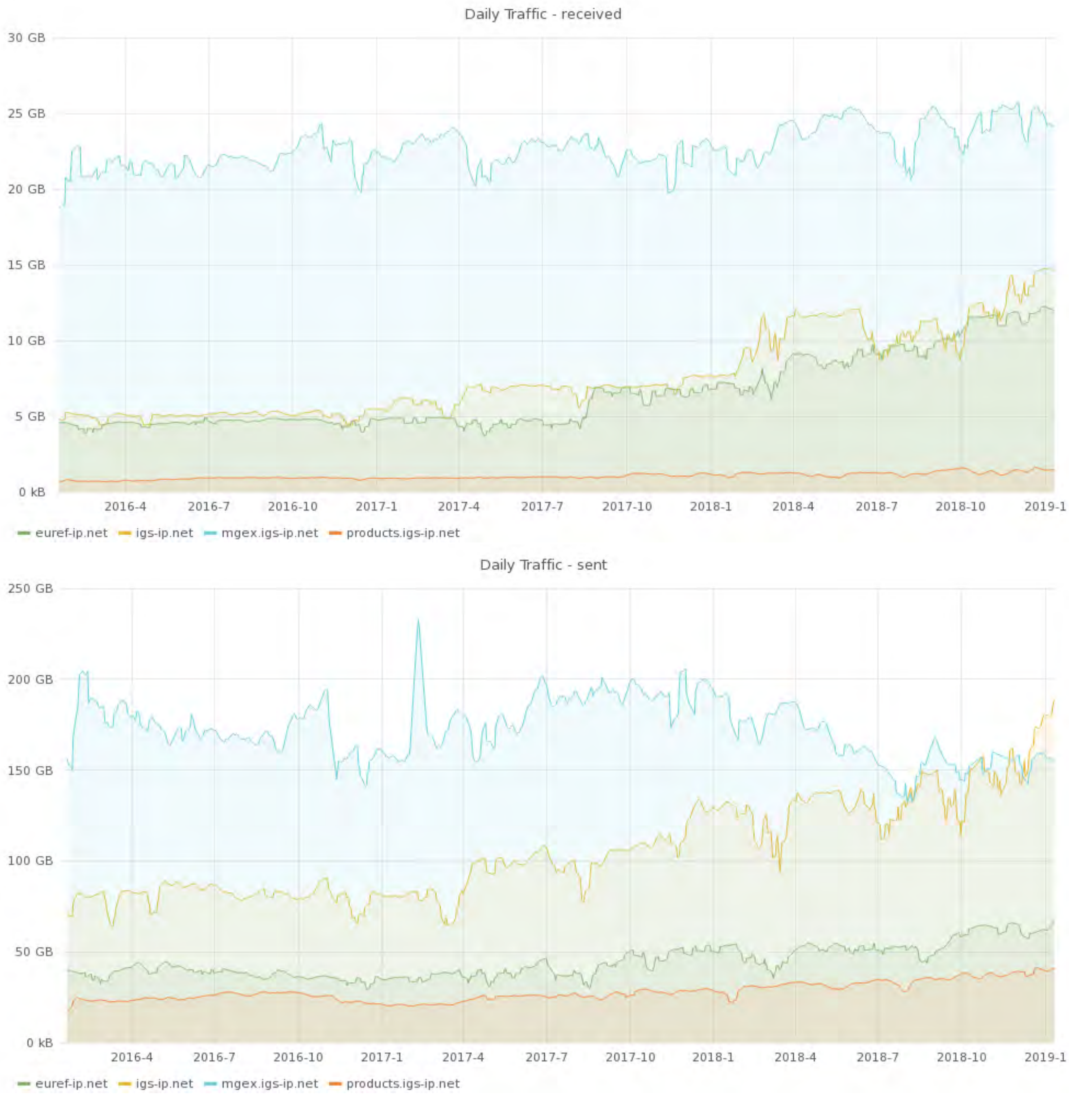

Figure 2: Daily received (i.e., upload to BKG, up) and sent (i.e., download from BKG) data volume at the BKG Broadcasters from 2016 to 2018

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2018

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1 Introduction

The IGS Antenna Workinggroup establishes a contact point to users of IGS products, providing guidance for antenna calibration issues and for a consistent use of IGS products. It maintains the IGS files related to receiver and antenna information, namely the IGS ANTEX file including satellite antenna and receiver type-mean calibrations.

Antenna phase center issues are related to topics such as reference frame, clock products, calibration, monumentation. The Antenna WG therefore closely cooperates with the respective working groups (Reference Frame WG, Clock Product WG, Bias and Calibration WG, Reanalysis WG), with antenna calibration groups, with the Analysis Center Coordinator and the Analysis Centers for analysis related issues, and with the Network Coordinator concerning maintenance of relevant files.

2 Chamber calibrated satellite patterns

2.1 Galileo and QZSS

In 2016, GSA (GSA 2017a, b) has disclosed the IOV satellite antenna calibrations followed by the FOC satellite antenna calibrations in October 2017. With their disclosure, the full GNSS constellation has been released. With the IGS ANTEX update (IGSMAIL #7572, igs14_1986.atx) the remaining constellation of the Galielo FOC satellites have been replaced by the chamber calibrations for FOC 1-14. The chamber calibrated satellite antenna pattern for latex FOC satellites (FOC-15 to FOC-22) are not yet disclosed and approximated using a mean PCO from FOC 2-14 without phase variations. As soon as

Table 1: Rob. : roboter receiver antenna calibrations
Cha. : chamber receiver antenna calibrations

GNSS	Frq	Sat.	Rob.	Cha.
GPS	L1			
	L2			
	L5			
GLO	G1			
	G2			
	G3			
GAL	E1		L1	
	E5a		L2	
	E5b			
	E5			
	E6			

GNSS	Frq	Sat.	Rob.	Cha.
BDS	B1		L1	
	B2		L2	
	B3			
QZSS	L1			
	L2			
	L5			

unknown	estimated	calibrated	approx.

those pattern are released, they will replace the current approximations in the IGS ANTEX file. The current situation of the antenna calibrations used within the IGS is shown in Table 1. Please note that currently only robot calibrations are used. One of the main activities within the AWG is to asses chamber calibrations for the receiver antennas. They could provide for many antenna types type-mean calibrations covering all frequencies, in particular E5.

2.2 Call for chamber calibrations

During the year 2018 the AWG made an effort to collect available chamber calibrated receiver antenna pattern in order to create type-mean pattern for testing purpose. More than eight institution share their calibrations with the AWK, including the University of Bonn which provided more than 250 individual calibrated patterns

From the collected chamber calibrations 37 atnenna/radome combined type-mean calibrations could be extracted covering almost 50% of all currently used antennas within the IGS.

3 Updates and content of the antenna phase center model

Table 2 lists all updates of the `igs14_wwww.atx` in 2018. 19 new antenna/radom combinations have been added. Moreover, the FOC satellite pattern where replaced with their chamber calibrations.

Table 2: Updates of the phase center model `igs14_wwww.atx` in 2018 (`wwww`: GPS week of the release date; model updates restricted to additional receiver antenna types are only announced via the *IGS Equipment Files* mailing list)

Week	Date	IGSMAIL	Change
2032			Added Decommision date: C001 (C30)
2031			Added LEIICG70 NONE
			MVECR152GNSSA NONE
			STXS900 NONE
2030			Added ARFAS13DFS ARFS
			TRM59800.00C NONE
2029			Added R857 (R15)
			Decommision date: R716 (R15)
			Added JAV_RINGANT_G3T JAVD
			JAVRINGANT_G5T JAVD
			JAVTRIUMPH_2A+P JVSD
			TPSHIPER_VR NONE
			TRMR10-2 NONE
2022			Preliminary PCO and PV for FOC-19 to FOC-22
			Added G036 (G04), E219 (E36), E220 (E13) E221 (E15), E222 (E33)
			Decommision date: G049 (G04)
			Added TRMSPS986 NONE
2017			Added C018 (C17), C019 (C16)
			Corrected commision date: R856 (R05)
			Corrected decommision date: R734 (R05)
2013			Added R856 (R05)
			Decommision date: R734 (R05)
2000			Added LEIGG04PLUS NONE
			NOV850 NONE
			STXS800 NONE
			STXS800A NONE
1992			Added G034 (G18)
			Decommision date: G054 (G18)
1986			Chamber calibrated PCO and PCV for Galileo FOC satellites: FOC-1 to FOC-14
			Added E215 (E21), E216 (E25), E217 (E27), E218 (E31)
1984			Calibrated PCO and PV for QZSS satellites: QZS-1,QZS-2,QZS-3,QZS-4
			Added J002 (J02), J003 (J07), J004 (J03)
			Added JAVTRIUMPH_2A+P JVGR
			TRM159800.00 NONE
			TRM159800.00 SCIS
			TRM159900.00 NONE
			TRM159900.00 SCIS

Table 3: Calibration status of 502 stations in the IGS network (logsum.txt vs. igs14_wwww.atx) compared to former years

Date		Absolute calibration (azimuthal corrections down to 0° elevation)	Converted field calibration (purely elevation-dependent PCVs above 10° elevation)	Uncalibrated radome (or unmodeled antenna subtype)
DEC 2009		61.4%	18.3%	20.2%
MAY 2012		74.6%	8.2%	17.2%
JAN 2013		76.8%	7.7%	15.5%
JAN 2014		78.7%	7.8%	13.5%
JAN 2015		80.1%	7.5%	12.4%
JAN 2016		83.0%	6.5%	10.5%
JAN 2017	igs08.atx:	84.9%	6.2%	8.9%
	igs14.atx:	90.7%	2.2%	7.1%
JAN 2018	igs14.atx:	92.1%	2.2%	5.7%
JAN 2019	**igs14.atx:**	**92.6%**	**1.8%**	**5.6%**

4 Calibration status of the IGS network

Table 3 shows the percentage of IGS tracking stations with respect to certain calibration types. For this analysis, 502 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general/`) were considered. At that time, 98 different antenna/radome combinations were in use within the IGS network. The calibration status of these antenna types was assessed with respect to the phase center model `igs14_wwww.atx` that were released in December 2018. The overall situation regarding the stations with state-of-the-art robot-based calibrations is similar to the one from 2017. After a increasment of 6% from igs08 to igs14 in 2017 another 2% of the IGS stations are covered by robot calibrations. In 2018 the situation has slighlty improved but is very similar to the sitation a year before.

5 Future work

During the splinter meeting at the IGS Workshop 2018 in Wuhan of the antenna working several important tasks were identified which need to be adressed:

- Encourage the calibration centers to start a dedicated validation campaign "ring-calibration". To be presented at the next IGS Workshop 2020.
- Recognizes the lack of missing E5 antenna calibrations. The AWG encourages the calibration centers to extend their software for multi-frequency capacity.
- Working towards a next IGS ANTEX including L5/E5 pattern.

- Provide the IGS ANTEX file for the next reprocessing by June 2019. This includes to explore the possibility to include E5 calibrations and Galileo satellite chamber calibrations
- Creation of a updated ANTEX format 2.0 (separating satellite metadata and antenna calibration).

References

CAO QZS 1-4 Satellite Information URL http://qzss.go.jp/en/technical/qzssinfo/index.html (accessed 2017/01/15)

GSA Galileo IOV and FOC Satellite Antenna Calibrations, SINEX code GSAT_1934 URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/ANTEX_GAL_FOC_IOV.atx (accessed 18/01/26)

GSA Galileo IOV and FOC satellite metadata URL: https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata (accessed 18/01/26)

European GNSS Service Centre. Galileo IOV satellite metadata. https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata, 2016.

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Bias and Calibration Working Group Technical Report 2018

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1 Introduction

The IGS Bias and Calibration Working Group (BCWG) coordinates research in the field of GNSS bias retrieval and monitoring. It defines rules for appropriate, consistent handling of biases which are crucial for a "model-mixed" GNSS receiver network and satellite constellation, respectively. At present, we consider: GPS C1W–C1C, C2W-C2C, and C1W–C2W differential code biases (DCB). Potential quarter-cycle biases between different GPS phase observables (specifically L2P and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and upcoming GNSS, like the European Galileo and the Chinese BeiDou, careful treatment of measurement biases in legacy and new signals becomes more and more crucial for combined analysis of multiple GNSS.

The IGS BCWG was established in 2008. More helpful information and related Internet links may be found at http://www.igs.org/wg. For an overview of relevant GNSS biases, the interested reader is referred to (Schaer 2012).

