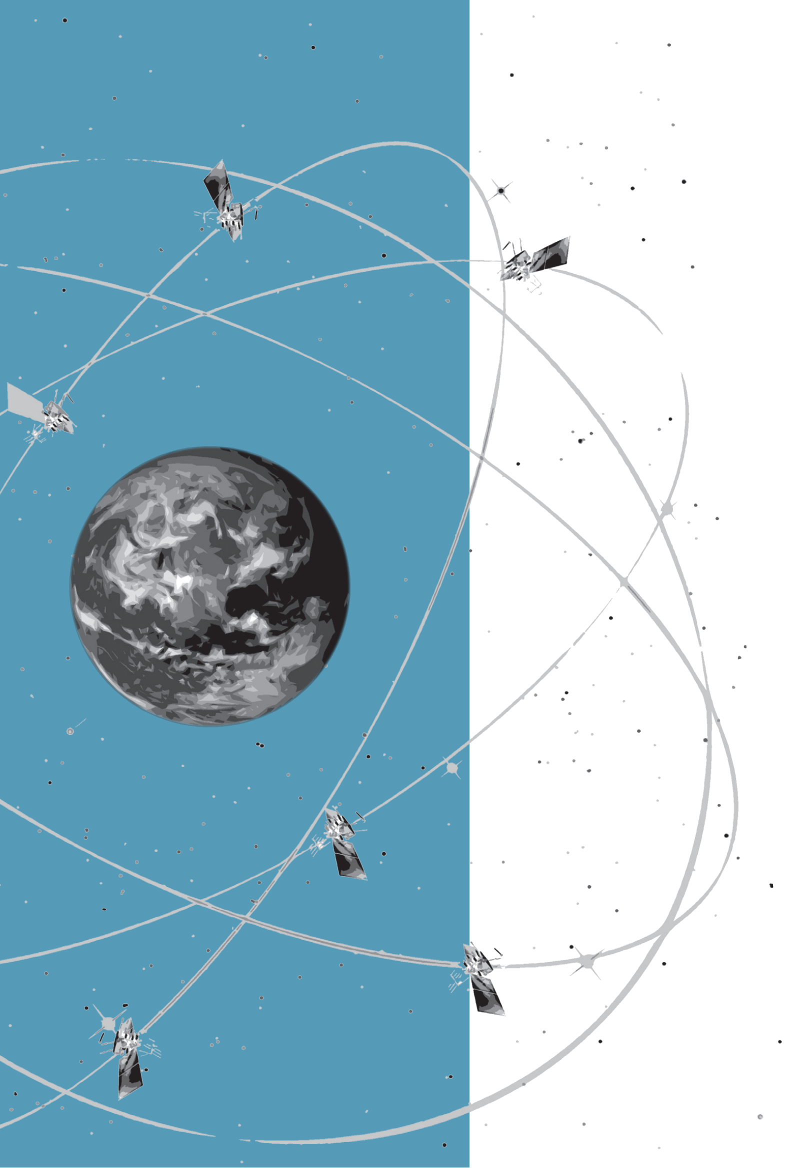
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2019



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International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

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Compiled in May 2020, by Arturo Villiger, Rolf Dach (Eds.)

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Technical Report 2019

IGS Central Bureau

http://www.igs.org

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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 2019* 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 2019.

This report is available in electronic version at
ftp://ftp.igs.org/pub/resource/pubs/2019_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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Part I

Executive Reports

2019 State of the Service: the IGS Governing Board Chair Report

G. Johnston[1], *F. Perosanz*[2]

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1 Introduction

For over twenty-five years, the International GNSS Service (IGS, where GNSS stands for Global Navigation Satellite Systems) has carried out its mission to advocate for and provide freely and openly available high-precision GNSS data and products. In 2019, the IGS continued to sustain our community's needs. While delivery of the IGS core reference frame, orbit, clock and atmospheric products continues to drive the core activities, the IGS transformation to a multi-GNSS service continues as more sites are added into the core IGS network.

The IGS operates as a service of the International Association of Geodesy (IAG), and a contributor to the Global Geodetic Observing System (GGOS). Accordingly, a number of the GB members participate in IAG and GGOS governance, bureaus, commissions and working groups, ensuring the IGS retains its strong level of international significance and sustainability. Importantly, GB members also participate in the United Nations Global Geospatial Information Management (UN GGIM) efforts on Geodesy, which aims to enhance the sustainability of the global geodetic reference frame through intergovernmental advocacy for geodesy.

This year's third IGS open Associate Member meeting took place in San Francisco, California, where Working Group Chairs (WG) interacted with the community members discussing the extensive developments of each working group and the ongoing achievements of their contributors in line with community requirements. Ten out of the Fourteen WG Chairpersons presented updates on their WG activities as well as plans for the upcoming year. Topics ranged from updates on the status of the IGS Antenna Network to plans for repro3 and ITRF2020. Additionally, discussions for "Vision 2020", a forward-looking IGS Strategic Plan addressing the role of IGS as facilitator, incubator, coordinator, and advocate on behalf of the community started in 2019. This discussion will continue during 2020 with the goal of having a published plan by 2021. The plan will focus on how the IGS maintains and enhances its leadership role within the broader GNSS community as societal demands for GNSS products and services continues to grow. Central to the discussion will be the complementary roles of the IGS as a collaborative research program, and an operational service. Maintaining an appropriate balance of the two roles will ensure ongoing support from Associate members and collaborating organisations.

Currently, the service is in the process of organizing its next IGS Workshop, which has been delayed from the planned August 2020 timeframe, and will now take place in Boulder, Colorado in mid 2021. A final date will be announced once some clarity around international travel restriction resulting from Covid-19 is available.

2 IGS Membership and Governance

2.1 Membership Growth and Internal Engagement

In 2019, IGS membership reached 329 Associate Members (AM), representing over 45 countries. The 36-member IGS Governing Board (GB) guides the coordination of over 200 contributing organizations participating within IGS, including 108 operators of GNSS network tracking stations, 6 global Data Centers (DCs), 13 Analysis Centers (ACs), and 4 product coordinators, 21 associate ACs, 23 regional/project DCs, 14 technical Working Groups (WG), two active pilot projects (i.e., Multi-GNSS and Real-time), and the CB. The IGS structure is depicted on Fig. 1.

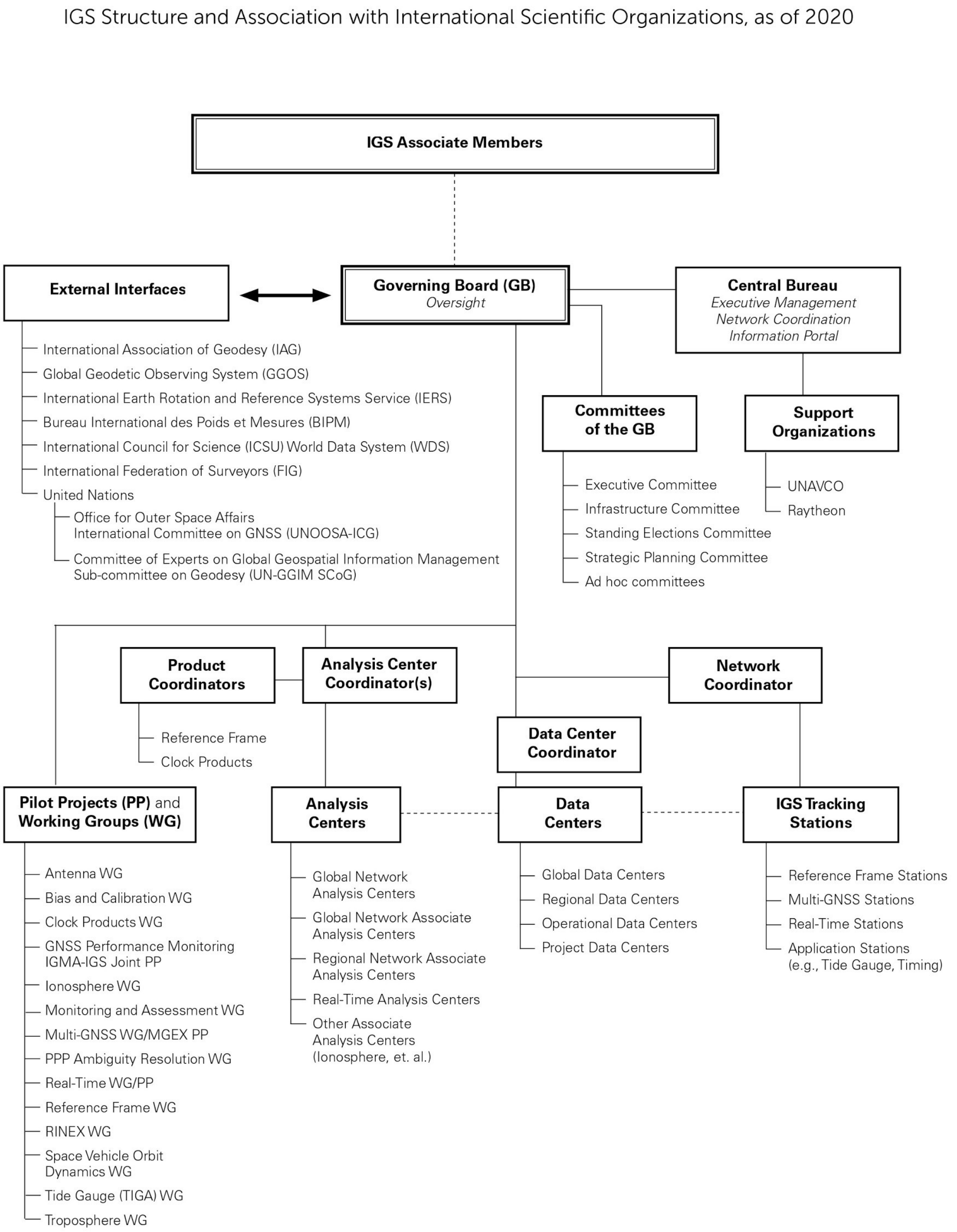

Figure 1: IGS Organizational Structure

Figure 2: IGS at a Glance

2.2 Governing Board Appointments and 2019 AM Elections

The IGS is led by an international Governing Board of members who represent the IGS community and its interests. The GB discusses the activities of the various IGS components, sets policies, and monitors the progress with respect to the agreed strategic plan and annual implementation plan. The IGS Governing Board Membership, as of the completion of the 54th GB meeting in December 2019, stands as follows:

Name	Institution	Country	Position
Gary Johnston	Geoscience Australia	Australia	Board Chair
Suelynn Choy	Royal Melbourne Institute of Technology (RMIT)	Australia	International Federation of Surveyors (FIG) Representative
Michael Moore	Geoscience Australia	Australia	Analysis Center Co-Coordinators
Ryan Ruddick	Geoscience Australia	Australia	Network Representative
Simon Banville	Natural Resources Canada / Ressources naturelles Canada	Canada	PPP-AR Working Group Chair
Qile Zhao	Wuhan University	China	Appointed (IGS)
Zuheir Altamimi	Institut National de l'Information Géographique et Forestière	France	IAG Representative
Felix Perosanz	Centre National d'Etudes Spatiales (CNES)	France	Vice Board Chair
Gérard Petit	Bureau International des Poids et Mesures (BIPM)	France	BIPM/CCTF Representative
Paul Rebischung	Institut National de l'Information Géographique et Forestière (IGN)	France	IGS Reference Frame Coordinator
Loukis Agrotis	ESA/European Space Operations Centre	Germany	Real-time Analysis Coordinator
Werner Enderle	ESA/European Space Operations Centre	Germany	Appointed (IGS)
André Hauschild	Deutsches Zentrum für Luft- und Raumfahrt	Germany	Real-time Working Group Chair
Benjamin Männel	Deutsches GeoForschungsZentrum (GFZ)	Germany	Analysis Center Representative
Oliver Montenbruck	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany	Multi-GNSS Working Group Chair
Ignacio Romero	ESA/European Space Operations Centre	Germany	Infrastructure Committee Chair
Laura Sánchez	Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)	Germany	Network Representative

Name	Institution	Country	Position
Tilo Schöne	Deutsches Geo-ForschungsZentrum (GFZ)	Germany	TIGA Working Group Chair
Wolfgang Söhne	Federal Agency for Cartography and Geodesy (BKG)	Germany	Network Representative
Tim Springer	ESA/European Space Operations Center	Germany	IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair Satellite Vehicle Orbit Dynamics Working Group Chair
Satoshi Kogure	National Space Policy Secretariat (NSPS), Cabinet Office	Japan	Appointed (IGS)
Basara Miyahara	Geospatial Information Authority of Japan (GSI)	Japan	IAG Representative
Andrzej Krankowski	University of Warmia and Mazury in Olsztyn	Poland	Ionosphere Working Group Chair
Rolf Dach	Astronomical Institute, University of Bern	Switzerland	Analysis Center Representative
Stefan Schaer	Federal Office of Topography - swisstopo	Switzerland	Bias & Calibration Working Group Chair
Arturo Villiger	Astronomical Institute, University of Bern	Switzerland	Antenna Working Group Chair
Sharyl Byram	United States Naval Observatory	USA	Troposphere Working Group, Chair
Michael Coleman	Naval Research Laboratory	USA	IGS Clock Products Coordinator
Allison Craddock	NASA Jet Propulsion Laboratory	USA	Director of IGS Central Bureau
Richard Gross	NASA Jet Propulsion Laboratory	USA	IERS Representative
Thomas Herring	Massachusetts Institute of Technology (MIT)	USA	Analysis Center Coordinator
David Maggert	UNAVCO	USA	Network Coordinator
Charles Meertens	UNAVCO	USA	Appointed (IGS)
Carey Noll	NASA Goddard Space Flight Center	USA	Data Center Coordinator (Data Center Working Group Chair
Mayra Oyola	NASA Jet Propulsion Laboratory	USA	Deputy Director of IGS Central Bureau & GB Executive Secretary
David Stowers	NASA Jet Propulsion Laboratory	USA	Data Center Representative

During 2019, several GB Members appointments were confirmed and renewed. Table 2 summarizes these renewals. Tim Springer was confirmed as the Chair of the Space Vehicle Orbit Dynamics WG, while the RINEX WG Chair position became vacant, after the retirement of Ken McLeod from National Resources, Canada (NRCan). The GB, along with the Standing Election Committee is formulating a plan to fulfill this vacancy.