2 Activities in 2018

- Regular generation of C1W–C1C (P1–C1) bias values for the GPS constellation (based on *indirect* estimation) was continued at CODE/AIUB.
- At CODE, a refined GNSS bias handling to cope with all available GNSS systems and signals has been implemented and activated (in May 2016) in all IGS analysis lines. As part of this major revision, processing steps relevant to bias handling and retrieval were reviewed and completely redesigned. In 2017, further refinements

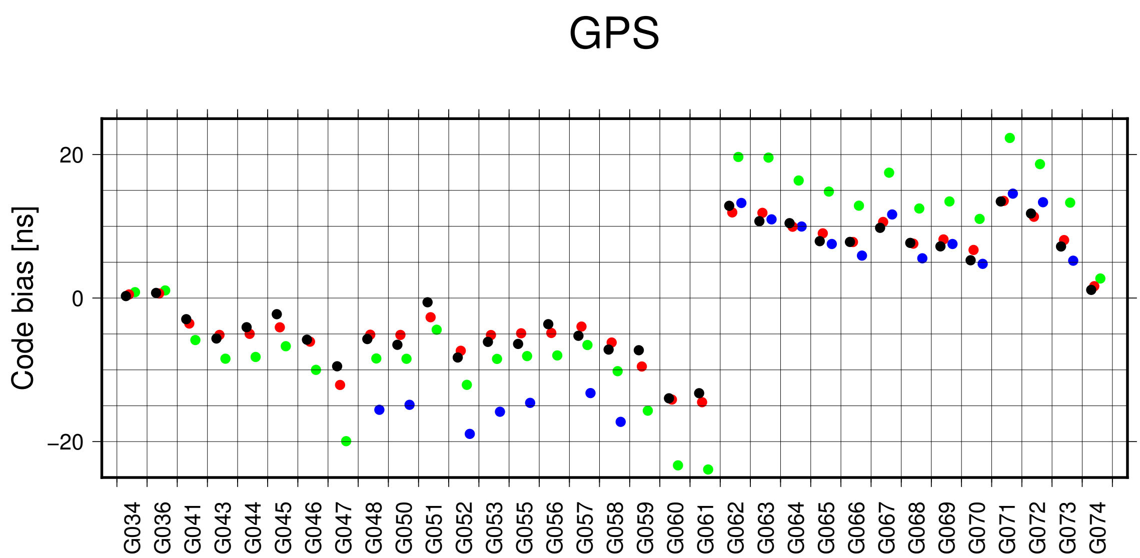

Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2019. Note that G034–G036 correspond to Block IIA; G041–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations and G074 corresponds to the first Block IIIA.

could be achieved concerning bias processing and combination of the daily bias results at NEQ level. A daily updated 30-day sliding average for GPS and GLONASS code bias (OSB) values coming from a rigorous combination of ionosphere and clock analysis is made available in Bias-SINEX V1.00 at:
`ftp://ftp.aiub.unibe.ch/CODE/CODE.BIA`
`ftp://cddis.gsfc.nasa.gov/gps/products/bias/code.bia`

- It should be mentioned that the current GPS C1W-C1C DSB (P1-C1 DCB) product provided by CODE (specifically in the Bernese DCB format) corresponds to a converted extract from our new OSB final/rapid product line.
- Our new bias implementation allows to combine bias results at normal-equation (NEQ) level. We are thus able to combine bias results obtained from both clock and ionosphere analysis, and, moreover, to compute coherent long-term OSB solutions. This could be already achieved for the period starting with epoch 2016:136 up to now. Corresponding long-term OSB solutions are updated daily (see GPS/GLONASS bias results shown in Figures 1 and 2).
- The tool developed for *direct* estimation of GNSS P1–C1 and P2–C2 DCB values is (still) used to generate corresponding GPS and GLONASS bias results on a daily basis.
- The ambiguity resolution scheme at CODE was extended (in 2011) to GLONASS

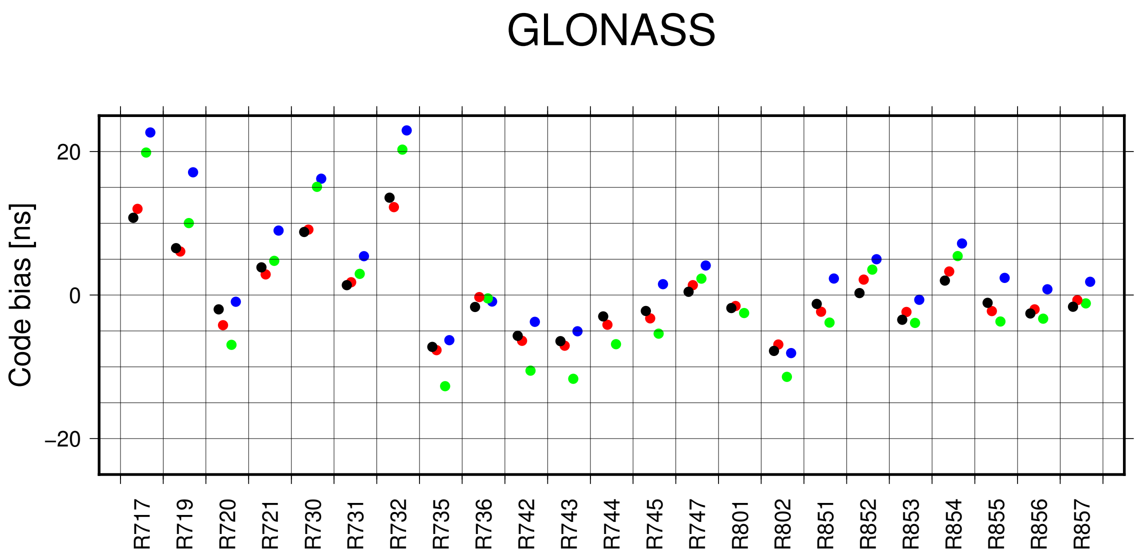

Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2019. Note that R717–R747 and R851–R857 correspond to GLONASS-M; R801–R802 correspond to GLONASS-K1 satellite generations.

for three resolution strategies. It is essential that *self-calibrating* ambiguity resolution procedures are used. Resulting GLONASS DCPB(differential code-phase bias) results are collected and archived daily.

- More experience could be gained concerning station-specific GLONASS-GPS intersystem translation parameters, which are estimated and accumulated as part of CODE's IGS analysis (but completely ignored for all submissions to IGS).

- CODE's enhanced RINEX2/RINEX3 observation data monitoring was continued. Examples may be found at:
  ftp://ftp.aiub.unibe.ch/igsdata/odata2_day.txt
  ftp://ftp.aiub.unibe.ch/igsdata/odata2_receiver.txt
  ftp://ftp.aiub.unibe.ch/igsdata/odata3_gnss_day.txt
  ftp://ftp.aiub.unibe.ch/igsdata/odata3_gnss_receiver.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata2_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata2_d335_sat.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata3_gps_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata3_glonass_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata3_galileo_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata3_beidou_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2018/odata3_qzss_d335.txt
  Internally, the corresponding information is extracted and produced using metadata stored in an xml database (established in December 2014).

3 Last Reprocessing Activities

In 2012: A complete GPS/GLONASS DCB reprocessing was carried out at CODE on the basis of 1990–2011 RINEX data. The outcome of this P1–C1 and P2–C2 DCB reprocessing effort is: daily sets, a multitude of daily subsets, and in addition monthly sets.

In 2016/2017: A GNSS bias reprocessing (for GPS/GLONASS) using the recently implemented observable-specific code bias (OSB) parameterization was initiated at CODE for 1994-2016 RINEX data. The outcome of this reprocessing effort are daily NEQs for GPS and GLONASS OSB parameters from both global ionosphere and clock estimation. A consistent time series of global ionosphere maps (GIMs) with a time resolution of 1 hour is an essential by-product of this bias reprocessing effort.

In 2017: 3-day combined ionosphere solutions were computed for the entire reprocessing period (back to 1994). The ionosphere (IONEX) results (for the middle day) of this computation effort were not yet made available to the public.

4 Computation of Coherent Long-Term GPS/GLONASS Code Bias Solution

The accumulated "bias-NEQs" from our 1994–2016 bias reprocessing in conjunction with those from our operational IGS processing allow us to compute a coherent long-term GPS/GLONASS code bias solution. Such a computation procedure could be successfully implemented. The bias combination procedure is executed on a daily basis thus yielding daily updates for our long-term GPS/GLONASS code bias solution. This NEQ-combined bias solution covers more than 24 years and provides one common datum over the entire period. This particular property is of great interest for those applications where long-term stability is crucial (e.g. for timing, or time transfer applications using GNSS).

The daily bias-NEQ results are re-aligned relying on the unique bias datum provided by our long-term bias solution. This re-alignment of all daily bias retrievals is done once a week. Examples of thus re-aligned time series are shown in Figure 3 for one selected GPS satellite (SVN G046).

A list of instantaneous discontinuities that could be collected as part of the implementation of the long-term code bias combination was an essential outcome. The epochs of this discontinuity list are then used to decide to which combination time window the daily NEQ contributions have to be referred to. Many of these epochs may be associated with a maintenance event as they were announced in GPS NANU messages. The first discontinuity in 2001 in Figure 3 may be attributed to such an event: NANU 2001120: SVN46 (PRN11) UNUSABLE JDAY 256/0030 - JDAY 256/0530.

A detailed description on how the coherent long-term GPS/GLONASS code bias solution

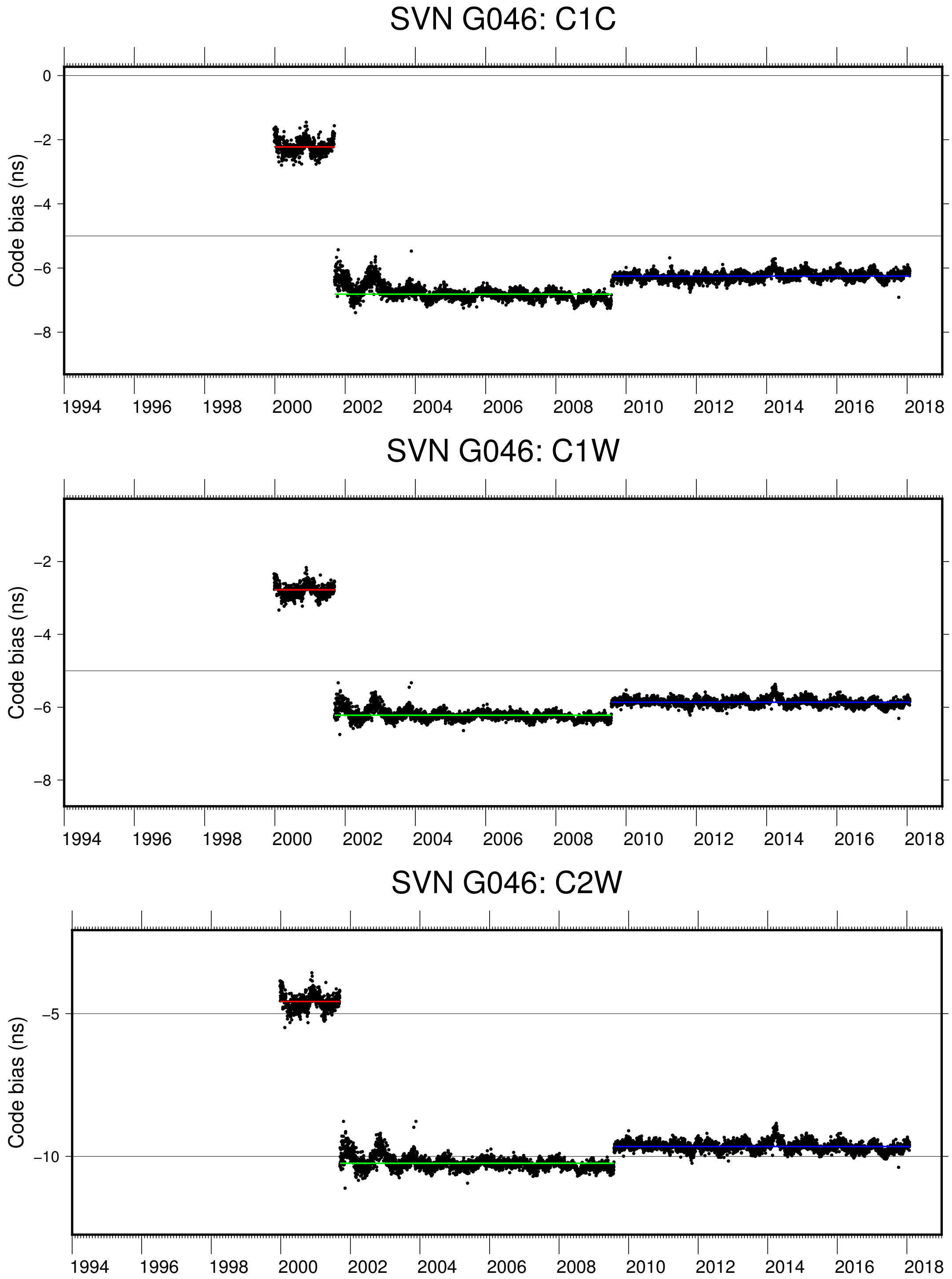

Figure 3: Time series of daily code bias (OSB) estimates for a selected GPS satellite (SVN G046) and various code observable types (C1C, C1W, C2W), computed at CODE on the basis of "bias-NEQs" from a dedicated reprocessing. Note that the daily results were realigned with respect to the combined bias solution (indicated with colored lines).

Code biases

Phase biases

```
OSB  G063 G01          C1C     2018:256:00000 2018:257:00000 ns               11.0960      0.0065
OSB  G063 G01          C2C     2018:256:00000 2018:257:00000 ns               18.2463      0.0103
OSB  G063 G01          C1W     2018:256:00000 2018:257:00000 ns               12.1990      0.0064
OSB  G063 G01          C2W     2018:256:00000 2018:257:00000 ns               20.1247      0.0084
OSB  G061 G02          C1C     2018:256:00000 2018:257:00000 ns              -12.8302      0.0066
OSB  G061 G02          C1W     2018:256:00000 2018:257:00000 ns              -14.1435      0.0065
OSB  G061 G02          C2W     2018:256:00000 2018:257:00000 ns              -23.2726      0.0084
OSB  G069 G03          C1C     2018:256:00000 2018:257:00000 ns                7.3892      0.0065
OSB  G069 G03          C2C     2018:256:00000 2018:257:00000 ns               14.5950      0.0103
OSB  G069 G03          C1W     2018:256:00000 2018:257:00000 ns                8.3351      0.0064
OSB  G069 G03          C2W     2018:256:00000 2018:257:00000 ns               13.8998      0.0084
OSB  G063 G01          L1C     2018:256:00000 2018:257:00000 ns              -0.40989     0.00000
OSB  G063 G01          L1W     2018:256:00000 2018:257:00000 ns              -0.40989     0.00000
OSB  G063 G01          L2C     2018:256:00000 2018:257:00000 ns              -0.67184     0.00000
OSB  G063 G01          L2W     2018:256:00000 2018:257:00000 ns              -0.67184     0.00000
OSB  G063 G01          L2X     2018:256:00000 2018:257:00000 ns              -0.67184     0.00000
OSB  G061 G02          L1C     2018:256:00000 2018:257:00000 ns              -0.86212     0.00000
OSB  G061 G02          L1W     2018:256:00000 2018:257:00000 ns              -0.86212     0.00000
OSB  G061 G02          L2C     2018:256:00000 2018:257:00000 ns              -1.31564     0.00000
OSB  G061 G02          L2W     2018:256:00000 2018:257:00000 ns              -1.31564     0.00000
OSB  G061 G02          L2X     2018:256:00000 2018:257:00000 ns              -1.31564     0.00000
OSB  G069 G03          L1C     2018:256:00000 2018:257:00000 ns              -0.32326     0.00000
OSB  G069 G03          L1W     2018:256:00000 2018:257:00000 ns              -0.32326     0.00000
OSB  G069 G03          L2C     2018:256:00000 2018:257:00000 ns              -0.43774     0.00000
OSB  G069 G03          L2W     2018:256:00000 2018:257:00000 ns              -0.43774     0.00000
OSB  G069 G03          L2X     2018:256:00000 2018:257:00000 ns              -0.43774     0.00000
```

Figure 4: Example for a set of *code* and *phase bias values* for three GPS satellites (G01, G02, G03) as included in a Bias-SINEX V1.00 file.

was computed may be found in (Villiger et al. 2019).

5 Determination of Fractional Phase Biases for Undifferenced Ambiguity Resolution

Our developments towards determination of fractional phase biases for *undifferenced* ambiguity resolution (AR) could be successfully completed. We could show that the new ambiguity-fixed IGS clock analysis product as generated at CODE may be used together with the accompanying bias product for *single-receiver* AR (PPP-AR) (Schaer et al. 2018).

Following our pseudo-absolute (OSB) bias treatment, the retrieved widelane (WL) and narrowlane (NL) fractional phase biases may be finally mapped to a set of L1 and L2 phase biases that is consistent to the two particular linear combinations (LC) that are essential for PPP-AR: namely WL and NL. An essential aspect of our bias treatment is that it is actually irrelevant whether phase-only or code-supported observations are considered when analyzing the ionosphere-free LC (specifically for NL AR).

Figure 4 illustrates how such a consistent set of code and phase bias values may be provided in a Bias-SINEX file. A user may just consider the given set of biases (in combination with a bias-consistent GPS clock product) for all involved code and phase observations (and accordingly derived LCs, such as Melbourne-Wübbena or ionosphere-free LC).

6 Bias-SINEX Format Version 1.00

The latest format document (and the entire format document history) may be found at:

http://www.biasws2015.unibe.ch/documents.html

See:

ftp://ftp.aiub.unibe.ch/bcwg/format/sinex_bias_100.pdf

Schaer et al. (2018) showed that the Bias-SINEX Format Version 1.00 is well suited to provide OSB information for PPP-AR in a consistent, very user-friendly manner (see also Section 5).

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Schaer, S., A. Viliger, R. Dach, L. Prange, A. Jäggi (2018): New ambiguity-fixed IGS clock analysis products at CODE. IGS Workshop 2018, Wuhan, China, 29 October – 2 November 2018.

Villiger, A., S. Schaer, R. Dach, L. Prange, A. Susnik, A. Jäggi (2019): Determination of GNSS pseudo-absolute code biases and their long-term combination. Paper submitted for publication.

IGS Data Center Working Group Technical Report 2018

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1 Introduction

The IGS Data Center Working Group (DCWG) was established in 2002. The DCWG has tackled many of the problems facing the IGS data centers; the WG has also put forward new ideas to aid users both internal and external to the IGS. The direction of the IGS has changed since its start in 1992 and many new working groups, projects, data sets, and products have been created and incorporated into the service since that time. The DCWG was formed to revisit the requirements of data centers within the IGS and to address issues relevant to effective operation of all IGS data centers, operational, regional, and global.

2 Recent Activities

Many of the topics addressed by the IGS DCWG have synergies with the IGS Infrastructure Committee (IC). Therefore, in the past few years, DCWG splinter meetings during IGS workshops have been held in conjunction with the IC splinter meeting. During 2018, work continued on several DCWG items, in particular the integration of GNSS data in RINEX V3 format into the operational archive directories. Although this integration task has progressed well in the past year, work remains to complete the effort for historical data (prior to 2016). The IC and IGS Network Coordinator (NC) continue to work with stations to submit data in RINEX V3 where appropriate.

2.1 Meetings

A meeting of the IGS DCWG was held as part of the IC and RINEX Working Group meeting during the 2018 IGS Workshop in Wuhan China (October 2018). The following recommendations from the IGS IC related to the DCWG were put forward at the Wuhan workshop:

- Prepare the necessary changes to the IGS Terms of Reference and DCWG Charter to end the DCWG and create the DC Coordinator position on the IGS Governing Board.
- Consolidate the 96 sub-hourly high-rate data files into one file (in tar format) per site across IGS DCs.
- Coordinate within the DCs, IC, and NC to move away from using UNIX (Z) compression for all IGS files (data and products), instead using gzip (.gz) for file compression.
- Integrate data prior to 2016 currently stored in MGEX campaign directories into the main GNSS directory structures at the DCs.
- Prepare and integrate GLONASS data and products into the main GNSS directory structures at the DCs.
- Prepare and integrate all MGEX data and products (archived in campaign directories) into the regular GNSS directory structure at the DCs.

2.2 Site Metadata Activities

Another area of interest for the IGS IC and DCWG involves metadata, particularly in the area of site logs. The IGS Central Bureau (CB) uses the Site Log Manager System for handling IGS site logs, which provides a basis for promoting the transmission of these logs in XML format. An XML/database management approach to site logs provides several advantages, such as rapid update of site log contents, utilization of consistent information across data centers, and availability of more accurate station metadata. Interested DCs have been asked to participate in a study organized by Geoscience Australia (GA) and international partners on an eGeodesy project based upon international standards (such as GeodesyML). This work will enable the machine-to-machine communication that will improve the efficiency, robustness, and accuracy with which data and metadata are shared in the IGS community and beyond.

3 Future Plans

The IGS Governing Board is working on updates to the IGS Terms of Reference that will move DCWG activities into the IGS Infrastructure Committee. The newly identified Data Center Coordinator will thus work within the IC, and with other IGS working groups, to address the recommendations from the 2018 IGS Workshop, particularly fully integrating RINEX V3 data and products (from an MGEX campaign directory structure) and GLONASS data and products into the operation, main data directories at the GDCs.

Ionosphere Working Group Technical Report 2018

A. Krankowski[1]*, *M. Hernandez-Pajares*[2]

1 Space Radio–Diagnostics Research Centre
University of Warmia and Mazury in Olsztyn, Poland (SRRC/UWM)
2 UPC–IonSAT, Barcelona, Spain

1 General goals

The Ionosphere Working group started the routine generation of the combine Ionosphere Vertical Total Electron Content (TEC) maps in June 1998. This has been the main activity so far, performed presently by the eight IGS Ionosphere Associate Analysis Centers (IAACs): CODE/Switzerland, ESOC/Germany), JPL/ U.S.A, UPC/Spain, CAS/China, WHU/China, NRCan/Canada and DGFI-TUM/Germany. Independent computations of rapid and final VTEC maps are provided by the each IAAC and with different approaches. Their GIMs are used by the UWM/Poland, since 2007, to generate the IGS combined GIMs. Since 2015 UWM/Poland generate also IGS TEC fluctuations maps.

2 Membership

1. Dieter Bilitza (GSFC/NASA),
2. Ljiljana R. Cander (RAL)
3. M. Codrescu (SEC)
4. Anthea Coster (MIT)
5. Patricia H. Doherty (BC)
6. John Dow (ESA/ESOC)
7. Joachim Feltens (ESA/ESOC)
8. Mariusz Figurski (MUT)
9. Alberto Garcia-Rigo (UPC)
10. Manuel Hernandez-Pajares (UPC)
11. Pierre Heroux (NRCAN)
12. Norbert Jakowski (DLR)
13. Attila Komjathy (JPL)
14. Andrzej Krankowski (UWM)
15. Richard B. Langley (UNB)
16. Reinhard Leitinger (TU Graz)
17. Maria Lorenzo (ESA/ESOC)
18. A. Moore (JPL)

*Chair of Ionosphere Working Group

19. Raul Orus (UPC)
20. Michiel Otten (ESA/ESOC)
21. Ola Ovstedal (UMB)
22. Ignacio Romero (ESA/ESOC)
23. Jaime Fernandez Sanchez (ESA/ESOC)
24. Schaer Stefan (CODE)
25. Javier Tegedor (ESA/ESOC)
26. Rene Warnant (ROB)
27. Robert Weber (TU Wien)
28. Pawel Wielgosz (UWM)
29. Brian Wilson (JPL)
30. Michael Schmidt (DGFI)
31. Mahdi Alizadeh (TU Vienna)
32. Reza Ghoddousi-Fard (NRCAN)
33. Yunbin Yuan (CAS)
34. Zishen Li (CAS)
35. Ningbo.Wang (CAS)
36. Qile Zhao (WHU)

3 Key Issues

a Activities of new IGS ionosphere Associated Analysis Centres: NRCan, CAS, WHU, DGFI-TUM (GIMs) and UWM (ROTI maps).

b Possibility of establishing new IONEX 1.1 format in agreement with IGS Bias and Calibration Working Group.

4 Key accomplishments

a Four new IGS ionospheric processing centres (NRCan, CAS, WHU and DGFI-TUM) have been introduced to the IGS community – already present in CDDIS,

b IGS TEC fluctuation product generated by UWM (ROTI polar maps) – already present in CDDIS,

c We continue the discussion with the IGS Bias and Calibration Working Group about new IONEX 1.1 format.

5 Recommendations after IGS Workshop 2018, Wuhan, China

a To accept DGFI-TUM as new Ionospheric Analysis Center, contributing to the IGS combined VTEC GIMs.

b To aim to additional real-time ionospheric analysis centers to join to the going-on experimental real-time IGS Global Ionospheric Maps combination.

c To aim to additional ionospheric analysis centers to join to the going-on experimental IGS ionospheric ROTI fluctuations maps combination.

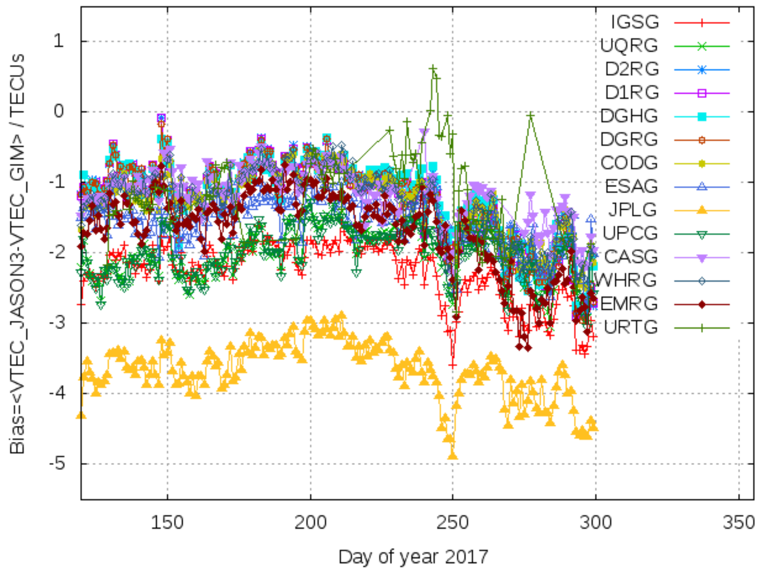

Figure 1: Bias [dV] vs time (from Hernández-Pajares et al. (2018a))

d Cooperation with IRI COSPAR group for potential improvement of both IRI and IGS TEC.

e Cooperation with International LOFAR Telescope (ILT) for potential synergies.