Table 2: 2019 Governing Board Member Renewals

Name	Institution	Country	Position
Zuheir Altamimi	Institut National de l'Information Géographique et Forestière	France	IAG Representative
Michael Moore	Geoscience Australia	Australia	Analysis Center Co-Coordinator
Loukis Agrotis	ESA/European Space Operations Centre	Germany	Real-time Analysis Coordinator
Werner Enderle	ESA/European Space Operations Centre	Germany	Appointed (IGS)
Ignacio Romero	ESA/European Space Operations Centre	Germany	Infrastructure Committee Chair
Richard Gross	Jet Propulsion Laboratory	USA	IERS Representative
Thomas Herring	Massachusetts Institute of Technology (MIT)	USA	Analysis Center Coordinator
Carey Noll	NASA Goddard Space Flight Center	USA	Data Center Coordinator (formerly Working Group Chair)
Michael Coleman	Naval Research Laboratory	USA	IGS Clock Products Coordinator
David Maggert	UNAVCO	USA	Network Coordinator
Sharyl Byram	United States Naval Observatory	USA	Troposphere Working Group, Chair

At the end of 2019, elections were conducted for the open positions of Anaysis Center and Network Representatives. By a majority of votes, Associate Members elected Benjamin Männel, (Deutsches GeoForschungsZentrum GFZ Potsdam, Germany) as Analysis Center Representative and Ryan Ruddick (Geoscience Australia) for the position of Network representative. Additionally, Mayra Oyola (NASA Jet Propulsion Laboratory, USA) was confirmed as IGS Central Bureau Deputy Director.

3 IGS Operational Activities

3.1 Network Growth

The IGS network (Fig.3) added 12 new stations and identified 6 stations for decommissioned in 2019, bringing the total to 507 stations. The number of muti-GNSS stations increased from 242 to 308; while real-time stations increased from 190 to 259. In collaboration with the IRNSS, the CB added 18 stations capable of tracking IRNSS, increasing the total number to 59. Additionally, 124 changes to the rcvr_ant.tab files were implemented with collaboration of the Antenna WG. At the end of the year, support for the Site Log Manager included 661 site log updates (50 per month) and 41 antenna changes (11 of those at IGS14 core stations).

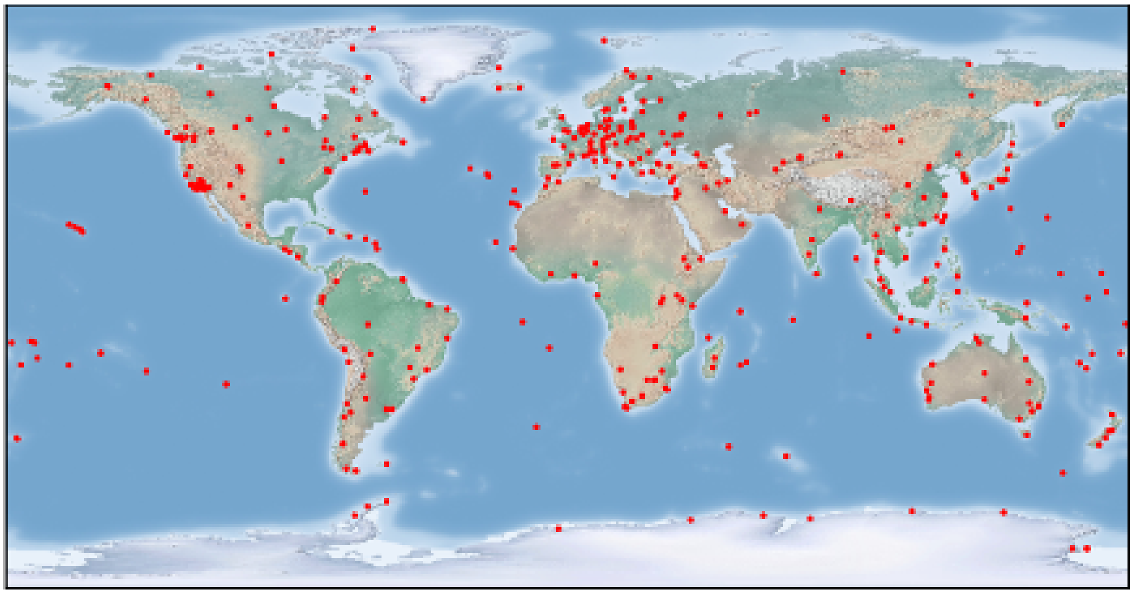

Figure 3: The 507 IGS stations as of January 31, 2019. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

The CB is operationally responsible for day–to–day management, interaction with station operators, and answering numerous questions and requests from users each month. All these activities are performed year-round, on a daily basis, with high redundancy and reliability – an impressive effort that is only made possible by the strong engagement of many individuals and the support of more than 200 institutions worldwide, in over 45 countries.

During 2019, 221 new user accounts were added to the CB real time caster. The CB Network Coordinator also responded to over 200 inquiries about data, products, or general IGS information. Station information was updated to include new photos and SONEL and tide gauge information. In order to comply with security requirements for the transition of FTP to secured FTP, the CB updated the internal scripts to use HTTPS/Curl for CDDIS data collection.

3.2 Product Generation and Performance

Joint management of the IGS ACC by Michael Moore, and Salim Masosumi 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 Repro3 and ITRF 2020

A third reprocessing effort by IGS analysis centres has commenced that will form the basis for the IGS contribution to ITRF2020. In the lead up to the reprocessing effort the analysis centres have been involved in extensive testing on the impact of multi-gnss solutions may have on the IGS reference frame, as well as assessing the impact of using the publicly released antenne calibration values for Galileo satellite phase centre offsets (PCO) can be used to help provide an IGS independent estimate of the reference frame scale.

The testing has indicated that there is no detrimental impact upon the reference frame, by incorporating multi-GNSS observations into the determination of station coordinates, and no detrimental impact to the satellite orbit and clocks.

As well as applying the key modelling required to be compatible with ITRF2020, such as the linear mean pole model, we are taking the opportunity to be better placed to develop IGS multi-GNSS products further. The majority of ACS will be providing 30s clocks, and accompanying bias SINEX file, and satellite attitude information based in quaternions form, so that the IGS will be in a position to test, develop and potentially implement integer phase bias clocks.The development of this products will greatly aid PPP applications using IGS products. In addition the majority of ACs will be providing troposphere SINEX files to aid climatological studies.

The past year has seen a great deal of work from many ACs and IGS working groups to support the testing and development of IGS products for the third reprocessing effort. Thanks to their efforts the IGS will be putting together multi-gnss products for testing obtained from repro3, and submitting and provide independent estimates of reference frame scale as part of it's contribution to ITRF2020. Whether it is accepted into the ITRF2020 combination is yet to be determined. Either way this reprocessing effort will mark the beginning of a large number of new analytical products that will better support IGS users.

3.4 Data Management

The amount of IGS tracking data and products hosted by each of the four global Data Centers on permanently accessible servers increased from 2 TB to 11 TB (135 million files) over the last 5 years, supported by significant additional storage capabilities provided by Regional Data Centers.

Twelve Analysis Centers and a number of Associate Analysis Centers utilize tracking data from between 70 to more than 500 stations to generate precision products up to four times per day. Product coordinators combine these products on a continuous basis and assure the quality of the products made available to the users.

The collective effort of the IGS produces 700 IGS final, rapid, ultra–rapid and Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS)– only product files, as well as 126 ionosphere files weekly. Furthermore, troposphere files for more than 300 stations are produced on a daily basis.

Delivery of core reference frame, orbit, clock and atmospheric products continues strongly. The IGS has also seen further refinement of the Real Time Service with considerable efforts being targeted towards development of Standards. The transition to multi GNSS also continues apace within the IGS, with additional Galileo and Beidou satellite launches bringing those constellations closer to operational status.

In one year, an average IGS Global Data Center can expect to register user activity totaling almost 2 billion files, equating to over 150 terabytes of GNSS data, and almost 20 million files equating to almost 60 terabytes of GNSS products. The intense interest of users in IGS data and products is reflected in the 2019 user activity recorded by the Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center.

As an example of user activity, at the CDDIS GDC in 2019, over 250K distinct hosts downloaded over 28TB from the over 1.5 billion IGS-related files currently available. Monthly averages in the past have been reported as:

- 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 Scientific Applications of IGS Data and Analysis Products Session at AGU 2019

The IGS organized a session at this year's American Geophysical Union (AGU) in San Francisco, CA, United States. The Session, number G12A: "Scientific Applications Enabled by the International GNSS Service (IGS) and by Improvements to GNSS Products," was convened by Governing Board Chair, Gary Johnston, Governing Board Vice Chair, Felix Perosanz and IGS Governing Board and Executive Committee member Rolf Dach of the University of Bern, Switzerland.

The description of the AGU 2019 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."

3.6 Web Services, Social Media and Knowledge Base

Regular improvements and enhancements to the current IGS website have taken place, however, primary efforts are focused on the next generation of the website, which is currently under development by the IGS CB and will be released in 2020.

A new and secured IGS website is being developed with the intent to replace the functionality of the very convoluted and unsecured http://igs.org. The new refresh focused on creating a more functional and easier to navigate platform while matching the requirements of the stakeholders, IGS members and community in general. At the same time, the CB focused on providing a platform that was easier to navigate than the previous website. The selected, platform (Wordpress), offers a modern interface, and allows the website and its content to be optimized for different devices, browsers, data speed, search engines, and users.

The transition to the new website, along with a HTTPS file transfer system, is expected to occur in August 2020. IGS continues to use social media platforms to facilitate sharable content and optimize engagement with IGS stakeholders.

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 2019 Update poster was developed by the Executive Committee with assistance from the Central Bureau, and has been presented in numerous meetings, to include the GGOS session at the 2019 EGU. The poster may be viewed and downloaded here: http://kb.igs.org/hc/en-us/articles/360022363911-EGU-2018-Poster.

4 IGS Governing Board Meetings in 2019

The GB meets regularly to discuss the activities and plans of the various IGS components, sets policies, and monitors the progress with respect to the agreed strategic plan and annual implementation plan. Meetings held in 2019 are described in the table below:

Date	Place	Comments
April, 2019	Vienna, Austria	Strategic Planning Meetings; held prior to, and during, the European Geosciences Union (EGU) Meeting
April, 2019	Vienna, Austria	52nd GB Meeting; held prior to the European Geosciences Union (EGU) Meeting
July, 2019	Montreal, Canada	53rd GB Meeting; held during the International Union of Geodesy and Geophysics (IUGG) General Assembly
December, 2019	San Francisco,CA, USA	3rd Associate Member/Open WG Meeting; held prior to the American Geophysical Union (AGU) Meeting
December, 2019	San Francisco,CA, USA	54th GB Meeting; held prior to the American Geophysical Union (AGU) Meeting

5 IGS Advocacy and External Engagement

IGS remains active in engaging with diverse organizations that have an interest in geodetic applications of GNSS.

5.1 United Nations GGIM Sub-Committee on Geodesy

IGS Associate and Governing Board members continue to participate in the UN Committee of Experts in Global Geospatial Information Management (UN GGIM) Subcommittee on Geodesy (SCoG) and its five working groups: Geodetic Infrastructure; Education, Training and Capacity Building; Outreach and Communication; Policy, Standards and

Convention; and Governance.

In support of the SCoG initiatives, IGS GB members have participated (together with IGS Associate Members) in several workshops and conferences; collaborating with UN ICG, UN-GGIM Asia-Pacific Working Group on Geodesy, International Federation of Surveyors (FIG) Asia-Pacific Capacity Development Network, and FIG Commission 5.

Following the implementation plan for the UN GGIM Global Geodetic Reference Frame Roadmap,http://ggim.un.org/meetings/GGIM-committee/8th-Session/documents/Road-Map-Implementation-Plan.pdf IGS GB members have contributed to efforts in support of the August 2019 recommendation to the GGIM to establish a Global Geodetic Centre of Excellence (GGCE).