6 Assessment of VTEC provided by DGFI and IGS GNSS-GIMs vs JASON3

The performance of VTEC for IGS and DGFI GIMs has been studied during days 200-303 of the year 2017 (Hernández-Pajares et al. 2018a). The direct and external VTEC measurements of JASON-3 altimeter, smoothed with an sliding window of 16 samples, has been taken as reference like in previous works with main focus on the Standard Deviation of the differences dV=VTEC[JASON]-VTEC[GIM], StDev[dV], not affected by the altimeter calibration bias, relatively important in the present season of low ionization, for which daily time series and cumulative distribution function is shown.

During the period of +100 days (200 to 303, 2017) the performance of final IGS maps, CASG, CODG, EMRG, ESAG, JPLG and UPCG continued being accurate and very consistent between them, with 95% of Std. Dev. of the deviations regarding to the VTEC (StdDev[dV]) directly measured by JASON3 over the oceans, typically far from the GNSS receivers, up to 3-4 TECU.

This is the case as well the new final WHU GIM (labelled so far as WHRG). It is rec-

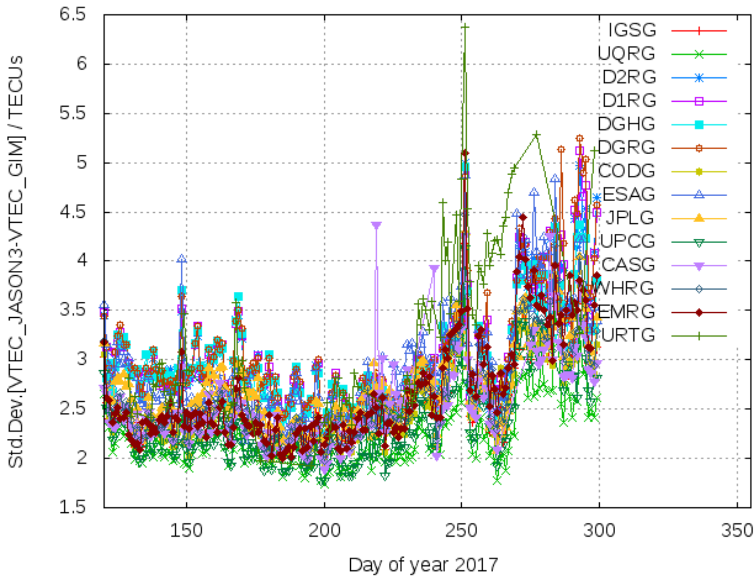

Figure 2: StDev [dV] vs time (from Hernández-Pajares et al. (2018b))

ommended to perform the replacement using the final identification (WHUG) in the IGS servers, like CDDIS.

The different DGFI GIMs are very consistent between them, and also with the final IGS maps, with 95% of the StdDev[dV] around 3.8 to 4.3 TECU. The performance of the rapid IGS seems to be slightly better than the performance of the final IGS. The 95% of daily StdDev[dV] values of RT UPC GIM are below 6 TECU approximately.

7 Looking for optimal ways to combine IGS Global Ionospheric Maps (GIMs) in real-time

At IGS Workshop 2018 in Wuhan the team of IGS IONO Working Group formed by David Roma-Dollase, Manuel Hernández-Pajares, Alberto García-Rigo, Andrzej Krankowski, Adam Fron, Denis Laurichesse, Alexis Blot, Raul Orus-Perez, Yunbin Yuan, Zishen Li, Ningo Wang, Michael Schmidt, Eren Erdogan has presented a recent progress on efforts towards elaboration of weighting scheme for future Real-Time Global Ionospheric Map (RT-GIM).

The increase in the availability of real-time (RT) GNSS receivers facilitates the generation of different RT global ionospheric maps (RT-GIMs) in the context of IGS affiliated institutes with different pros and cons and in a process of continuous improvement. This situation is similar to the one in 1998, which opened the way to generate postprocessed global ionospheric maps (P-GIMs).

Indeed, the P-GIMs have been generated on daily basis uninterruptedly since June 1, 1998, with latencies of one day for rapid and several days for final ionospheric product. The independently computed GIMs of the different analysis centers, presently seven, have been combined thanks to a simple weighting scheme. It is based on the daily-global RMS obtained from the discrepancies between observed and modelled STEC changes over a set of 15 receivers worldwide distributed. This approach has been working reasonably well for 20 years.

During previous IGS2017 workshop, different possibilities for adapting the postprocessing weighting scheme to real-time were initially discussed.

This result is representative of the very first combined RT-IGS maps, by using a single worldwide weight, recomputed each 20 minutes. The RT combined GIM is performing slightly better (2.85 TECUs St.Dev. vs JASON3 VTEC) than the three RT-GIMs, and only 0.6 TECU worse than the rapid UQRG GIM.

A first combination of RT GIMs (IRTG) is continuously and consistently working at UPC facilities, fulfilling the commitment from previous IGS WS 2017 and is being obtained by computing, each 20 minutes, a new global weight for each one of the three independent RT-GIMs: from CAS (CAS05), CNES (CLK91) and UPC (URTG).

The weights are given by the inverse of the squared RMS of the dSTEC error, taking as reference observation the first one of each given phase-continuous-transmitter-receiver arc during the last hour with elevation higher than 10°, and with a difference of at least 25° with the first one, and a minimum of 50 observations per arc.

The performance of the first RT combinations, compared with the external JASON-3 VTEC, seems slightly better than the one of the combined RT-GIMs, while the potential performance improvement after double checking the RTCM encoding of all the GIMs and after adding a geographical variability in the weight, including the spectral domain, can be studied in the future.

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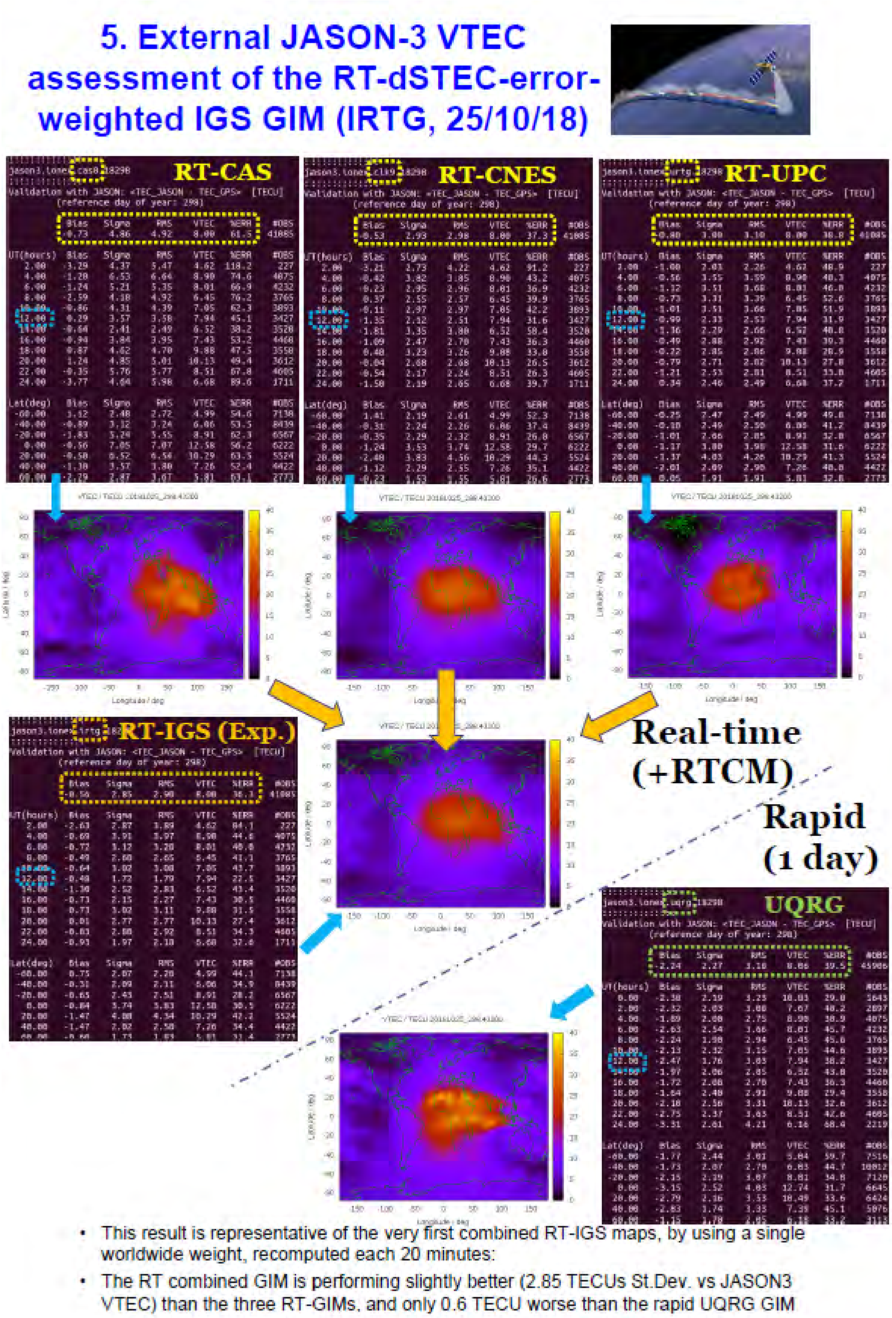

Figure 3: EExternal JASON-3 VTEC assessment of the RT-dSTEC-error- weighted IGS GIM (IRTG, 25/10/18)

Multi-GNSS Working Group Technical Report 2018

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1 Introduction

The Multi-GNSS Working Group (MGWG) is coordinating the activities of the Multi-GNSS Pilot Project (MGEX). MGEX is providing multi-GNSS products focusing on the global systems Galileo and BeiDou as well as the regional QZSS and IRNSS (NavIC). A few changes of membership of the MGWG occurred during the reporting period:

- Lars Prange succeeded Rolf Dach as representative of CODE
- Shuli Song joined the MGWG representing SHAO
- Sebastian Strasser of TU Graz joined the working group
- Ahmed ElMowafy, Heinz Habrich, and Rene Warnant left the working group

2 GNSS Evolution

The numerous 2018 satellite launches of the four global systems GPS, GLONASS, Galileo, and BeiDou as well as the regional IRNSS are listed in Table 1. Altogether 16 BeiDou-3 medium Earth orbit (MEO) satellites and one BeiDou-3 geostationary Earth orbit (GEO) satellite have been launched. The Interface Control Document (ICD) for the BeiDou open service signal B3I transmitted by BeiDou-2 and BeiDou-3 satellites has been published in February 2018 (CSNO, 2018). Based on a constellation of 18 BeiDou-3 MEO satellites, global services were declared on 27 December 2018.

The Galileo quadruple launch in July 2018 completed the nominal Galileo constellation paving the road for full operational capability with now 26 satellites in orbit. Two

Table 1: GNSS satellite launches in 2018.

Date	Satellite	Type
11 Jan 2018	BeiDou-3 M7 and M8	MEO
12 Feb 2018	BeiDou-3 M3 and M4	MEO
29 Mar 2018	BeiDou-3 M9 and M10	MEO
11 Apr 2018	IRNSS-1I	IGSO
17 Jun 2018	GLONASS 856	MEO
09 Jul 2018	BeiDou-2 IGSO 7	IGSO
25 Jul 2018	Galileo FOC-19 – 22	MEO
29 Jul 2018	BeiDou-3 M5 and M6	MEO
24 Aug 2018	BeiDou-3 M11 and M12	MEO
19 Sep 2018	BeiDou-3 M13 and M14	MEO
15 Oct 2018	BeiDou-3 M15 and M16	MEO
01 Nov 2018	BeiDou-3 GEO	GEO
03 Nov 2018	GLONASS 857	MEO
18 Nov 2018	BeiDou-3 M17 and M18	MEO
23 Dec 2018	GPS III-1	MEO

GLONASS-M satellites were launched in 2018, launches of the next generation GLONASS-K2 satellites are expected for 2019. The IRNSS-1I satellite is a replacement for IRNSS-1A suffering from clock failures but still transmitting navigation signals. L5 signal transmission of IRNSS-1I started on 8 November 2018 with PRN I09. Finally, the first GPS III satellite was launched on 23 December 2018. Whereas no QZSS satellites were launched in 2018, the QZSS services officially started on 1 November 2018 (GPS World Staff 2018).