Also adopted at the GGIM August 2019 meeting was the "Agreement on International Terrestrial Reference System and Frame" (E/C.20/2020/7/Add.1) This agreement ensures that geospatial data managed by UN Member States is mathematically aligned to the ITRS/ITRF to ensure compatibility with GNSS positioning, and to allow consistency and interoperability. This will further the standardization efforts of geodetic information, ensure interoperability across national, regional and global geodetic reference systems and contribute to the overarching Integrated Geospatial Information Framework.

The IGS, as one of the key IAG services contributing to the global reference frames, has responded to a call for input into current and future infrastructure requirements issued by the UN GGIM SCoG Geodetic Infrastructure working Group. This document is intended to describe the infrastructure requirements of the IGS in order to achieve sustainability and enhancement of our contribution to the ITRF.

For the most recent details and proceedings of the UN GGIM: http://ggim.un.org/meetings/GGIM-committee/9th-Session/documents/

5.2 United Nations International Committee on GNSS

The IGS continues to strongly engage with the International Committee on Global Navigation Systems (ICG) as co-chair of the ICG Working Group D (WG-D) on Reference Frames, Timing and Applications in partnership with the International Federation of Surveyors (FIG) and the International Association of Geodesy (IAG).

In December 2019, Central Bureau Director Allison Craddock represented the IGS in the annual UN International Committee on GNSS meeting in Bangalore, India. New GB Member (FIG Liaison) Suelynn Choy serves as the FIG representative. In the absence of an IAG representative (due to conflict with the American Geophysical Union meeting) IGS and FIG were supported in their WG-D duties by representatives from BIPM (Patrizia Tavella) and CNES (Jerome Delporte).

Major topics for discussion were GNSS timescales, infrastructure development in collaboration with the Indian NavIC regional system, interoperability of GNSS Precise Point Positioning (PPP) Services and collaborative capacity building initiatives with the UN GGIM Subcommittee on Geodesy. Complete ICG-14 meeting materials are available here: https://www.unoosa.org/oosa/en/ourwork/icg/meetings/ICG-2019.html

GB member Tim Springer leads the IGS contribution the ICG-IGS Joint Trial Project (IGMA), which aims to provide monitoring and assessment products for all GNSS constellations. Central Bureau Deputy Director Mayra Oyola also participates as the Central Bureau representative to IGMA.

5.3 United States PNT Advisory Board

IGS interests are represented by the IAG participation in the United States National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board (http://www.gps.gov/governance/advisory/), which in 2019 included presentations on key issues and IAG/IGS updates from former GB member Gerhard Beutler.

5.4 International Association of Geodesy – Executive Participation

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

5.5 IAG Global Geodetic Observing System – Executive Participation

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 conjunction with the SIRGAS 2019 Symposium at the Brazilian Institute of Geography and Statistics (IBGE) in Rio de Janeiro, Brazil.

6 Outlook 2020

It was expected that in 2020 the IGS workshop participants will travel to Boulder, Colorado for the 2020 IGS Workshop hosted by UNAVCO and the University Corporation for Atmospheric Research (UCAR). The IGS is committed to minimizing the impact of COVID-19, therefore decided to postpone its IGS 2020 Workshop: Science from Earth to Space, to 2021.

The IGS will continue being an impressive organization, with a large number of individuals from many institutions from all over the world devoting their expertise and investing their time in an exemplary spirit of cooperation. The active participation of associate members will remain vital to face in particular the challenge of the development of the various GNSS and their uses in real time. The GB will also monitor the activities relating to the Repro3 reprocessing campaign, which will be a fundamental contribution of the IGS to the realization of the next ITRF. The results of a survey will be used to advance the updating of the IGS strategic plan with the objective of publication in 2021. In addition, efforts to enhance advocacy for the IGS will be continued in order to retain its strong level of relevance and impact, and therefore sustainability. In this perspective, and with the fundamental support of the CB, the GB will be working within both the science and the intergovernmental community.

Governing Board members are gratefully acknowledged for the cooperation and support as well as all those associated with the IGS for their continuing effort and support for advancing our Service. The help of the Central Bureau was again fundamental and really appreciated. We congratulate and particularly thank Mayra Oyola as the new Deputy Director of the IGS Central Bureau.

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 2019

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1 Introduction

For twenty-six 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 (GB). 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 2019.

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 Summary of Accomplishments

The IGS CB runs under the leadership of Ms. Allison Craddock since 2017, who has focused into developing a “resilient, interdisciplinary, and interoperable” IGS by ensuring successful completion of essential tasks, developing procedures on IGS structure and governance and increasing the IGS engagement and external relations. Craddock has sought to develop a vision for the CB that aligns with the recommendations from the CB Review Panel conducted in 2018, which were extremely helpful in outlining and leveraging resources needed for IGS operations in 2019 and forward. One major feedback addressed in the 2018 review panel was the need of a fully staffed CB in order to provide a steadfast advantage to support a growing IGS and the increasing demands of the Geodesy community. As a result, the gaps in the CB have been filled by highly qualified and motivated individuals. In February 2019, Dr. Mayra Oyola (NASA JPL, USA) was appointed as the acting Deputy Director of the CB, having transitioned officially into the role after the 54th GB meeting in December 2019. She was also appointed as the Executive Secretary of the GB and a member of the Executive Committee. Besides supporting the organizational and administrative tasks of the IGS, Oyola’s appointment leverages new connections and outreach opportunities to the weather and climate community given her background in both fields, a priority for the IGS. Mr. David Maggert (UNAVCO, USA) continues to serve as the IGS Network Coordinator; and Mr. Robert Khachikyan (Raytheon, USA), who had previously served as the Network Coordinator, was appointed as the new CBIS Engineer. His reinstatement as a member of the CB has allowed the development of the new IGS website, which is planned to become fully operational in early 2020.

Daily operations are the heart of the IGS. Various components of the service ensure that tracking data and products are made publicly available every day. Over 500 IGS Network tracking stations (Fig. 1) 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 CB works as the coordination center for these operations, organized by the Network Coordinator.

The CB, as part of its work program carrying out the business needs of the IGS, implements

Table 1: IGS Central Bureau Staff (2019)

Name	Affiliation	Role
Allison Craddock	NASA Jet Propulsion Laboratory	Director
Mayra I. Oyola	NASA Jet Propulsion Laboratory	Deputy Director
David Maggert	UNAVCO	Network Coordinator
Robert Khachikyan	Raytheon Corporation	CBIS Engineer
David Stowers	NASA Jet Propulsion Laboratory	CBIS Advisor

actions defined by the GB. In 2019, this included a thorough analysis and refresh of the IGS Terms of Reference (ToR) and establishment of Standing Election Procedures, supporting the ongoing update of the Associate Members (AM) database, organizing the third Associate Member Open Meeting during the American Geophysical Union Fall meeting, conducting the GB elections, supporting WG operations, and actively organizing three GB meetings. Additionally, the CB organized monthly Executive Committee (EC) meetings, and led initial conversations pertaining the 2020 Strategic Plan.

The CB continued to develop communications, advocacy, and public information initiatives on behalf of the GB. The CB actively works with other IAG components to promote communications and outreach, including the IAG Communications and Outreach Branch and GGOS Coordinating Office. Furthermore, IGS CB members also served in leadership roles in the United Nations International Committee on GNSS (ICG), including the Working Group D on Reference Frames, Timing, and Applications, and the IAG Inter-Commission Committee on Geodesy for Climate Research (ICCC).

3 Executive Management and Governing Board Participation

The CB coordinated the necessary logistics and administrative organization for Governing Board (GB) meetings held in April (hosted by TU Wien in Vienna, Austria), July (during the International Union of Geodesy and Geophysics (IUGG) in Montreal, Canada and hosted by CB/UNAVCO) and December (hosted by the CB/UNAVCO in San Francisco, California, USA). The EC met additionally by teleconference on a monthly basis. Staff of the CB, as part of its work program carrying out the business needs of the IGS, implemented actions defined by the GB throughout the year. A comprehensive list of these activities is included in Table 2.

The CB also continued to play an active role in supporting the organization of the 2020 Workshop in Boulder, Colorado, USA, as well as holding a call for proposals for the 2022 and 2024 is workshops.

Table 2: Comprehensive list of activities in 2019.

Date	Place	Comments
7 April, 2019	Vienna, Austria	GB 52: Business Meeting prior to the European Geosciences Union Meeting
23 July, 2015	Montreal, Quebec, Canada	GB 53: During IUGG/IAG General Assembly
09 December, 2019	San Francisco, California, USA	GB 54: Prior to American Geophysical Union Meeting

4 Strategic Planning and Progress

Preliminary discussions regarding a new strategic plan have commenced with two strategic planning dialogue sessions, led by the CB and GB Chair, during EGU 2019 in Vienna.

5 Communications, Advocacy, and Public Information

The CB continued to develop communications, advocacy, and public information initiatives on behalf of the GB. As part of this commitment, the Third Open Working Group and Associate Member Meeting took place on 08 December 2020 in San Francisco, California. Ten out of the Fourteen WG Chairpersons presented updates on their WG activities as well as plans for the upcoming year. Topics ranged from updates on the status of the IGS Antenna Network to plans for repro3 and ITRF2020. An update on presentations and covered topics will be included in the IGS website.

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 regularly maintained by CB staff and continued to grow in followers in 2019, 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 (1116 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 Network Coordination and User Community Support

With the assistance of the CB Network Coordinator and the Infrastructure Committee, the IGS network added 12 new stations and identified 6 stations for decommissioned in 2019, bringing the total to 507 stations. The number of muti-GNSS stations increased from 242 to 308; while real-time stations increased from 190 to 259. In collaboration with the IRNSS, the CB added 18 stations capable of tracking IRNSS, increasing the total number to 59. Additionally, 124 changes to the rcvr_ant.tab files were implemented with collaboration of the Antenna WG. At the end of the year, support for the Site Log Manager included 661 site log updates (50 per month) and 41 antenna changes (11 of those at IGS14 core stations).

During 2019, 221 new user accounts were added to the CB real time caster. The CB Network Coordinator also responded to over 200 inquiries about data, products, or general IGS information. Station information was updated to include new photos and SONEL and tide gauge information. In order to comply with security requirements for the transition of FTP to secured FTP, the CB updated the internal scripts to use HTTPS/Curl for CDDIS data collection.

For additional statistics and information about the IGS Network, please refer to the Gov-

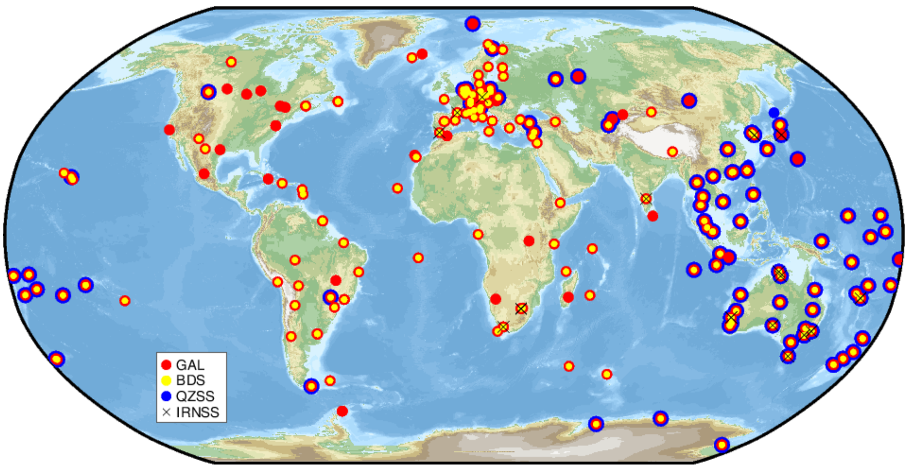

Figure 1: IGS Multi-GNSS Tracking Network map, courtesy of Geoscience Australia.

erning Board chapter of this report.

7 Web Development and Information Technology Support

Based on user feedback and evolving web design and use trends, the CB has commenced a website refresh for IGS.org, which is expected to be completed by the end of 2019.

In 2017, IGS Product access was redirected from IGS CB mirrors to the Crustal Dynamics Data Information System (CDDIS, ftp://cddis.gsfc.nasa.gov/gnss/products/), Institut National de l'Information Géographique et Forestière (IGN, ftp://igs.ensg.ign.fr/pub/igs/products/) and Scripps Institution of Oceanography (SIO, ftp://garner.ucsd.edu/pub/products/) to ensure global access to over 20 years of analysis products, as well as enabling access to data.

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 2019 Governing Board meetings and elections.
- Improvement of Working Group and Infrastructure Committee coordination and cross-communication.

9 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 and the International Federation of Surveyors (FIG, represented by IGS GB member S. Choy), in close collaboration with BIPM (G. Petit).

10 Publications

- IGS 2018 Technical Report, IGS Chapter
- NASA SGP/ICPO annual progress update, NASA internal publication
- Craddock, A., Johnston, G., Dach, R., Meertens, C., Moore, M., Oyola, M. (2019, April). International GNSS Service Update. Poster session presented at the meeting of the European Geophysical Union, Vienna, Austria.

11 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.

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2019

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1 Introduction

The IGS Analysis Center Coordinator (ACC) is responsible for monitoring the quality of products submitted by individual analysis centers, and combining them to produce the official IGS product. The IGS products continue to perform at a consistent level, and in general the solutions submitted by the analysis centers maintain a consistent level of performing.

In 2019, the testing and solutions for the third IGS reprocessing effort has started. In parallel to this, we are developing the next version of the IGS combination platform to allow multi-GNSS combined products. We have built the main orbit combination modules, and have started to assess the clock combination procedure developed by Natural Resources Canada (Banville et al. 2020), and potentially the software developed at Wuhan University.

The different analysis centers contributing to the IGS products, as well as those contributing to the Multi-GNSS Experiment (MGEX) and used in our experimental multi-GNSS combinations, are listed in Table 1. Table 1 also shows the abbreviations used across this report for the analysis center products.

2 Product Quality and Reliability

For 2019, with a few exceptions the delivery of ultra-rapid, rapid and final products have been well within the expected latencies. There were a few occasions where rapid and ultra-rapid products were delivered with a few hours delay, which mostly occurred due to errors

Table 1: The abbreviations used by the IGS ACC in this report for different products of the individual analysis centers. All the orbits submitted for the third reprocessing effort are called the same as the final orbits, with the exception of the reprocessing orbits submitted by TUM, which are called TUG.

Analysis center	Ultra-rapid	Rapid	Final	MGEX
Center for Orbit Determination in Europe (CODE)	COU	COD	COD	COM
Natural Resources Canada (NRC)	EMU	EMR	EMR	
European Space Agency (ESA)	ESU	ESA	ESA	
GeoForschungsZentrum Potsdam (GFZ)	GFU	GFZ	GFZ	GFM
Centre National d'Etudes Spatiales (CNES/CLS)			GRG	GRM
Japan Aerospace Exploration Agency (JAXA)				JAM
Jet Propulsion Laboratory (JPL)	JPU	JPL	JPL	
Massachusetts Institute of Technology (MIT)			MIT	
NOAA/National Geodetic Survey (NGS)	NGU	NGS	NGS	
Shanghai Observatory (SHAO)				SHM
Scripps Institution of Oceanography (SIO)	SIU	SIO	SIO	
Technical University of Munich (TUM)				TUM
The United States Naval Observatory (USNO)	USU	USN		
Wuhan University	WHU	WHU		WUM
IGS product	**Description code**			
IGS ultra-rapid adjusted part	IGA			
IGS ultra-rapid predicted part	IGU			
IGS real-time	IGC			
IGS rapid	IGR			
IGS final	IGS			
IGS second reprocessing	IG2			

in the automated running of combination, and were resolved by manually intervening the combinations.

2.1 Ultra-rapid

The ultra-rapid is one of the heaviest utilized IGS products, often used for real-time and near-real time applications. For 2019, the IGS has been receiving 8 submissions from different ACs for combined IGS ultra-rapid products (see Table 2 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

Table 2: ACs contributing to the Ultra-rapid products, *W* signifies a weighted 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 center	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

been consistently at this level since GPS week 1500. In addition over the past 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. The weighted Root-Mean-Square (RMS) error of the individual orbit submissions from the analysis centers with respect to the combined ultra-rapid products are plotted in Figure 3. The orbit solution from GFZ was de-weighted from GPS week 2038, when there was an issue in their orbits due to a bug in the network selection algorithm used. This was quickly resolved and GFZ were fully weighted from GPS week 2042. Wuhan's orbit and ERP solutions were added as a weighted solution since GPS week 2039. Recently, NGS stopped submitting ultra-rapid orbits to the IGS since their orbits started to diverge from the IGS combination; they plan to resume submitting the ultra-rapid orbits in future after they resolve the issues in their ultra-rapid orbit products.

2.2 Rapid

There are nine individual analysis centers contributing to the rapid IGS products (see Table 3). 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 of 6-7 mm since approximately GPS week 1500 (see Figure 4). There was no change to the IGS rapid combination procedure in 2019.

2.3 Final

There are nine individual ACs contributing to the IGS final products (see Table 4). Most AC final solutions are comparing at less than 5 mm to each other (see Figure 5). The orbit solutions from NGS and GFZ started to become closer, in terms of comparability,

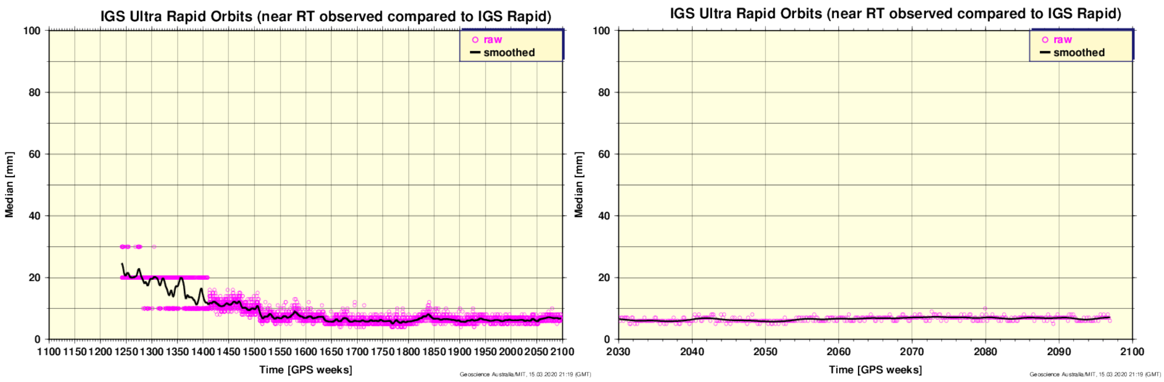


Figure 1: The median difference of the fitted component of the IGS ultra-rapid (IGU) combined orbits with respect to the IGS rapid (IGR) orbits. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

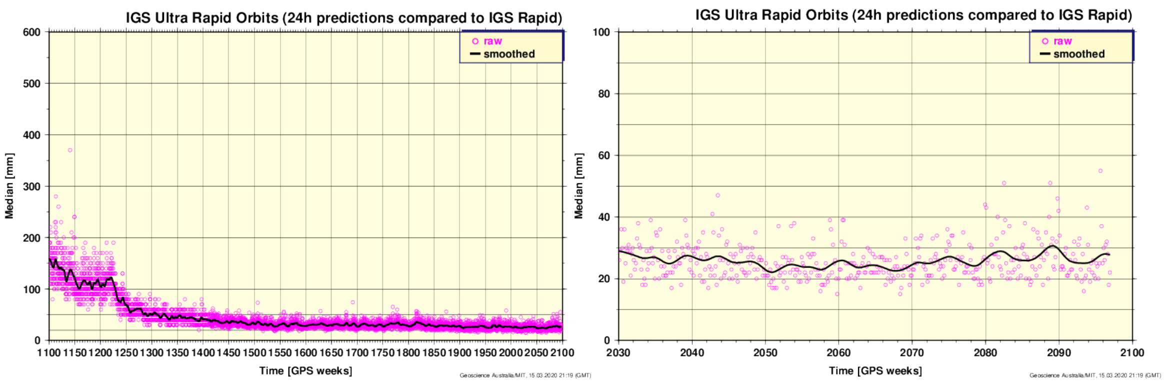


Figure 2: Median of IGU combined predicted orbits compared to IGR. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

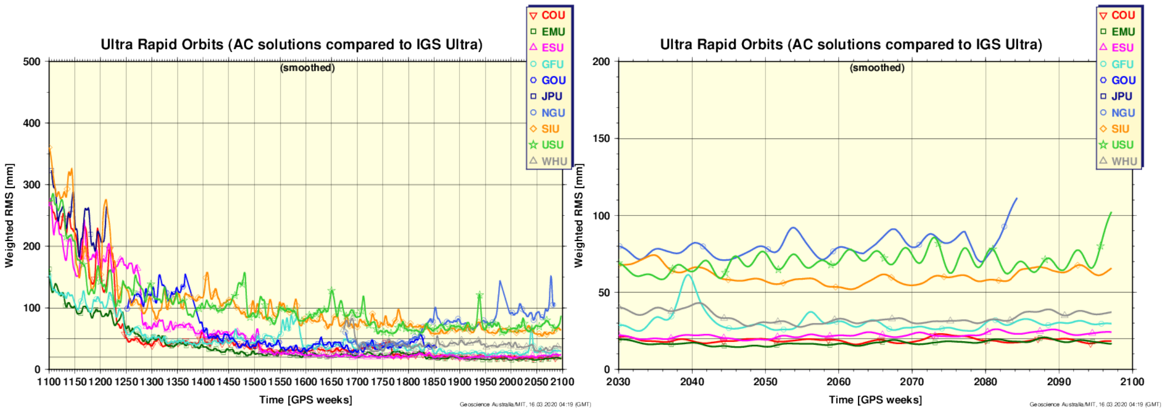


Figure 3: Weighted RMS of AC Ultra-rapid orbit submissions (smoothed)

Table 3: ACs contributing to the IGS Rapid products, *W* signifies a weight contribution, *C* is comparison only. The USN ERP solutions are not weighted into the combination, with the exception of the length of day estimate, which is a weighted value.

Analysis center	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 (LoD W)	C
WHU	W	W	C

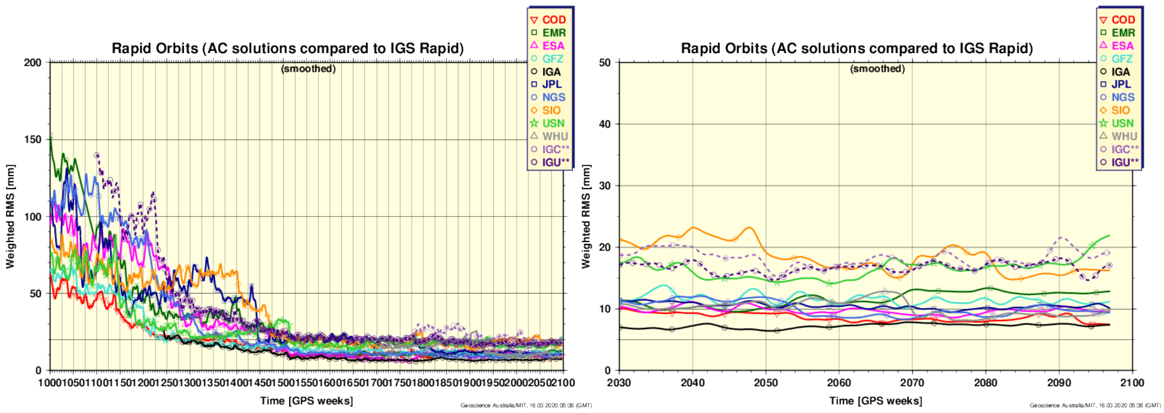


Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed)

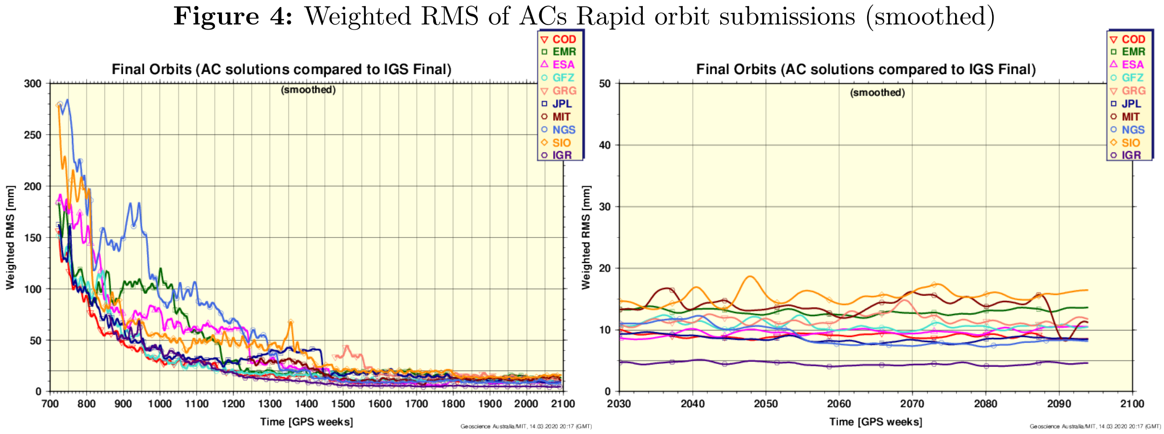


Figure 5: Weighted RMS of IGS Final orbits (smoothed)

Table 4: 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 center	Orbit	ERP	Clock
COD	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

to the orbit solutions by JPL, COD and ESA since about mid 2019. Recently, the orbits from MIT also significantly became closer to the orbits from JPL, COD and ESA. This happened after MIT added a procedure for the radiation pressure stochastic modelling, refreshed their a priori coordinates of the stations, and fixed some bugs in their processing software.