In November 2018, the updated RINEX 3.04 file format (IGS RWG and RTCM, 2018) was published including the definition of observation codes for the new signals of BeiDou-3 and QZSS Block II satellites, as well as GLONASS Code Devision Multiple-Access (CDMA) signals planned for the GLONASS-K2 satellites.

BeiDou-3 signals:

- B1A BOC(14,2) authorized signal at the GPS L1 frequency of 1575.42 MHz.
- B1C BOC(1,1) and QMBOC(6,1,4/33) open service signals at 1575.42 MHz (CSNO, 2017a).
- B2a QPSK(10) open service signal at the GPS L5/Galileo E5a frequency of 1176.45 MHz (CSNO, 2017b).
- B2b QPSK(10) open service signal at the Galileo E5b frequency of 1207.14 MHz (no ICD available). This frequency is used by BeiDou-2 satellites for the open service BPSK(2) and the authorized service BPSK(10) signals.
- B2 (=B2a+B2b) ACE-BOC(15,10) open service signal at the Galileo E5 frequency

of 1191.795 MHz (no ICD available).

- B3A QPSK(10) authorized signal at 1268.52 MHz.

QZSS Block II signals:

- L5S Positioning Technology Verification Service signal at 1176.45 MHz (IS-QZSS-TV-001 2018).

- L62 Centimeter Levels Augmentation Service (CLAS) signal at 1278.75 MHz (IS-QZSS-L6-001 2018).

GLONASS CDMA signals:

- G1a BPSK(1) open service signal at 1600.995 MHz (Russian Space Systems 2016a).

- G2a BPSK(1) open service signal at 1248.06 MHz (Russian Space Systems 2016b).

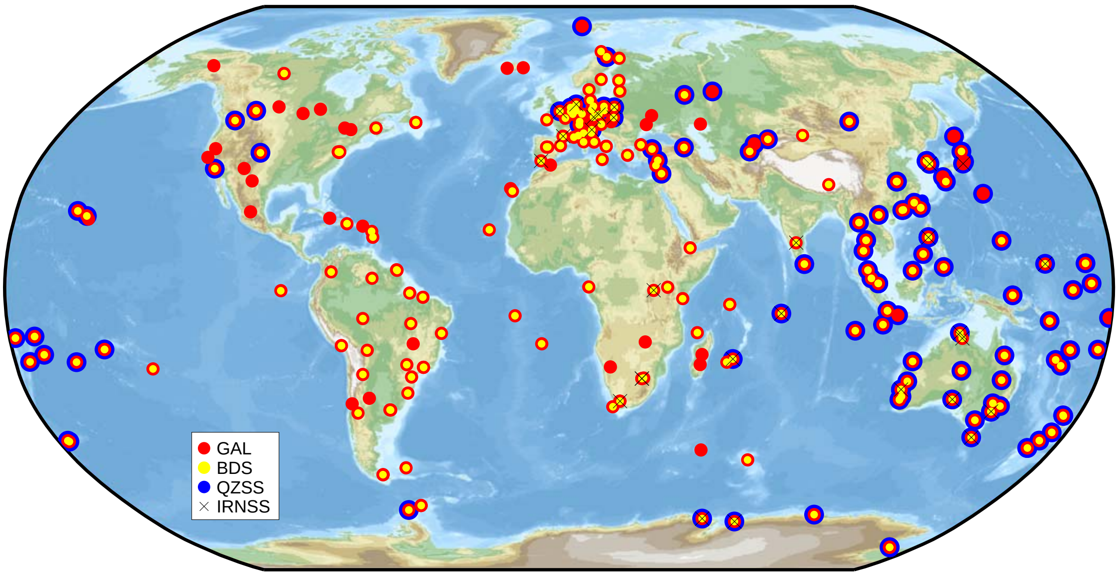

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2019.

3 Network

As of January 2019, the IGS multi-GNSS tracking network comprises 278 stations. Compared to the end of 2017, this is an increase of 60 stations mainly due to updates of existing IGS stations with multi-GNSS receivers. However, five of these stations did not provide any tracking data in 2018. Since the global service declaration of BeiDou, the tracking of BeiDou-3 signals by IGS receivers has significantly improved although there are currently

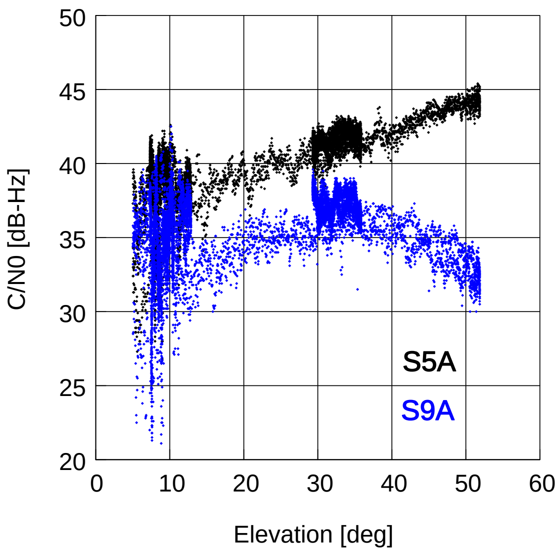

Figure 2: Carrier-to-noise-density ratio for IRNSS L5 (S5A) and S-band (S9A) tracking of the IGS station Ganovce (GANP00SVK).

still several limitations:

- Trimble NetR9 receivers are limited to PRNs up to C30
- Septentrio and Javad receivers are limited to PRNs up to C37
- No receiver of the IGS network supports tracking of PRNs beyond C37 (currently C57 and C58 are used by two BeiDou-3S MEO satellites and C59 by a BeiDou-3 GEO satellite)
- Javad TRE_G3TH, Leica, and Septentrio PolaRx4 receivers provide only single-frequency observations (B1-2)
- Septentrio PolaRx5 receivers need firmware 5.2.0 to provide dual-frequency observations (B1-2 and B3)
- Trimble NetR9 receivers need firmware 5.37 to provide dual-frequency observations (B1-2 and B3)
- Trimble Alloy receivers with firmware 5.37 support tracking of three different signals (B1-2, B2a, B3)
- Javad TRE_3 receivers with firmware 3.7.5 support tracking of five different signals (B1-2, B2a, B2b, B2, B3)

However, deviations from the general tracking capabilities listed above may occur for individual stations and satellites. As already mentioned before, the B2b signals differ for BeiDou-2 and BeiDou-3. Therefore, different observation codes are used for these signals in RINEX 3.04. However, the BeiDou-2 B2b RINEX observation codes are still used for BeiDou-3 B2b signals by several stations.

Since beginning of 2018, the first commercial receiver providing IRNSS S-band tracking is available. As of the end of 2018, two stations of the IGS network operate such a receiver but only one station provides IRNSS observations. However, the S-band signal quality is degraded due to the lack of an appropriate receiver antenna, see Fig. 2.

4 Products

The current list of MGEX analysis centers as well as the GNSSs covered by their orbit and clock products are given in Table 2. A complete list of products generated by the individual analysis centers is available at the MGEX website at http://mgex.igs.org/IGS_MGEX_Products.php. Shanghai Observatory (SHAO) joined the group of MGEX analysis centers providing a rapid product covering the four global systems. Further updates of the MGEX orbit and clock products include:

- The QZSS GEO satellite J003 (PRN J07) is included in the GFZ products since 261/2018 and in the TUM products since 281/2018.
- CODE provides an ambiguity-fixed clock solution for GPS and Galileo since GPS week 2006 (Dach et al. 2018).
- CNES/CLS introduced ambiguity fixing for Galileo in their MGEX contribution in GPS week 2022. As a consequence, the products allow for integer PPP with Galileo (Katsigianni et al. 2019).
- Starting with GPS week 2025 CNES/CLS uses long filenames (Steigenberger and Montenbruck 2018) for their products.

Multi-GNSS differential code bias (DCB) products are generated by CAS (daily rapid product) and DLR (quarterly final product). Galileo C1C-C6C as well as QZSS DCBs were added to the CAS product on day of year 237/2018 and BeiDou-3 C2I-C7I DCBs are included in the DLR product starting with the first quarter of 2018.

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	GRG0MGXFIN	GPS+GLO+GAL
CODE	COD0MGXFIN	GPS+GLO+GAL+BDS+QZS
GFZ	gbm	GPS+GLO+GAL+BDS+QZS
JAXA	JAX0MGXFIN	GPS+GLO+QZS
SHAO	SHA0MGXRAP	GPS+GLO+GAL+BDS
TUM	tum	GAL+QZS
Wuhan University	wum	GPS+GLO+GAL+BDS+QZS

5 Satellite Metadata

During 2018, the satellite metadata extension for the solution independent exchange (SINEX) format already presented in Steigenberger and Montenbruck (2018) was consolidated. The preliminary format description is available at http://mgex.igs.org/IGS_MGEX_Metadata_Format.php, example files at http://mgex.igs.org/IGS_MGEX_Metadata.php. The latter are presently maintained and updated by DLR on reasonable-effort basis.

Reverse PPP analysis of Dilssner (2018) revealed that the BeiDou-2 IGSO 7 satellite (C019) does also not enter orbit-normal mode like selected other BeiDou-2 satellites (Dilssner 2017). For the BeiDou-3 MEO satellites manufactured by Shanghai Engineering Center for Microsatellites (SECM) a subset of metadata was published: mass, dimensions, satellite antenna phase center offsets, laser retroreflector offsets, and attitude law (SECM, 2018). Corresponding information for the second type of BeiDou-3 MEO satellites by China Academy of Space Technology (CAST) is currently not available.

Acronyms

CAS Chinese Academy of Sciences

CLS Collecte Localisation Satellites

CNES Centre National d'Etudes Spatiales

CODE Center for Orbit Determination in Europe

DLR Deutsches Zentrum für Luft- und Raumfahrt

GFZ Deutsches GeoForschungsZentrum

JAXA Japan Aerospace Exploration Agency

SHAO Shanghai Observatory

TUM Technische Universität München

WU Wuhan University

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IGS Realtime Service

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1 Introduction

The Real Time Service (RTS) expands the capacity of the International GNSS Service (IGS) to support applications requiring real-time access. It utilises a global receiver network and provides infrastructure for data and product dissemination. Analysis products include clock and orbit correction estimates for GPS and GLONASS by individual Analysis Centres (AC) as well as combination solutions. More and more AC include other constellations such as Galileo, Beidou and QZSS and estimate for additional SSR parameters, such as bias parameters or ionospheric delays. The IGS-RTS supports a large variety of potential applications with a strong focus on science and education.

2 Observation network and real time data centers

The IGS-RTS is based on a global network of IGS stations providing data streams to the RTS observation broadcasters. All stations are operated by a large number of contributors on a best effort basis. Many stations broadcast multi GNSS observation data from GPS, GLONASS, Galileo, Beidou, QZSS and SBAS satellites (Figure 1). Currently, the main IGS observation casters on the first level are operated by BKG, CDDIS and the IGS Central Bureau (Figure 2, Table 1). All casters require individual registration on their webpages.

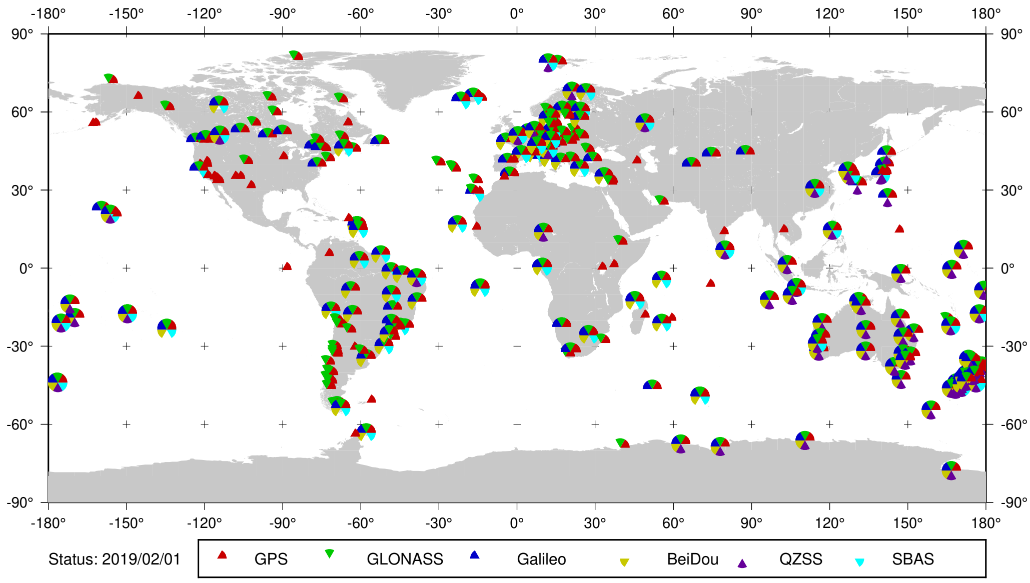

Figure 1: Multi GNSS observation data delivered by the IGS global observation network.