3 Third Reprocessing Effort

The third reprocessing effort will reanalyse the full history of GNSS data collected by the IGS global network in a consistent way, by applying the latest standards for models and processing methodology. The solutions obtained from the reprocessing effort will then be combined and submitted as the IGS contribution to the next version of the International Terrestrial Reference Frame, ITRF2020. For the first time IGS will be providing its own independent estimates of scale of the reference frame.

Before analysis centers commence their full reprocessing run, they are submitting reprocessed test solutions using the reprocessing 3 standards applied to 2014. This is then being used to confirm that the standards appear to have been applied correctly. To date seven ACs have submitted test solutions upon which we have performed a combination in 'rapid' mode; i.e. no reference frame alignment was applied. The median RMS of the individual GPS satellites for each analysis center with respect to the IGS combination is shown in Figure 6 for the test analyses over 2014.

4 Experimental multi-GNSS combinations

In 2019, we started trialing experimental multi-GNSS orbit combinations by adapting the existing combination software. We made modifications to the source code of the current combination software to allow it to process GALILEO, BeiDou and QZSS orbit files in addition to the current GPS and GLONASS constellations that are currently combined. The intention of this experiment is to be a baseline to assess how a new developed multi-GNSS combination software will perform.

The experimental products have been made available since GPS week 2050 (April 2019) on a weekly basis, with a delay of 13 to 20 days, similar to the final combination. Since the purpose of this trial is to compare as many products as available, we include in the combination all available Multi-GNSS Experiment (MGEX) submissions, rapid or final, as well as all available standard GPS-only and GLONASS-only submissions. The alignment of the orbits with the IGS reference frame is not performed in these experimental combinations. The clock combinations are not yet being performed, and are planned to be included in a future version of the combination software.

The experimental multi-GNSS orbit combinations as sp3 files and summary files, as well as plots of the orbit RMS and transformations are stored on the ACC webpage at `http://acc.igs.org/mgex_experimental.html`.

The comparisons of the orbit submissions with the combined solutions are shown in Figure 7 for different satellite systems. As shown in Figure 7(a), the experimental combined GPS orbits agree to the standard IGS final and rapid combinations (IGS and IGR) at a below 5 mm level, and the experimental GLONASS combination also agrees to the current GLONASS combinations (IGL) at around 15 mm level (Figure 7(b)). For GLONASS, the orbit solutions from different analysis centers are generally below 40 mm level. The GALILEO orbit solutions from COM, GFM, GRM, WUM and more recently (since GPS week 2088) SHM show very good agreements of below 15 mm, similar to the consistency

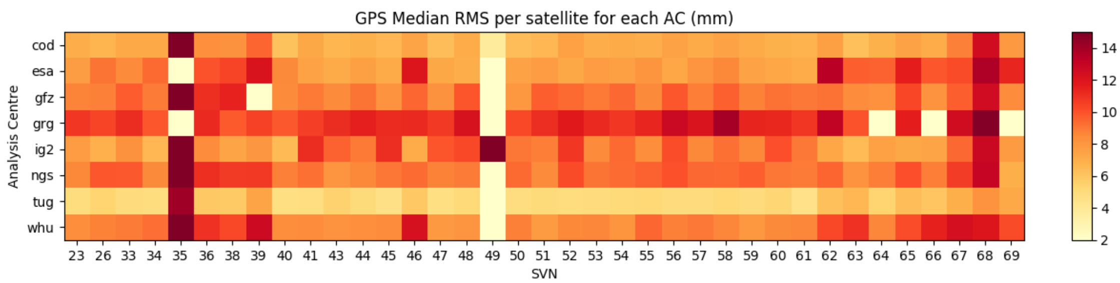


Figure 6: Median RMS of the individual GPS satellites by SVN number, compared to the combined orbits for the test solutions of ACs for 2014. Note ig2 are combined orbits obtained from repro2.

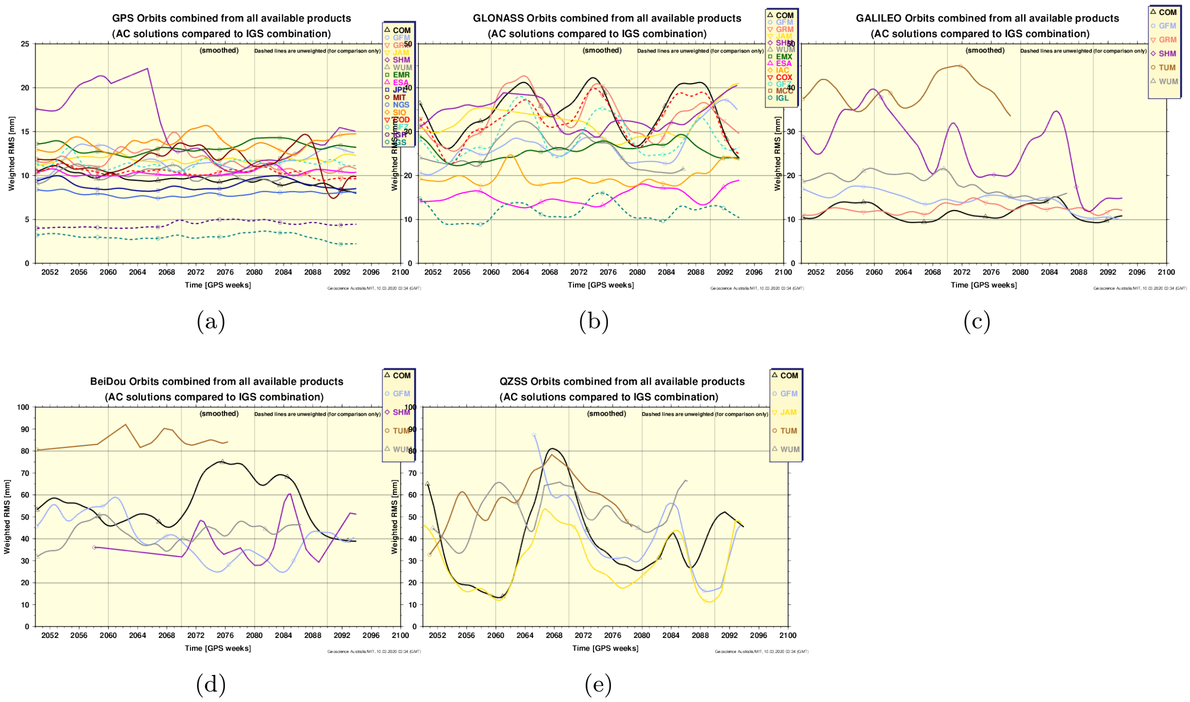


Figure 7: Smoothed weighted RMS of the different orbit submissions compared to the combined solution for a) GPS, b) GLONASS, c) GALILEO, d) BeiDou, and e) QZSS. The solid lines depict the orbits included in the combination, and the dashed lines are the orbits that are only compared to the combined orbit. The center names with 'M' as the last letter are the MGEX submissions. IGS, IGR and IGL orbits are the IGS standard final solution, IGS standard rapid solution, and the IGS GLONASS solution based on the standard orbit submissions.

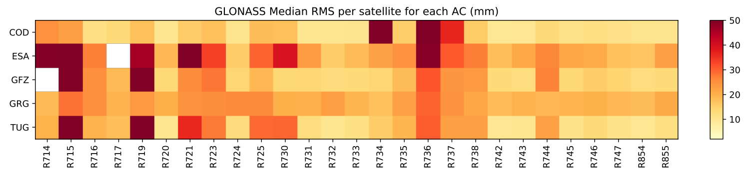
levels for GPS. This is very promising for GALILEO combinations. The BeiDou orbits from different ACs agree at a level of around 40 mm, and the QZSS orbits, which only include four satellites, generally agree at about 40-60 mm with more fluctuations than the other systems. A few of the MGEX submissions had poor consistencies at some days compared with the other (standard and other MGEX) submissions to a point that we had to remove them from the combination manually in order for the combination procedure to be completed. However, in general, the MGEX submissions have been performing with reasonable comparability when compared to the standard submissions. A detailed assessment of the quality of the orbits was performed by Sośnica et al. (2020), where the orbits were evaluated both by investigating the consistency of the orbit solutions included in the combinations and by comparing the combined orbits to satellite laser ranging observations.

4.1 Development of a new version of the ACC combination software

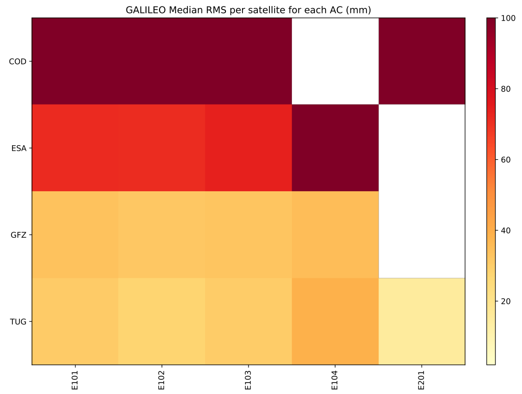
While the robust algorithm used in the current combination software has proved to fulfill the needs of the IGS combined orbits and clocks, there are a few limitations in the software that make it challenging to still get adapted for performing multi-GNSS combinations. Although we have already adapted the software to process orbits from other GNSS software than GPS and GLONASS, we are still limited to processing the satellite systems separately, or at best to process multiple systems together with the same weighting technique, ignoring the differences between the quality of the orbits of different satellite systems. Therefore, we are currently in the process of developing a fresh version of the combination software which is more flexible for including orbits from multi-GNSS satellites, is capable of combining multiple GNSS systems together in one combination, and contains improved weighting techniques which are necessary when including multiple GNSS systems in a combination. The priority in the new version will be to maintain the robustness of the IGS products.

For the third reprocessing effort in addition to the standard orbit combination, we plan to run orbit combinations using the adapted combination software for multi-GNSS, as well as to run combinations using the new version of the combination platform. We performed analyses using the new version of the combination platform on the test solutions of the third reprocessing effort. The median RMS of the individual GLONASS and GALILEO satellites compared to the combined orbits using the new software are shown in Figure 8. Except for a few satellites, most of the ACs have performed at below 30 mm in terms of comparability for the GLONASS system. For GALILEO satellites for this test period of 2014, the orbit solutions from GFZ and TUG are closer to each other and to the combined orbit, as compared to the solutions from COD and ESA. However, there have been only five operational GALILEO satellites in 2014, and a more recent time period of analyses is needed to have a better understanding of the differences in orbit solutions. This will be performed as we process more reprocessing 3 combinations.

Most of the orbit combination modules of the new version of the ACC combination software



(a)



(b)

Figure 8: Median RMS of the individual GLONASS (top) and GALILEO (bottom) satellites compared to the combined orbits for the test solutions of the ACs over 2014.

have been built and tested successfully against the current software, and we are currently adding pre- and post-processing screening algorithms to make the orbit combination fully-operational. The clock combination is underway, and we will be incorporating the existing software by Natural Resources Canada (Banville et al. 2020) and potentially by Wuhan University, with a priority to preserve the integer nature of the clocks for use in ambiguity resolution.

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Center for Orbit Determination in Europe (CODE) Technical Report 2019

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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(/Galileo) 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/

CODE's contribution to the IGS MGEX project is a five-system solution considering GPS, GLONASS, Galileo, BeiDou, and QZSS where 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

By December 10th, 2019 CODE started to publish the daily code and phase bias products from the final and MGEX (GPS and Galileo only) solution series, see Schaer et al. (2018); Dach et al. (2019). At this date, also the values back to December 2018 have been made available. Instructions, how to use the phase bias products for ambiguity resolution are provided in ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT .

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 containing station coordinates, ERPs, and satellite antenna offsets
COD_TRO.SNX_U.Z	CODE ultra-rapid solution, as above but with troposphere parameters for selected sites, SINEX format
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, GLONASS, and Galileo 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	SINEX file from the CODE rapid solution containing station coordinates, ERPs, and satellite antenna offsets
CODwwwwd_TRO.SNX_R.Z	CODE rapid solution, as above but with troposphere parameters for selected sites, 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
CODE_MONTHLY.BIA	Cumulative monthly OSB satellite solution in 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).

Long-term archive of selected
CODE *rapid* products available at ftp://ftp.aiub.unibe.ch/CODE/yyyy_M/

`yyyy_M/CODwwwwd.EPH_M`	CODE final rapid GNSS orbits: GPS+GLONASS+Galileo (before September, 23rd 2019 only GPS+GLONASS)
`yyyy_M/CODwwwwd.ERP_M`	CODE final rapid ERPs belonging to the final rapid orbits
`yyyy_M/CODwwwwd.CLK_M`	CODE GNSS clock product related to the final rapid orbit, clock RINEX format

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.BIA.Z`	CODE daily code and phase bias solution corresponding to the above mentioned clock products See `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT` for the usage of the phase biases.
`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

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

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

`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 and phase (GPS and Galileo only) biases related to the MGEX final clock correction product, bias SINEX format v1.00 See `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT` for the usage of the phase biases.
`yyyy/COMwwwwd.DCB.Z`	GNSS code biases related to the MGEX final clock correction product, Bernese format

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. During the year 2019 the MGEX solution did include up to 93 satellites.

The network used by CODE for the final processing is shown in Figure 2. Less then 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

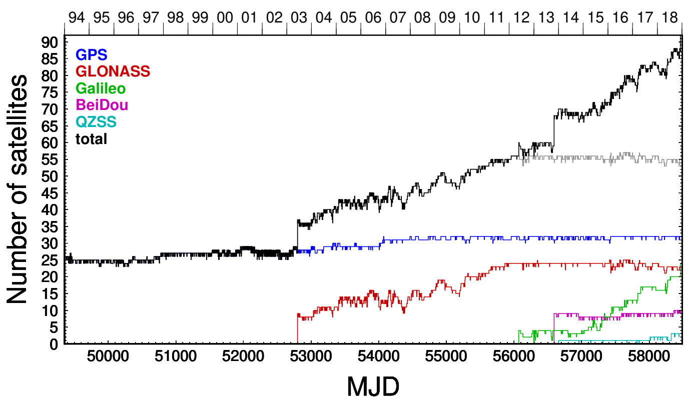


Figure 1: Development of the number of satellites in the CODE orbit products.

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.bia.Z`	CODE daily code and phase bias solution corresponding to the above mentioned clock products
`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

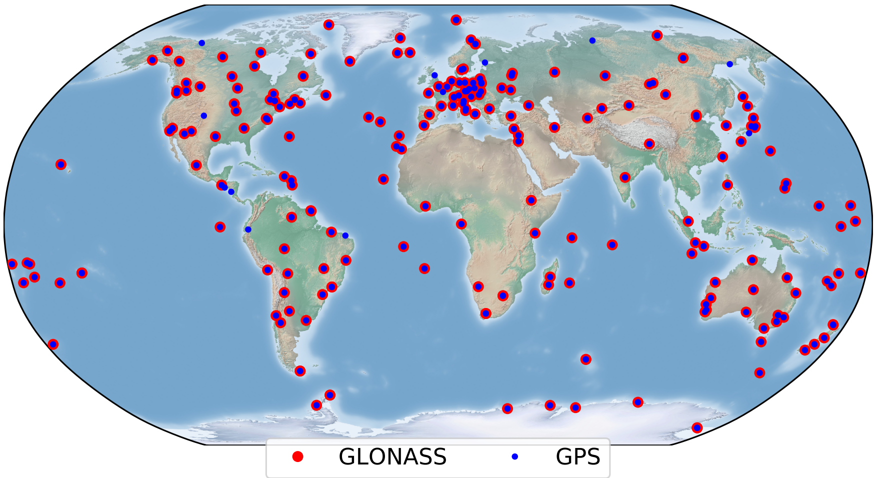
Note, that the `COD`–series is identical with the files posted at the CODE's aftp server, see Table 1.

Files generated from pure one–day solutions:

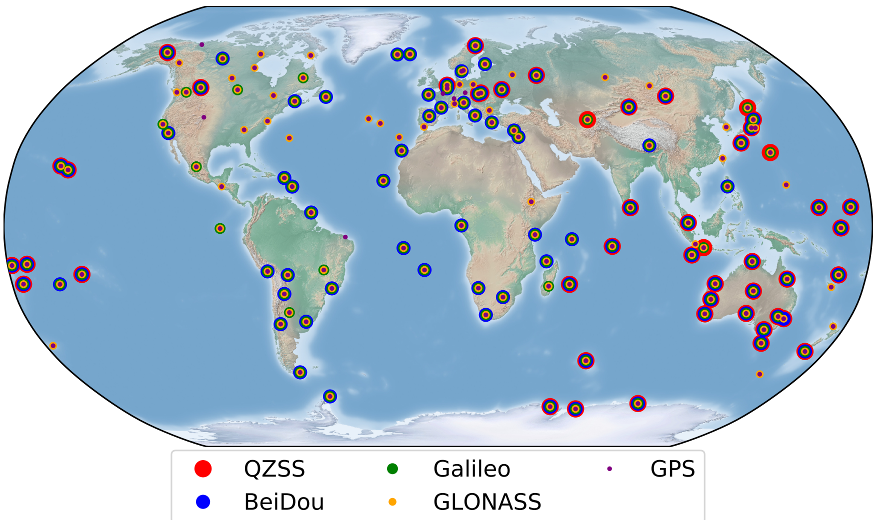
`cofwwwwd.eph.Z`	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a pure one–day solution
`cofwwwwd.snx.Z`	GNSS daily coordinates/ERP/GCC from the pure one–day solution in SINEX format
`cofwwwwd.clk.Z`	GNSS satellite and receiver clock 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



(a) final solution



(b) MGEX solution

Figure 2: Network used for the processing at CODE by the end of 2019.

data are available only to a sufficient amount for a reasonable orbit determination by the end of 2019. 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. The tracking situation in the IGS network regarding satellite R26 did improve with the beginning of 2019 allowing for a solution for a few epochs per day since March 2019 . By day 258 of year 2019 (August 5, 2019) the satellite switched the frequency number from −5 to −6 . Obviously not only the frequency number of changed since the current tracking situation allows a nearly complete provision of the satellite clock corrections.

On the right hand plots the performance 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 satellite. Satellite G18 (since Jan. 2018) is even a reactivated Block IIA satellite. 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. The satellite G04 is from January to July 2019 as well as again from October onward the new Block IIIA satellite. The period inbetween with the reduced performance the old Block IIA satellite (SVN 36 launched in 1994) was reactivated. 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.

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 (2019). *CODE ultra-rapid product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75676.3 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2019). *CODE rapid product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75854.3 .
- 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 Institute, 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 Institute, Uni-

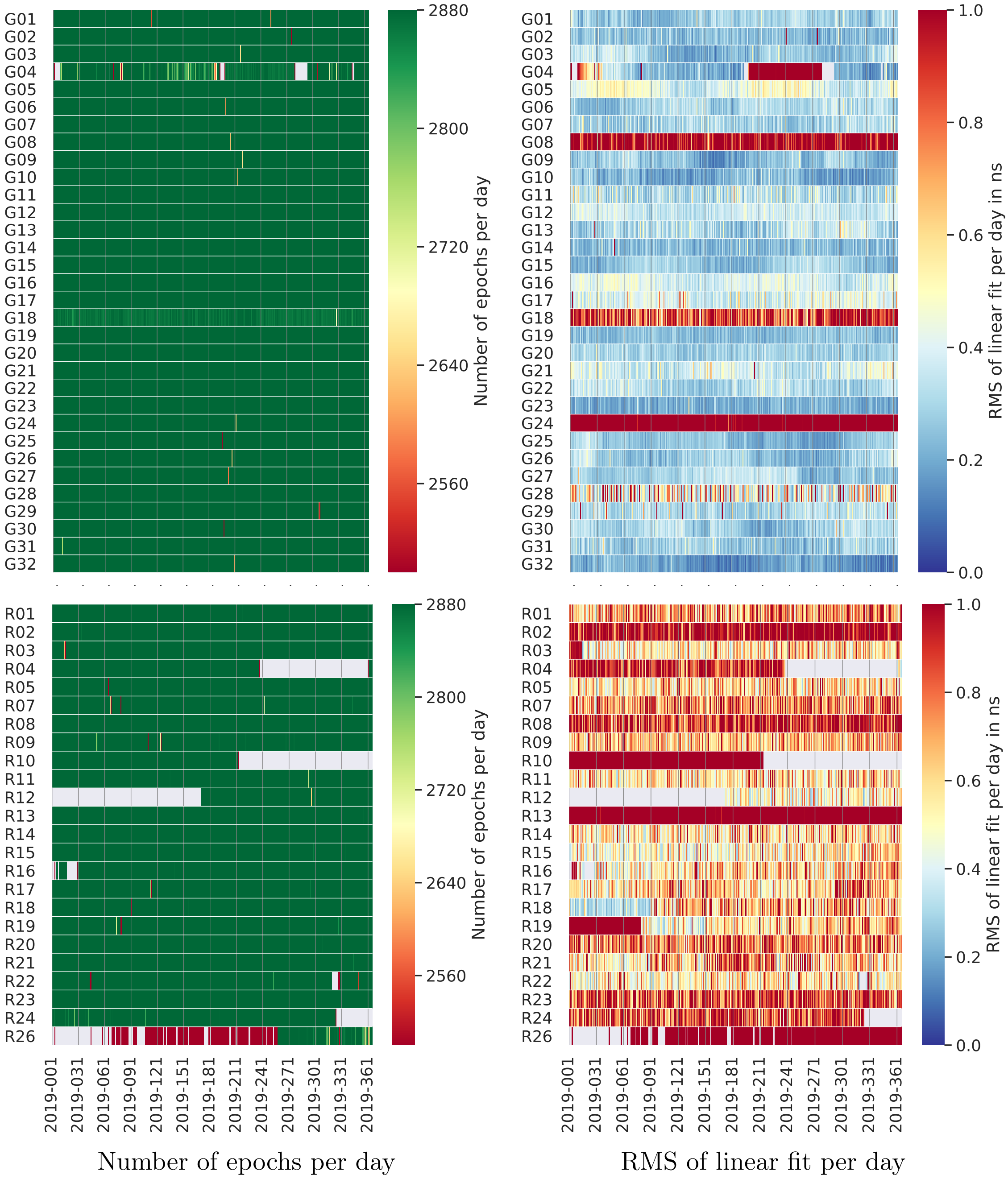


Figure 3: Completeness and performance of the GPS (top) and GLONASS (bottom) satellite clock corrections as provided in the CODE final solution (30-second sampling).

versity 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. (2019).

In Section 3.1 we give an overview of important development steps in the year 2019. One of the highlights was certainly the extension of the operational rapid and ultra-rapid product chain by Galileo (see Section 3.2). An important advance of the Galileo orbit modelling described in Section 3.3 was established already earlier in 2019 in the MGEX environment. Prange et al. (2020) provides am overview on the current status of the MGEX processing at CODE.

3.1 Overview of changes in the processing scheme in 2019

Table 3 gives an overview of the major changes implemented during the year 2019. 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.

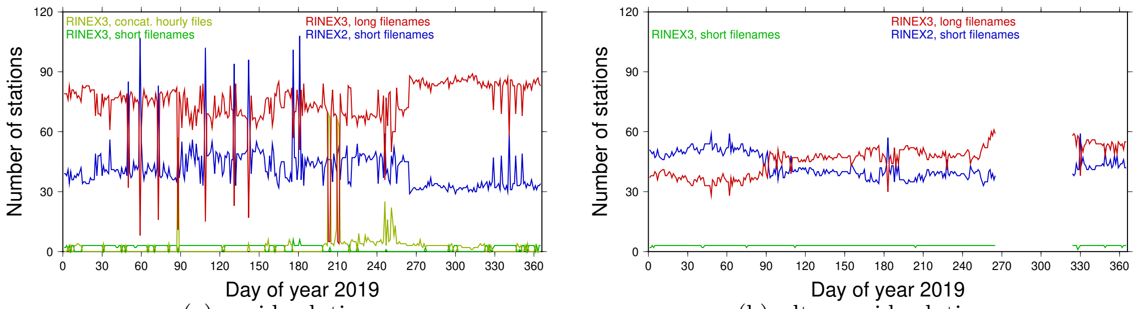
Use of RINEX 3 data in the IGS rapid and ultra-rapid product generation

Since end of January 2017, CODE is using also RINEX 3 files to generate the IGS final products, in the rapid and ultra-rapid product generation since April 2018 . Also merged hourly RINEX 3 files are considered if they contain more epochs than the original RINEX 3 files generated at the stations. A related statistic in provided in Figure 4 .

During the year 2019 the number of RINEX 3 files in the final and rapid solution did slightly increase. With the inclusion of Galileo in the rapid and ultra-rapid processing chain, the station selection was slightly adapted resulting in more RINEX 3 files in the processing in order to improve the global coverage of the third GNSS.

Table 3: Selected events and modifications of the CODE processing during 2019.