Table 1: First level observation broadcasters of the IGS RTS.

Data center	Caster Adress
BKG IGS-Caster	`http://igs-ip.net`
BKG MGEX-Caster	`http://mgex.igs-ip.net`
BKG Products-Caster	`http://products.igs-ip.net`
IGS Central Bureau	`http://gnssdata-ch1.cosmic.ucar.edu`
CDDIS	`https://cddis-caster.gsfc.nasa.gov`
ESAC	(tbc)

The caster managed by the IGS Central Bureau and operated at the University Corporation for Atmospheric Research (UCAR) is going to be decommissioned in the near future. Its data streams will be serviced by other first level IGS casters.

A new first level caster has been installed by the European Space Agency at the European Space Astronomy Center (ESAC). Several independent casters support the IGS RTS concept of at least two individual data streams from the observation sites to one of the global data centres in order to improve redundancy of the network in the case of a casters failure.

The IGS supports open data standards and all casters provide data streams following the RTCM (Radio Technical Commission for Maritime Services) standard. The new constellations Galileo, BeiDou and QZSS are supported by the RTCM3 Multi-Signal-Messages (RTCM-MSM) only. There is a significant increase of receivers providing RTCM-MSM data streams directly in the last years. Now, about 60% of the data streams on BKG's caster `igs-ip.net` are disseminated in RTCM-MSM format (Figure 3). 28% of the RTCM-MSM streams are MSM4, 8% MSM5 and 64% MSM7 data streams (Figure 4).

BKG's MGEX-caster (`mgex.igs-ip.net`) disseminates data streams which were converted form raw format into RTCM-MSM7 by an external software tool. As soon as receiver generated RTCM-MSM are available, the data streams are transferred to the `igs-ip.net` caster and the MGEX-caster will become obsolete over time.

Figure 5 gives an overview of constellations within the RTCM-MSM streams on both BKG casters.

In addition to the three first level casters, regional caster cover a large amount of work load. Among others, regional casters are operating at Wuhan University/China and Geoscience Australia. Other regional data centres are proposed for North and South America and Europe.

The RT-WG endorsed a new schema for naming the observation mount points across all IGS casters. The BKG and the IGS CB and have widely introduced the new mount point names. The CDDIS caster operators have started the transition to the long mountpoint names.

3 State Space Representation correction streams

In 2018, eight real time Analysis Centres (AC) provided epoch-wise orbit and clock products and ensure a high redundancy of the service on the one hand and a strong quality control on the other hand. The estimates are converted into RTCM SSR format and can be accessed via IGS RTS product caster at BKG and the first level casters of CDDIS and IGS Central Bureau (cf. Table 1). The orbit products are available with respect to the satellite Antenna Phase Centre (APC) and in most cases they are also available with

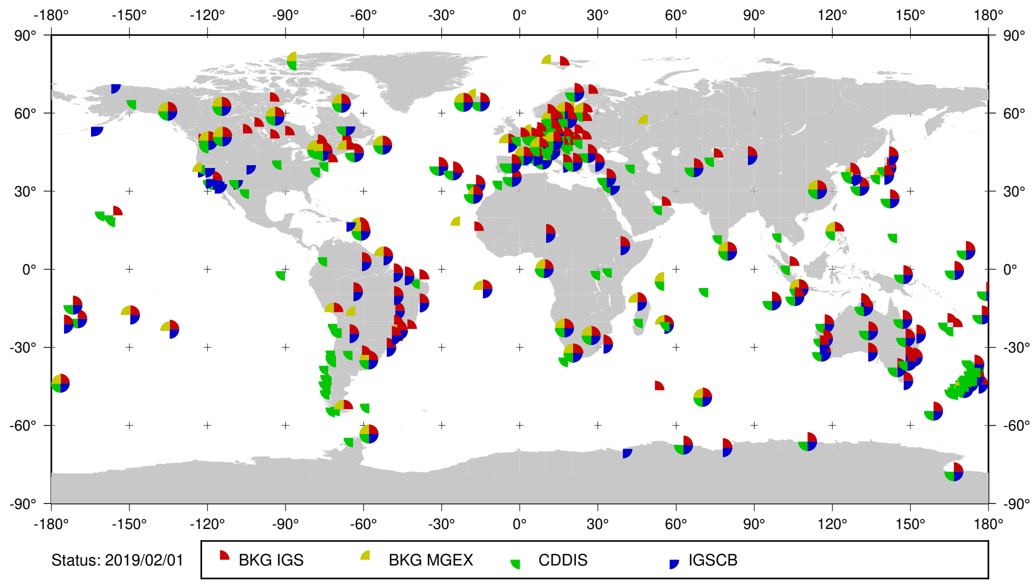

Figure 2: Station network of the IGS real time service delivered by the different first level casters (cf. Table 1).

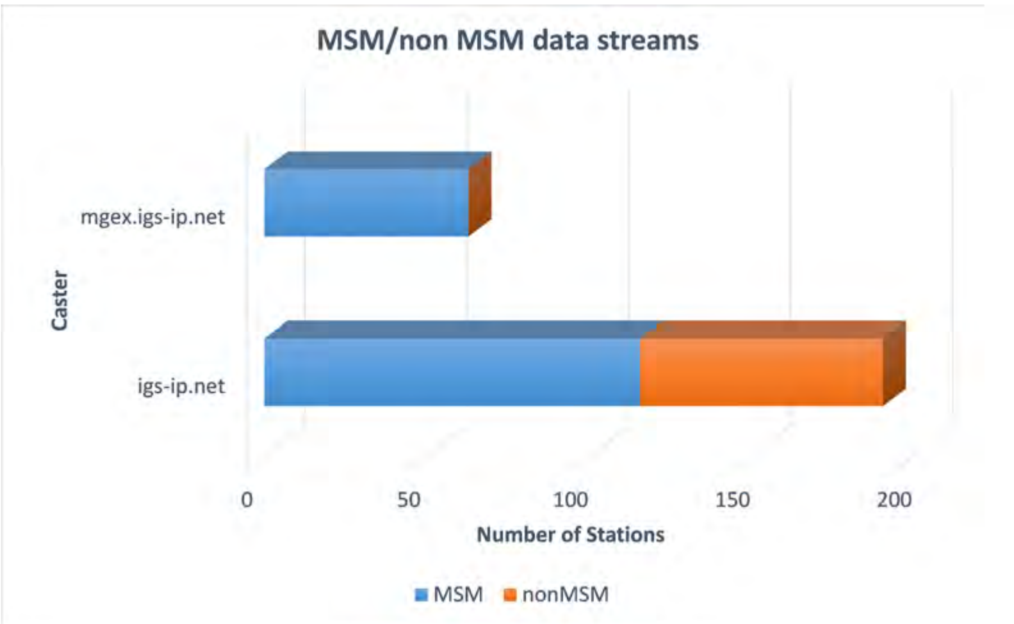

Figure 3: Number of stations of the global IGS RT network broadcasting receiver generated RTCM3 Multi-Signal-Messages (MSM).

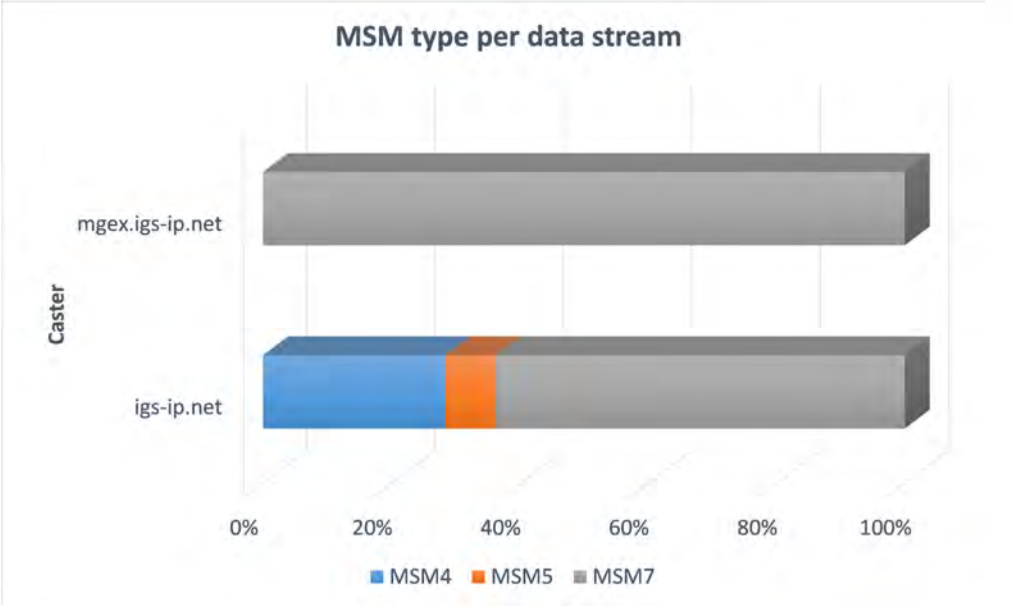

Figure 4: Fractions of the different RTCM3 Multi-Signal-Message types, MSM4, MSM5 and MSM7 respectively delivered by the global IGS RT network. The MSM7 observation streams on the BKG MGEX-caster are software generated streams. All streams in the BKG IGS-caster are receiver generated streams.

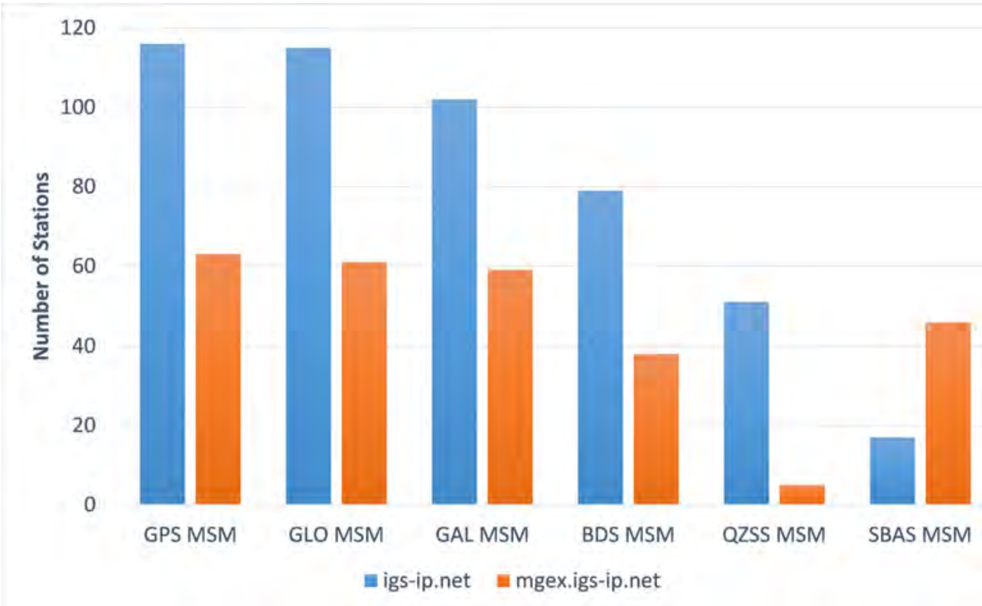

Figure 5: Number of stations broadcasting RTCM3 Multi-Signal-Messages for different GNSS constellations. Streams at the BKG IGS-caster are receiver generated, streams at the BKG MGEX-caster are software generated.

respect to the Centre of Mass (CoM). The clock products are updated every 5 seconds. In addition to GPS and GLONASS corrections, the ACs at CNES, GFZ and DLR provide satellite orbit and clock corrections for Galileo and Beidou. GMV provides in addition to GPS and GLONASS solutions code biases for Galileo.

Because the SSR format description for Galileo and Beidou satellite orbit and clock corrections has not yet been endorsed by the RTCM SC104 committee proposed message formats are used. Table 2 gives a summary of all individual product streams by the different ACs.

After processing the individual AC solutions in real time, RTS combination products are made available to users of the service (Table 3). Two basic techniques, a single epoch combination developed by ESOC and a Kalman filter based combination developed by BKG and Prague Technical University, are used. Although a combination increases the robustness of the product it also increases the latency of the combined product significantly. Since many of the individual streams have a latency of about 10s or less, the latency of the combined product is in the range of 20-30s. The reduction of latency is an important goal of the real time service and requires an optimized selection of reference stations and processing schemes. The website `https://igs.bkg.bund.de/ntrip/ppp` gives additional information of the actual performance of the service.

Figure 6 shows GPS orbit and clock performance of the individual AC solutions using daily comparisons against the IGS rapids. Most solutions show a similar consistency and ESOC orbit results and CNES clock results bound the lower end of the respective scale. After a new software was deployed by GMV, their orbit and clock results have improved considerably in October 2018.