Date	DoY/Year	Description
01-Feb-2019	032/2019	Antenna corrections updated concerning satellite G04 (first Block IIIA, see also IGSMAIL#7733). Final solutions containing this satellite (e.g., since day 009 of year 2019) reprocessed with the updated values.
08-Apr-2019	098/2019	Activated ambiguity resolution for the new satellite G04 (Block IIIA) starting with GPS week 2049 (just after GPS week rollover).
06-May-2019	120/2019	Activated RINEX 3 for 5 second clock densification
29-May-2019	149/2019	corrupted ION/INX and DCB final products detected: • from yyddd 10276 (wwwwd 16040) • to yyddd 10346 (wwwwd 16140) Mean TEC level is significantly off (too high). Note: yymm 1010, 1011, 1012 monthly combinations affected.
05-Jun-2019	156/2019	Switch to satellite-specific empirical models: • RAP from day 157 2019, • FIN from GPS week 2056, • MGEX from day 142 2019. activate the extended thermal radiation modelling for Galileo satellites in the MGEX solution
11-Jul-2019	192/2019	Corrected error in thermal radiation modelling for Galileo satellites which was applied in the $-Y$ instead $-X$ direction in the satellite-fixed coordinate system. The effect was mostly compensated by the empirical Y-bias estimate in the ECOM2 model. MGEX solutions from day 142 to 188 of year 2019 are affected and reprocessed.
12-Jul-2019	193/2019	Extend checking the consistency between filenames, satellite identifiers, and content for the predictions of the GNSS satellites provided to the ILRS
29-Aug-2019	241/2019	Some confusion regarding available source from VMF coefficients from the server in Vienna
03-Sep-2019	246/2019	Fitting the precise orbit files for prediction using ECOM instead of ECOM2 orbit parametrization.
22-Sep-2019	265/2019	**Galileo activated in rapid and ultra-rapid processing** including the ambiguity resolution, allowing in particular the ambiguity resolution in PPP when introducing the related phase bias products
23-Sep to 17-Nov 2019		All operational processing of the CODE analysis center has been performed on a backup system because the main processing cluster of the University was in reconstruction in order to increase its capacity. Until end of November the processes and results have been synchronized back to the main system.
08-Oct-2019	281/2019	Extending the considered RINEX 3 observation types for GPS by C2S and C2L
30-Oct-2019	303/2019	Reprocessing the rapid solutions since day 265 of year 2019 because a Galileo-relevant orbit parameter was missing in the related normal equation
10-Dec-2019	344/2019	Phase bias corrections allowing for ambiguity resolution in a PPP application (description in Schaer et al. 2018; Dach et al. 2019) for the final and MGEX (only GPS and Galileo) solution series has been published back to December 2018 See `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT` for further explanations.
15-Dec-2019	349/2019	Ocean tidal loading correction table was incomplete (since an unknown epoch); at least stations ASCG, KIRI, LAUT, NAUR did run w/o corrections



(a) rapid solution (b) ultra-rapid solution

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

In the ultra-rapid processing only hourly RINEX files are considered. Here at the beginning of the year less than half of the processed stations did provide their observations in hourly RINEX 3 files. This changed during the year – since April more than half of the processed stations do distribute their measurements in hourly RINEX 3 files.

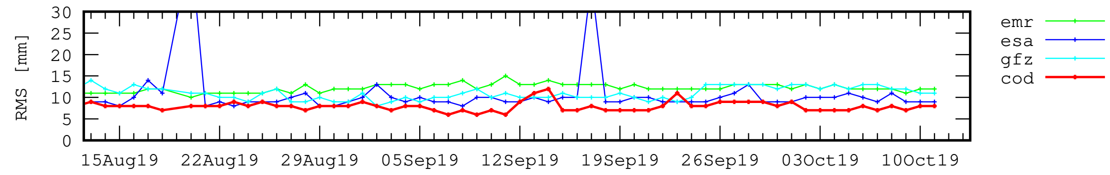
3.2 Extension of the CODE rapid und ultra-rapid product by Galileo

By 23$^{\text{rd}}$ September 2019 CODE started to include Galileo into its operational rapid (since day of year 265) and ultra-rapid (since day of year 266) solutions. With this step, all three fully established GNSS, namely GPS, GLONASS, and Galileo, are included resulting in a consistent solution of 80 satellites.

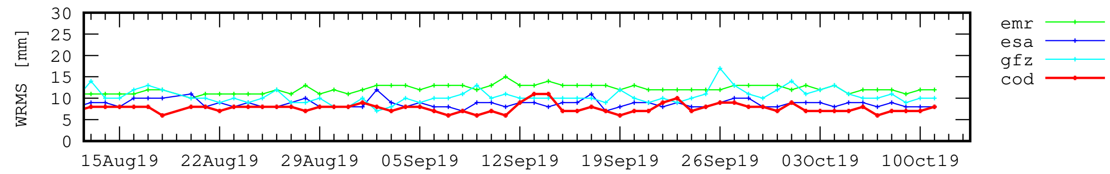
Figure 5 shows the impact of this extension on the combination of the rapid (GPS) orbits as provided by the analysis center coordinator (ACC). Note that only a subset of the ACs are included in this figure in order to keep it more clear. The plot confirms that the inclusion of Galileo did not degrade the products for the other satellite systems.

There is also no influence on the transformation parameter published in the combination protocols visible for this day in the CODE solution. The only exception is the scale parameter what is displayed in the lower plot of Figure 5 for the rapid and in Figure 6 for the ultra-rapid combination. The inclusion of the Galileo measurements causes a change in the scale of about $+0.1 ppb$ for GPS and about $+0.2 ppb$ for GLONASS with respect to the combined IGS solution. When interpreting these numbers, one should keep in mind that only about half of the stations in the CODE ultra-rapid solution do provide Galileo measurements.

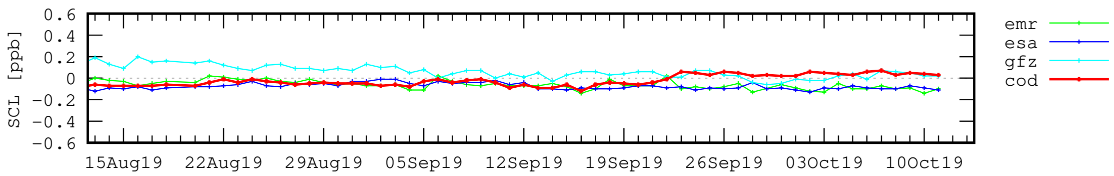
A reason for the discrepancy in scale is that the receiver antenna corrections for GPS are also used for Galileo to keep the consistency with the IGS14 antenna correction set. At the same time, for the satellite antenna corrections the values published by the system provider (GSA 2016, 2017, 2019) are used. The consequence of this assumption is studied in the frame of the antenna working group during Summer 2019 (Villiger et al. 2020).



(a) RMS

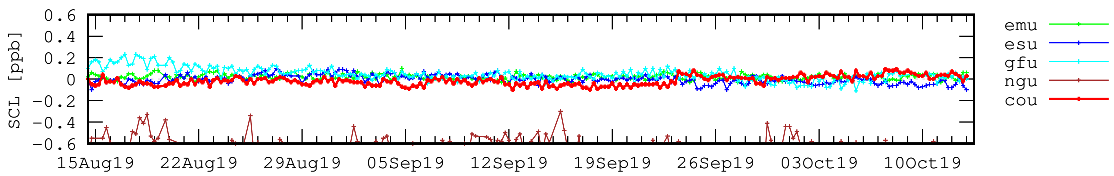


(b) WRMS

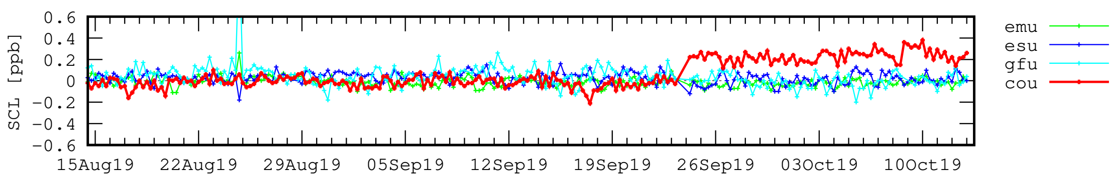


(c) Scale

Figure 5: Extract from the IGS rapid combination (http://acc.igs.org accessed in October 2019).



(a) Scale for GPS satellites



(b) Scale for GLONASS satellites

Figure 6: Extract from the IGS ultra-rapid combination (http://acc.igs.org accessed in October 2019).

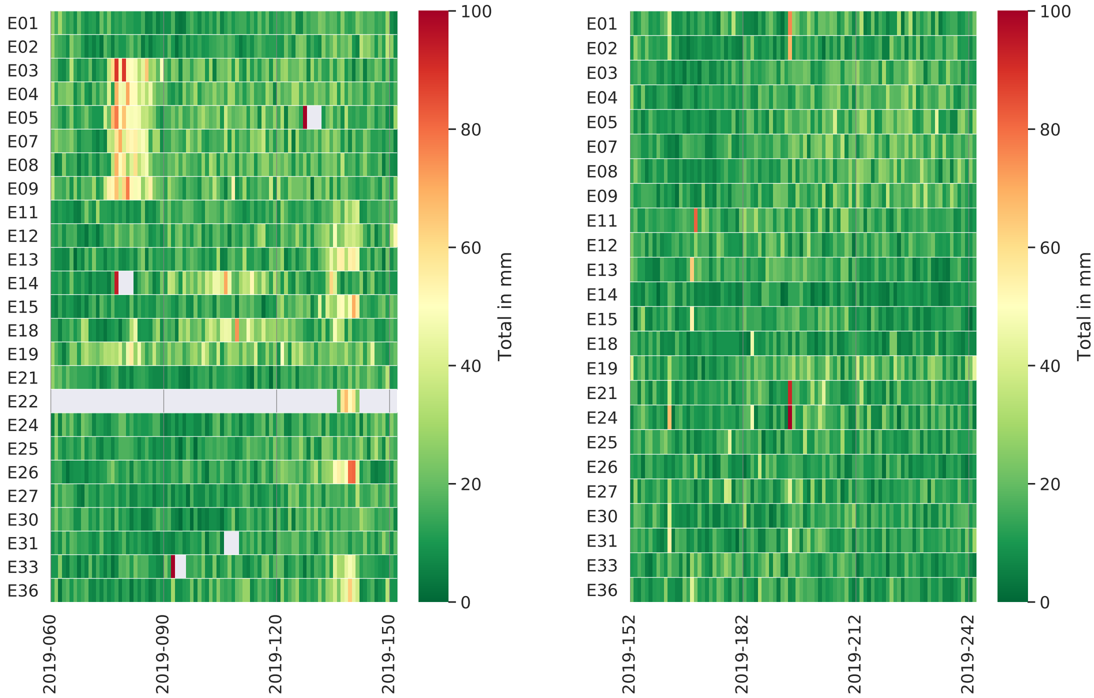
3.3 Advancing Galileo orbit modelling in eclipse season

It was observed in the frame of the MGEX environment, that Galileo satellites from CODE have degraded orbits when the Sun is close to the orbital plane (small β-angles). Compared to MGEX solutions from other ACs this effect was more prominent in the CODE solution. It turned out that this effect is reduced in all usual orbit validation measures if shorter orbit arcs than 72 hours is used.

Investigations of the effect resulted in Sidorov et al. (2020) where the asymmetric location of the radiators at the Galileo satellites have been identified to be responsible for additional along-track accelerations. They can be absorbed to a certain extent by the usually estimated parameters from the ECOM2 orbit model (Arnold et al. 2015). Since these parameters are inactive during the eclipse phase of the satellite orbit, a modelling deficiency resulted.

For that reason starting from day 142 of year 2019 (May, 22$^{\text{nd}}$) the following extension w.r.t. the ECOM2 has been activated:

- in order to compensate for the thermal emissions from the $-X$ radiators of Galileo



(a) before advancing the orbit model

(b) after advancing the orbit model

Figure 7: Orbit misclosures for Galileo satellites from 3-day solutions in the MGEX processing

satellites, an a priori acceleration in the satellite $+X$ direction equivalent to 300 W for all β-angles is assumed.

- An additional once-per-revolution periodic term in the satellite-Sun direction for Galileo satellites during eclipse seasons shall account for along-track accelerations potentially originating from other thermal effects during these periods. This term shall remain active also in the Earth's shadow transition due to the thermal nature of the associated forces.
- The constant term along the solar panel axis remains active in eclipses for the Galileo FOC satellites, in order to compensate for the thermal imbalance between the radiators on the $+Y$ and $-Y$ faces of these spacecrafts.

The positive effect of this extension becomes evident in most of the orbit quality criteria as Sidorov et al. (2020) has shown. Here only the orbit misclosures from 3-day long-arc solutions are shown in Figure 7 . The same extended ECOM2 orbit modelling is applied together with an a priori box-wing model to compensate for the Solar radiation pressure effect based on the published optical properties (GSA 2016, 2017, 2019) for orbit modelling of the Galileo satellites in the rapid and ultra-rapid solution (since September 2019) but also for the reprocessing effort for ITRF2020.

4 Preparation for IGS-Reprocessiong

As a global analyis center CODE contributes to the IGS reprocessing effort for the ITRF 2020. In this context several changes with respect to the operational final solution from CODE have been implemented and tested. The test solutions for the year 2014 have been provided to the IGS in time; the reprocessing itself will be carried out in 2020 at IAPG/TUM .

In this section the most important changes in the processing scheme are described.

Background models:

An update of the IERS and background models has been establised with respect to

- mean pole model (Petit and Luzum 2010),
- high frequency pole model (Desai and Sibois 2016), and
- ocean tidal loading corrections for station deformation and gravitational effect on satellite orbits is now based on FES2014b (Carrere et al. 2016) .

Updating the orbit modelling:

CODE is using ECOM2 (Arnold et al. 2015) as the basic orbit model for the GNSS satellites. In the operational solutions so called stochastic pulses (empirical velocity changes, see Beutler et al. 1994) are introduced every 12 hours (at noon for one-day and at noon and midnight for three-day solutions). These pulses are now shifted to orbit midnight which improves, e.g., the orbit misclosures for the GPS satellites by about 10%.

To make this change more efficient, the reprocessing solution will base on three-day long-arc solution. In order to meet the requirement of the IERS to have no non-removable constraints between daily solutions, the daily coordinate and Earth rotation parameter estimates are only connected via constraints but not combined on parameter level as it is done in the operational solution.