Figure 7 represents the availability of individual GPS solutions with respect to the maximum number of 8928 samples. Most solutions provide full corrections for 30 to 31 satellites. The DLR and WUHAN solutions have been unavailable temporarily but recovered in the meanwhile.

Figure 8 reports on the orbit and clock performance of the IGC01 combined solution from ESOC. There is a increased orbit scatter since October 2014, mainly due to unmodelled Block II-F events. The combination significantly reduces the orbit scatter in comparison to individual AC solutions. The clock results show a good consistency.

Figure 9 displays the GLONASS orbit and clock solution performance. The orbit results are 2 to 3 times worse than the GPS solution and also the clocks show a significantly higher scatter than GPS. The availability of currently three individual GLONASS solutions makes it difficult to provide a fully available combination. The clock solutions show a similar consistency for all ACs. The combined result has a higher standard deviation than the individual AC but this does not seem to affect the PPP performance.

The transition of the IGS RTS towards a real multi GNSS service is a clear necessity in order to serve science and society in agreement to the IGS mission. The observation

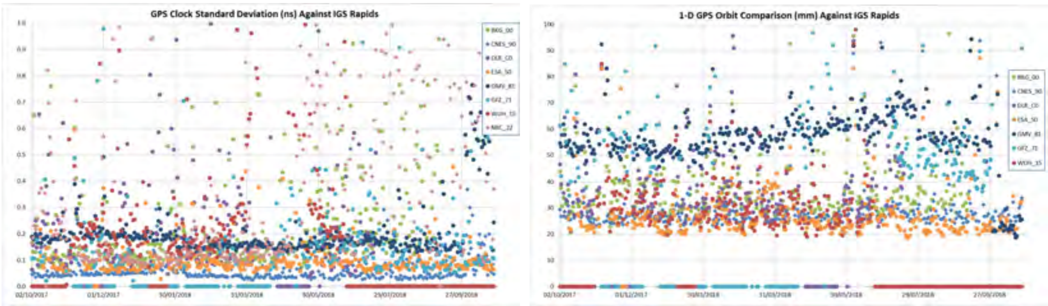

Figure 6: Performance of orbit and clock estimates for the IGS RTS GPS solutions. Left: orbit solutions, right: clock solutions.

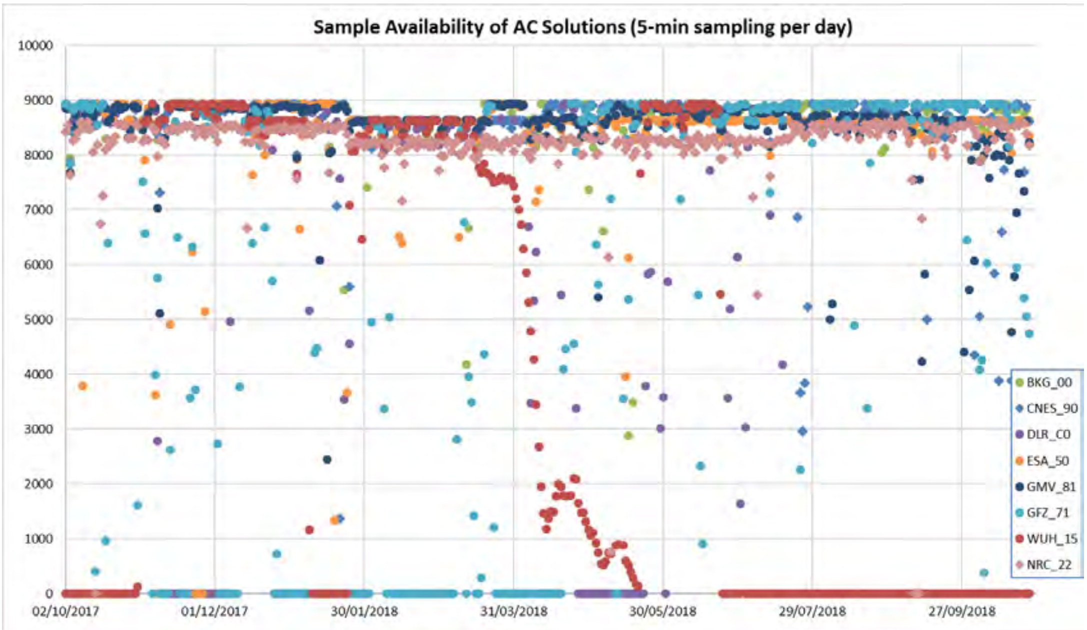

Figure 7: Availability of GPS solutions. A full availability for 31 satellites implies 8928 samples.

network provides multiGNSS observations already with a good global coverage and more and more ACs submit multiGNSS SSR correction data to the IGS RTS product casters. In the future, new capabilities for comparison and combination of these new products need to be developed. In addition, the developement and approval of new SSR data formats by the RTCM need to be encouraged and supported.

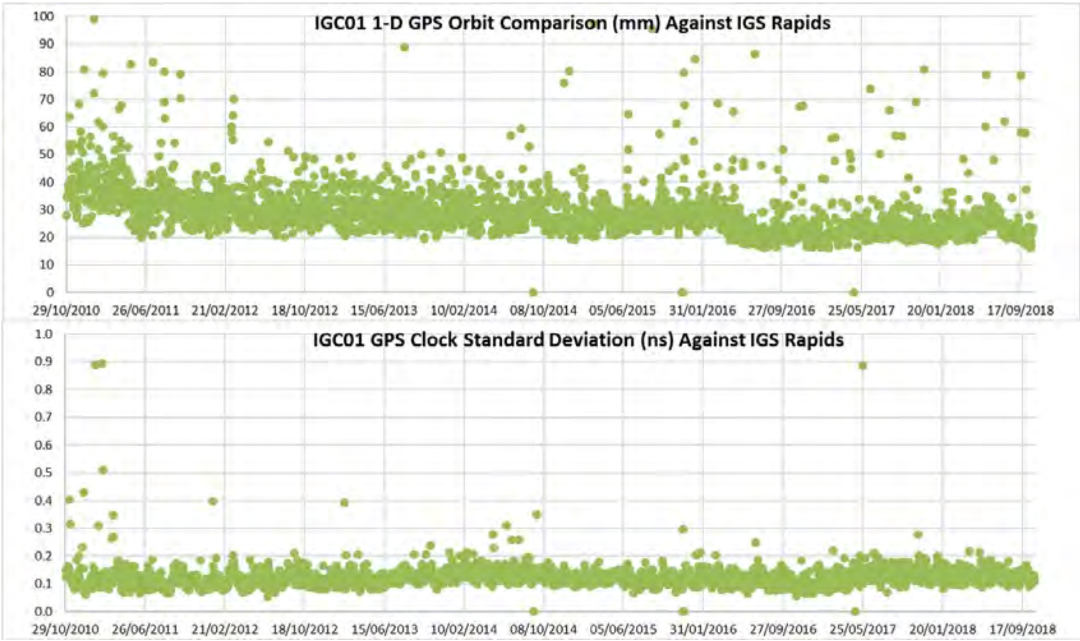

Figure 8: IGC01 ESOC combined solution performance of GPS orbit and clock solutions. Top: 1 day orbit comparison against IGS rapid products [mm]. Bottom: GPS clock standard deviation against IGS rapid products [ns].

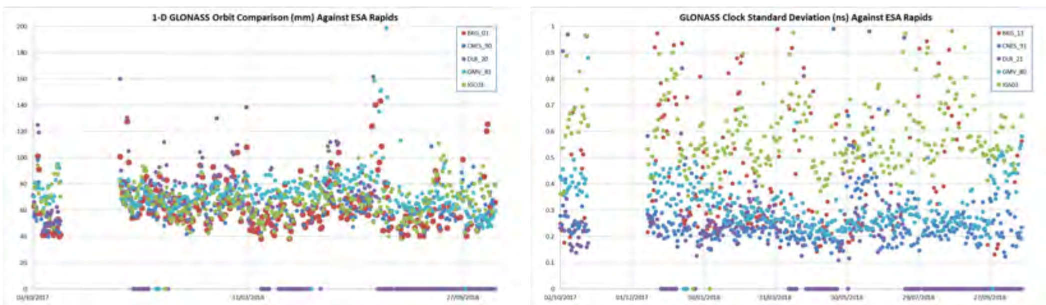

Figure 9: Performance of orbit and clock estimates for the IGS RTS GLONASS solutions. Left: orbit solutions, right: clock solutions.

Table 2: Correction streams from IGS Real Time Service by individual ACs

Center	Description	NTRIP MP CoM/APC
BKG	GPS GPS + GLONASS RT orbits and clocks using IGU orbits	CLK00/10
	GPS + GLONASS RT orbits and clocks using IGU orbits	CLK01/11
CNES	GPS+GLONASS orbits and clocks	CLK90/91
	GPS+GLONASS+Galileo+Beidou orbits and clocks	CLK92/93
DLR	GPS+GLONASS+ Galileo+Beidou RT orbits and clocks	CLK20/21
ESOC	RT orbits and clocks using NRT batch orbits every hour which are based on IGS Batch hourly files	CLK50/51
	RT orbits and clocks using NRT batch orbits every hour which are based on RINEX files generated from the RT stream	CLK52/53
GFZ	GPS+GLONASS+Galileo+Beidou RT orbits and clocks	CLK70/71
GMV	GPS + GLONASS orbits and clocks based on NRT orbit solution + Galileo Code Biases	CLK81/80
NRCan	GPS orbits and clocks using NRT batch orbits every hour	-/CLK22
WUHAN	GPS orbits and clocks based on IGU orbits	CLK15/16

Table 3: Combined correction stream by IGS Real Time Service by individual Combination Centres

Centre	Description	NTRIP MP
ESOC	GPS-only combination – epoch-wise approach	IGC01/IGS01
BKG	GPS-only combination – Kalman filter approach	-/IGS02
	GPS+GLONASS combination – Kalman filter approach	-/IGS03

4 Summary

The observation data and products of the IGS RT Service rely on the effort of a large number of contributors: Station operators, software developers, data centers and analysis centers. Real time orbit and clock products allow users a real time positioning at decimetre accuracy using PPP.

The IGS RTS ensures open access to its data and products and supports open standards and data formats. Data and products are provided via TCP/IP connections. The range of applications is focused on scientific and educational topics, such as positioning, navigation and timing, Earth observations and research; and other applications that benefit the scientific community and society.

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RINEX/RTCM Working Group Technical Report 2018

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1 2018 Highlights

1. RINEX Version 3.04 released in November 2018. Most significant updates: support for new BeiDou 3, QZSS 2 and GLONASS CDMA signals and numerous text and message clarifications.
2. RTCM SC-104 Activities: the IGS Real-Time Service uses RTCM State Space Representation (RTCM-SSR) messages. Currently, several draft messages have been defined and are at the interoperability testing stage. These draft messages include: phase bias, Vertical TEC (VTEC), Galileo and QZSS orbit and clock corrections. The phase bias messages have held up the approval process as the RTCM SC-104 has determined that there has been insufficient interoperability testing. Geo++ are leading this effort and are reassessing their options and deciding how to proceed. IGS partners are using draft message formats. While not having official RTCM messages is inconvenient, it has not severely affected IGS operations.
3. RTCM SC-104/IGS GNSS Receiver Calibration Working Group. One zero baseline data collection session has been completed and results presented. Another data collection session will take place when GNSS receivers are capable of tracking BeiDou 3 signals.

2 2019 Plans

1. Continue to update the RINEX 3.0x documentation to meet the needs of the GNSS community. Work with RTCM SC-104 to define new navigation messages to support

the contents of the CNAV and CNAV 2messages. Work with the RINEX WG to define a RINEX generic navigation message. Release a draft CNAV format in 2019.

2. Work with the IGS and RTCM Bias Working group to define the standard operating procedure of the working group. Conduct a data collection session when GNSS receivers support new BeiDou or GLONASS signals. Data from receivers running released firmware will be freely available.

3. Attend RTCM SC-104 North American meetings. Work with the BeiDou, QZSS and GLONASS RTCM SC-104 working group chairpersons to update the RTCM-MSM signal mapping tables. Ensure that RTCM SC-104 messages meet the needs of the IGS and high precision GNSS community. Communicate and coordinate IGS partners needs to the RTCM. Prepare meeting reports for the IGS Governing Board.

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Tide Gauge Benchmark Monitoring Working Group Technical Report 2018

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1 Introduction

The Tide Gauge Benchmark Monitoring Working Group (TIGA) of the IGS continues its support for climate and sea level related studies and organizations concerned herewith (e.g., GGOS, OSTST, UNESCO/IOC). The TIGA WG provides vertical geocentric positions, vertical motion and displacements of GNSS stations at or near a global network of tide gauges and works towards establishing local geodetic ties between the GNSS stations and tide gauges. To a large extend the TIGA Working Group uses the infrastructure and expertise of the IGS.

The main aims of the TIGA Working Group are:

1. Maintain a global virtual continuous GNSS @ Tide Gauge network
2. Compute precise coordinates and velocities of GNSS stations at or near tide gauges. Provide a combined solution as the IGS-TIGA official product.
3. Study the impacts of corrections and new models on the GNSS processing of the vertical coordinate. Encourage other groups to establish complementary sensors to improve the GNSS results, e.g., absolute gravity sites or DORIS.
4. Provide advice to new applications and installations.

2 Main Progress in 2018

- Working group meeting during the IGS Workshop in Wuhan/China. The participation was limited, but the TIGA-AC's considering the participation in IGS-repro3 or planning to align their activities with IGS-repro3.
- With the help of the TIGA Data Center, IGS, UNAVCO and the IGS-IC the integration of Tide Gauge information into the IGS Web Site (http://www.igs.org/network) was planed, programmed and is now online.
- TIGA Network operator continues to works with Tide Gauge and GNSS station operators to make existing stations available to TIGA, a main (ongoing) task is to continuously update the current database of existing local ties between GNSS and tide gauge benchmarks. By the end of 2018 about 197 local ties information are available at http://www.sonel.org/-Stability-of-the-datums-.html?lang=en. The current number of GNSS@TG stations is 1103 (TIGA: 125 stations) stations (with 163 stations decommissioned). Still there are 166 stations where the GNSS data is not (yet) available for scientific research.
- Combination of TIGA solutions carried out by the TCC at University of Luxembourg was continued, but delayed do to staff member changes and technical issues. In a first step for the new combination and together with GFZ it was ensured that all TAC solutions had been updated as not all SINEX files were available on the server previously. In collaboration with Paul Rebischung issues with one TAC solution were investigated which have previously prohibited the solution from this TAC to be included in the CATREF combination. The work will be continued in 2019.

3 Related important Outreach activities in 2018

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Abraha K.E. MULTI-GNSS ERROR CHARACTERISTICS AND BENEFITS TO LONG-TERM MONITORING APPLICATIONS IN GEOSCIENCES. PhD Thesis, University of Luxembourg, 2018, http://hdl.handle.net/10993/37191

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Teferle N., A. Hunegnaw, K. Abraha, Ph. Woodworth, S. Williams, A. Hibbert, R. Smalley, I. Dalziel, and L. Lawver Vertical Land Movements and Sea Level Changes around South Georgia Island: Preliminary Results, Poster Presentation. Poster EGU2018-12154, European Geoscience Union General Assembly EGU 2018, Vienna, Austria, 8-13 April 2018, http://hdl.handle.net/10993/35399

4 Current data holding of TIGA reprocessed individual solutions

Table 1: Current data holding of TIGA reprocessed individual solutions.

TIGA Analysis Center (TAC)	Start GPS week	End GPS week
AUT (Geoscience Australia)	0834	1891
BLT (University of Nottingham , University of Luxembourg)	0782	1722
DG2 (DGFI/TUM Germany)	0887	1824
GT2 (GFZ Potsdam TIGA Solution)	0730	1877
UL2 (University La Rochelle)	0782	1773

5 TIGA Working Group Members in 2018

Working group members are listed in Table 2.

Table 2: TIGA Working Group Members in 2018

Name	Entity	Host Institution	Country
Guy Wöppelmann	TAC, TNC, TDC	University La Rochelle	France
Laura Sánchez	TAC	DGFI/TUM Munich	Germany
Heinz Habrich	TAC	BGK, Frankfurt	Germany
Minghai Jia		GeoScience Australia	Australia
Paul Tregoning		ANU	Australia
Zhiguo Deng	TAC	GFZ Potsdam	Germany
Daniela Thaller	Combination	BGK, Frankfurt	Switzerland
Norman Teferle	TAC/Combination	University of Luxembourg	Luxembourg
Richard Bingley	TAC	University of Nottingham	UK
Allison Craddock	IGS Central Bureau	ex officio	USA
Tom Herring	IGS AC coordinator	ex officio	USA
Michael Moore	IGS AC coordinator	ex officio	Australia
Carey Noll	TDC	CDDIS, NASA	USA
Tilo Schöne	Chair TIGA-WG	GFZ Potsdam	Germany
Simon Williams	PSMSL	PSMSL, NOC Liverpool	UK
Gary Mitchum	GLOSS GE (current chair).	University of South Florida	USA
Mark Merrifield	GLOSS GE (past chair)	UHSLC, Hawaii	USA
Matt King		University of Tasmania	Australia

IGS Troposphere Working Group Technical Report 2018

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1 Introduction

The IGS Troposphere Working Group (IGS TWG) was founded in 1998. The United States Naval Observatory (USNO) assumed chairmanship of the WG as well as responsibility for producing IGS Final Troposphere Estimates (IGS FTE) in 2011.

Dr. Christine Hackman chaired the IGS TWG through December 2015. Dr. Sharyl Byram has chaired it since then and also oversees production of the IGS FTEs. IGS FTEs are produced within the USNO Earth Orientation Department GPS Analysis Division, which also hosts the USNO IGS Analysis Center.

2 IGS Final Troposphere Product Generation/Usage 2018

USNO produces IGS Final Troposphere Estimates for nearly all of the stations of the IGS network. Each 24-hr site result file provides five-minute-spaced estimates of total troposphere zenith path delay (ZPD), north, and east gradient components, with the gradient components used to compensate for tropospheric asymmetry.

Since the implementation of the ITRF2014 reference frame in January 2017, the IGS Final Troposphere estimates have been generated with Bernese GNSS Software 5.2 (Dach et al., 2015). The processing uses precise point positioning (PPP; Zumberge et al. (1997)) and the GMF mapping function (Boehm et al. 2006) with IGS Final satellite orbits/clocks and earth orientation parameters (EOPs) as input. Each site-day's results are completed approximately three weeks after measurement collection as the requisite IGS Final orbit

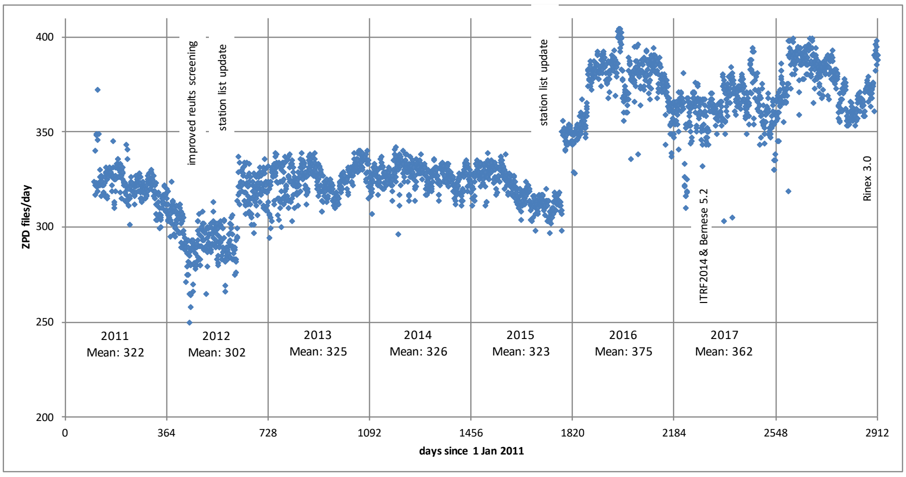

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011-8. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011.)

products become available. Further processing details can be obtained from (Byram and Hackman 2012).

Fig. 1 shows the number of receivers for which USNO computed IGS FTEs 2011-8. The average number of quality-checked station result files submitted per day in 2018 was 376, slightly higher than the 2017 average value of 362 due to the implementation of processing of both Rinex 2 and Rinex 3 observation file formats near the end of 2018. The result files can be downloaded from `ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd`. 32.8 million files were downloaded in 2018 by users from over 1000 distinct hosts (Noll 2019).

3 IGS Troposphere Working Group Activities 2018

The goal of the IGS Troposphere Working Group is to improve the accuracy and usability of GNSS-derived troposphere estimates. It does this by coordinating (a) working group projects and (b) technical sessions at the IGS Analysis Workshops.

The group meets twice per year: once in the fall in conjunction with the American Geophysical Union (AGU) Fall Meeting (San Francisco, CA, USA; December), and once in the spring/summer, either in conjunction with the European Geosciences Union (EGU) General Assembly (Vienna, Austria; April) or at the IGS Workshop (location varies; dates typically June/July).

Meetings are simulcast online so that members unable to attend in person can participate. Members can also communicate using the IGS TWG email list.

3.1 2018 Working Group Meetings

The working group met once in 2018 in conjunction with the October 2018 IGS Workshop in Wuhan, China.

The October 2018 meeting lead by Dr. Rosa Pacione featured presentations by:

- WG chair S Byram on (1) the quality and production of IGS Final Troposphere Estimates, (2) the status of current working-group projects, and (3) a discussion of future projects
- Dr. Pacione on the status of the standardization of the tropo_sinex format (see "Working Group Projects," below)

Presentations from the meeting can be obtained by contacting this report's author.

3.2 Working Group Projects

3.2.1 Automating comparisons of troposphere estimates obtained using different measurement or analysis techniques

One way to assess the accuracy of GNSS-derived troposphere estimates is to compare them to those obtained for the same time/location using an independent measurement technique, e.g., VLBI [1] DORIS[2], radiosondes, or from a numerical weather model. Comparisons of GNSS-derived troposphere estimates computed by different analysis centers or using different models can also serve this purpose.

The IGS TWG has therefore since 2012 been coordinating the creation of a database/website to automatically and continuously perform such comparisons.

Dr. Jan Douša, Geodetic Observatory Pecny (GOP; Czech Republic) has been spearheading the development of the database Douša and Győri (2013); Győri and Douša (2016), with contributions from other scientists at GOP, GeoForschungsZentrum (GFZ; Germany) and USNO. This database is now beta-complete and open for testing. Interested users can contact Dr. Dousa at jan.dousa@pecny.cz. The website was made available to the community in late 2018.

This system has received interest from climatologists/meteorologists, e.g., those associated with the GRUAN[3] and COST[4] Action 1206 (GNSS4SWEC) projects, as it will simplify quality-comparison and perhaps acquisition of data used as input to their studies.

[1] Very Long Baseline Interferometry
[2] Doppler Orbitography and Radiopositioning Integrated by Satellite
[3] GCOS (Global Climate Observing System) Reference Upper Air Network: http://www.gruan.org
[4] European Cooperation in Science and Technology: http://www.cost.eu

3.2.2 Standardization of the tropo_sinex format

The IGS Troposphere Working group also supports a project to standardize the tropo_sinex format in which troposphere delay values are disseminated. At issue is the fact that different geodetic communities (e.g., VLBI, GNSS) have modified the format in slightly different ways since the format's introduction in 1997. For example, text strings STDEV and STDDEV are used to denote standard deviation in the GNSS and VLBI communities respectively. Such file-format inconsistencies hamper inter-technique comparisons.

This project, spearheaded by IGS Troposphere WG members Drs. Rosa Pacione and Jan Douša, is being conducted within the COST Action 1206 (GNSS4SWEC) Working Group 3. This COST WG consists of representatives from a variety of IAG[5] organizations and other communities; its work is further supported by the EUREF Technical Working Group[6] as well as E-GVAP[7] expert teams. The WG is currently defining in detail a format able to accommodate both troposphere values and the metadata (e.g., antenna height, local pressure values) required for further analysis/interpretation of the troposphere estimates, with progress made in 2018, and a format has been circulated for discussion/approval in late 2018. For more information, please contact Dr. Pacione at rosa.pacione@e.geos.it or Dr. Dousa.

3.2.3 Automated Analysis Center Estimate Comparisons

A suggestion was made by an IGS Analysis Center representative that the next working group project should be to re-establish the troposphere estimate comparisons for each AC. This project would consist of first comparing the Repro2 Analysis Center results in the comparison database developed by J Dousa and then automating the comparison of the final troposphere estimates of the ACs as they become available. A survey asking for interest and participation in such a comparison was sent via the IGS TWG email list (message IGS-TWG-143) and AC email list (message IGS-ACS-1088).

3.3 Activities at the 2018 IGS Workshop

WG chair Dr. Sharyl Byram and Dr. Rosa Pacione co-organized troposphere-related activities for the 2018 IGS Workshop, soliciting presenters for the troposphere plenary and poster sessions, and holding the working-group meeting.

There were six plenary talks with an additional 17 posters presentations in the troposphere sessions. All presentations can be viewed at http://www.igs.org/presents/workshop2018.

[5]International Association of Geodesy
[6]http://www.euref.eu/euref_twg.html
[7]EUMETNET EIG GNSS Water Vapour Programme; http://egvap.dmi.dk/

4 How to Obtain Further Information

IGS Final Troposphere Estimates can be downloaded from: ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd

For technical questions regarding them, please contact Dr. Sharyl Byram at sharyl.byram@navy.mil.

To learn more about the IGS Troposphere Working Group, you may:

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- visit the IGS Troposphere Working Group website: http://twg.igs.org, and/or
- subscribe to the IGS Troposphere Working Group email list: https://lists.igs.org/mailman/listinfo/igs-twg

5 Acknowledgements

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