As the experience from Lutz et al. (2015) shows longer arcs are beneficial for the obtained Earth rotation parameters. After rescheduling the stochastic pulses the three-day long-arc solution helps to increase the related benefit, e.g., if orbit midnight gets close to the end of a day.

Downweighting of misbehaving GPS satellites:

Some of the GPS satellites have been identified in Springer (2000) as "satellites experiencing momentum wheel problems". This list of satellites was updated and extended up to 2007 when the last of these satellites was decommisioned. These satellites are downweighted in the solution because their orbits cannot be modelled properly. To prevent a degradation of geophysically relevant results from the reprocessing (e.g., station coordinates or Earth orientation parameters), these satellites are downweighted (Dach et al. 2018).

Inclusion of Galileo:

For Galileo the satellite antenna calibration was published by the system provider (GSA 2016, 2017, 2019). Because meanwhile also consistent mutli-GNSS receiver antenna calibrations are available, the GNSS contribution becomes from the theoretical side capable to contribute to the scale of the upcoming ITRF 2020 solution. This is motivation to include Galileo starting from 2012 (beginning of the MGEX project) as the third GNSS besides GPS and GLONASS. Towards the end of the reprocessing series it will contain the solution for 80 satellites.

Satellite clock corrections with consistent phase biases:

The satellite clock corrections will be provided with consistent phase biases as it is available for the operational final solution (Schaer et al. 2018; Dach et al. 2019). It is planned to extend the currently available series of phase biases back to 2013 for Galileo and 2000 for GPS.

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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 2019

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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 2019 (products labelled 'em*'). Additionally, changes to the stations and services 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. The NRCan-AC is located at the Canadian Geodetic Survey (CGS).

2 NRCan Core Products

The Final GPS products continued to be estimated with JPL's GIPSY-OASIS software in 2019, 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). The Final GLONASS products are taken from a separate GNSS Final run coming from the Bernese software version 5.2.

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.

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 (proposed) • Interval: 5 sec

3 Ionosphere and DCB monitoring

NRCan's global ionosphere Total Electron Content (TEC) maps at 1 hour intervals (emrg[ddd]0.[yy]i), which include GPS and GLONASS differential code biases (DCBs), continued to be available at CDDIS with a latency of less than 2 days. Apart from near-real-time maps, a daily 3-constellation (GPS, GLONASS, and Galileo) global TEC mapping and DCB estimation process continued to run internally as its performance was being monitored. Global RMS TEC maps by IGS and two of its analysis centres have been investigated over the Canadian region during a two-year period (Ghoddousi-Fard, 2020) and the importance of evaluation, more sophisticated quality control and strategies used to generate RMS maps by each centre were emphasized. Station and satellite specific GLONASS DCB estimation using about 250 IGS stations collecting GLONASS measurements continued to be monitored. Characteristics of higher order ionospheric effects on GNSS observations using IGS network (Ghoddousi-Fard 2019) and their impacts on satellite orbit and clock estimation during geomagnetic storm periods were presented (Ghoddousi-Fard and Mireault 2019). 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 (Prikryl et al. 2019).

4 Real-time correction service

NRCan has started encoding its ultra-rapid ionosphere product (Garcia-Rigo et al. 2019) for real-time distribution in the RTCM format. We are distributing proposed RTCM SSR message type 1264 at a 30 sec rate from a development platform. The ionosphere product is uploaded every 15min (at 5, 20, 35 and 50min after the hour).

NRCan has developed a prototype real-time platform to investigate the possible replacement of its third-party software. The goal is to maximise flexibility when generating multiple constellation corrections in real-time.

5 CSRS-PPP service

The CSRS-PPP engine was updated to SPARK v.2.26.1 in 2019. CSRS-PPP now provides an estimate of uncertainties related to epoch changes, made possible by the February 2019 release of NAD83(CSRS) v7 and its new velocity model NAD83v7VG, which now includes an uncertainty grid (Robin et al. 2019).

Table 2: NRCan Station Upgrades in 2019.

Station	Date	Remarks
albh	2019-01-16	Station receiver upgraded to SEPT POLARX5
alrt	2019-08-24	Station receiver upgraded to SEPT POLARX5
drao	2019-05-31	Station receiver upgraded to SEPT POLARX5
nain	2019-10-07	Station receiver upgraded to SEPT POLARX5
picl	2019-08-26	Station antenna upgraded to TWIVC6150 NONE
qiki	2019-07-29	Station receiver upgraded to SEPT POLARX5
sask	2018-01-22	Station receiver upgraded to JAVAD TRE_G3TH
sch2	2019-04-02	Station receiver upgraded to JAVAD TRE_3N
yell	2019-09-04	Station external frequency standard changed

6 Operational NRCan stations

In addition to routinely generating all core IGS products, NRCan also provides public access to GNSS data for more than 100 Canadian stations. This includes 35 stations currently contributing to the IGS network through the CGS's Canadian Active Control System (CGS-CACS), the CGS's Regional Active Control System (CGS-RACS), and the Canadian Hazards Information Service's Western Canada Deformation Array (CHIS-WCDA). In addition to the 35 stations NRCan contributes to the IGS network, a further 31 GNSS stations are submitted to IGS data centers. Several upgrades/changes to NRCan's IGS stations were completed in 2019 and these are listed in Table 2. Figure 1 shows a map of the NRCan GNSS network as of January 2020. Further details about NRCan stations and access to NRCan public 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: 20190497

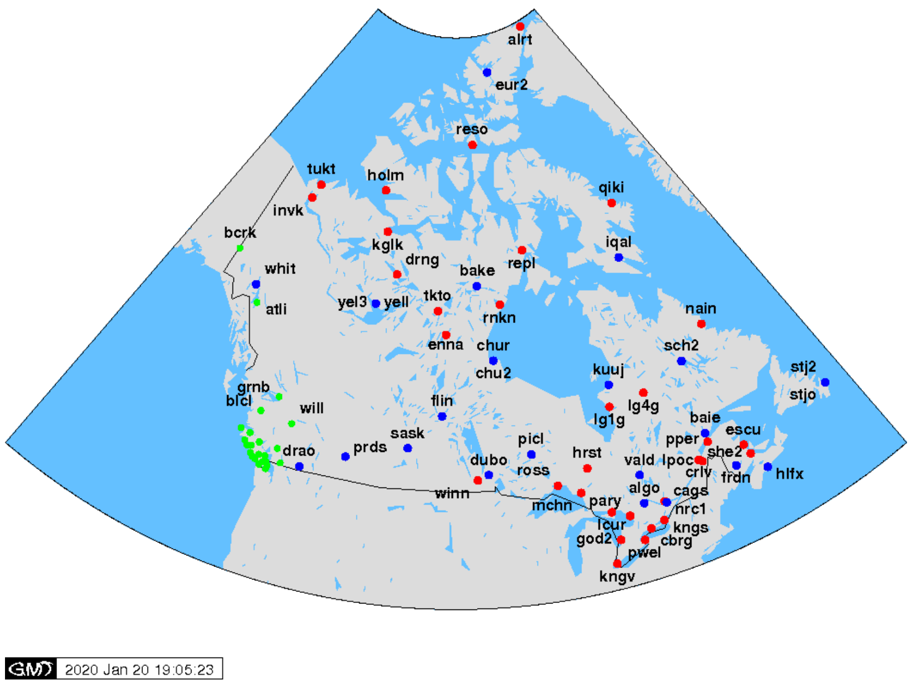

Figure 1: NRCan Public GNSS Stations (CGS-CACS in blue, CGS-RACS in red and CHIS-WCDA in green)..

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The ESA/ESOC IGS Analysis Centre Technical Report 2019

T.A. Springer, L. Agrotis, F. Dilssner, J. Feltens, M. van Kints, V. Mayer, I. Romero, W. Enderle, E. Schoenemann, R. Zandbergen

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1 Introduction

The IGS Analysis Centre of the European Space Agency (ESA) is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The ESA/ESOC Analysis Centre has been involved in the IGS since its very beginning in 1992. In this report we give a summary of the IGS related activities at ESOC in 2019.

2 Overview

2.1 Routine Products

The ESA/ESOC IGS Analysis centre contributes to all the core IGS analysis centre products, being:

- Final GNSS (GPS+GLONASS) products
  - Provided weekly, normally on Friday after the end of the observation week
  - Based on 24hour solutions using 150 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks (30s), daily SINEX with station coordinates and EOPs, and Global Ionosphere Maps

- Rapid GNSS (GPS+GLONASS) products
  - Provided daily for the previous day
  - Available within 3 hours after the end of the observation day
  - Based on 24hour solutions using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, EOPs, and hourly and 2-hourly ionosphere maps and ionosphere predictions
  - Rapid SINEX with station coordinates and EOPs available as well
- Ultra-Rapid GNSS (GPS+GLONASS) products
  - Provided 4 times per day covering a 48 hour interval; 24 hours of estimated plus 24 hours of predicted products
  - Available within 3 hours after the end of the observation interval ending at 0, 6, 12, and 18 hours UTC
  - Based on 24 hours of observations using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, and EOPs
- Real-Time GNSS services
  - Generation of two independent real-time solution streams
  - Analysis Centre Coordination
  - Generation and dissemination of the IGS Real Time Combined product stream
  - The RTACC represents the IGS at TRCM SC-104 meetings
- GNSS Sensor Stations
  - A set of 10 globally distributed GNSS sensor stations
  - Station data available in real-time with 1 second data sampling

A general overview of all the different ESA GNSS products may be found at:
http://navigation-office.esa.int/GNSS_based_products.html An up to date description of the ESA IGS Analysis strategy may always be found at:
http://navigation-office.esa.int/products/gnss-products/esa.acn

2.2 Multi-GNSS Products

At the end of 2017 ESOC has started to routinely publish its experimental multi-GNSS products on a best effort basis using the normal IGS products and naming convention. We have selected *esm* as three character indicator for our ESA/ESOC Multi-GNSS solutions. Meanwhile we have done a reprocessing of all data since 2014 to have a homogeneous time series and to apply all "lessons learned" also to the older products. The products we provide on our web-site are:

- Daily SP3 orbits with 5 min sampling to enable proper interpolation of the eccentric satellites (Galileo and QZSS), normal IGS 15 min sampled SP3 files are *not* sufficient for interpolation of the eccentric orbits
- Daily ERP file in normal IGS format
- Daily Clock-RINEX files with 30 second sampling of the clocks
- Daily bias files with the estimated intersystem biases, relative to the GPS system
- Daily summary file

The ESA/ESOC multi-GNSS products (esm) are publicly availabe from our web-site under:
http://navigation-office.esa.int/products/gnss-products/

An up to date description of the ESA Multi-GNSS Analysis strategy may be found at:
http://navigation-office.esa.int/products/gnss-products/esm.acn

2.3 Product Changes

The main changes in our processing in 2018 and 2019 were the following:

- Several updates of the NAPEOS software from 4.0 to version 4.4
- Change of the sub-daily EOP model from the Gipson model to the Desai model as selecte by the IERS
- Improvements in and tunding of the GNSS box-wing models
  - Include Power Thrust for GPS and GLONASS
  - Box-wing for IIF turned back on, was turned off in 2016, after tuning some of the material properties
  - But still investigating the IIF satellite performance (on-going)

2.4 Product Highlights

The ESA/ESOC Analysis Centre products are among the best and most complete products available from the individual IGS analysis centres. We provide a consistent set of GNSS orbit *and* clock products that can be used for mulit-GNSS precise point positioning. In particular for this purpose, the sampling rate of our final GPS+GLONASS clock products is 30 seconds. A special feature of the ESA products is that they are based on completely independent 24 hour solutions. Although this does not necessarily lead to the best products, as in the real world the orbits and EOPs are continuous, it does provide a very interesting set of products for scientific investigations as there is no aliasing and no smoothing between subsequent solutions. An other unique feature is that our rapid products are one of the most timely available products. Normally our rapid GNSS products are available within 2 hours after the end of the observation day whereas the official GPS-only IGS products become available only 17 hours after the end of the observation day, a very significant difference. Another important feature of the ESA products is that we use a box-wing model for the GNSS satellites to a priori model the Solar- and Earth Albedo and IR radiation pressure. The GNSS block type specific models were tested thoroughly in the scope of our IGS reprocessing and the results were presented at the IGS workshop citeSpringer2014. Significant improvements were observed for most, if not all, estimated parameters. Last but not least it is wortwhile to mention that besides being an analysis center in the IGS ESA/ESOC is also an analysis center in the IDS and the ILRS. This represents a rather unique achievement in that one single software version, NAPEOS Springer (2009), contributes to the products and solutions of three different space geodetic techniques. Work is in progress to also add VLBI to our processing capabilities.

2.5 Reprocessing Activities

ESA/ESOC has participated in the IGS reprocessing efforts (repro1 and repro2) for the IGS contribution to the realisation of the International Terrestrial Reference Frame 2008 and 2014 (ITRF2008, and ITRF2014). And we will again participate in the repro3 activity as contribution to the realisation of the ITRF2020. For this reprocessing effort ESA will reprocess all historic GNSS data of the IGS from 1995 to today. This reprocessing is devided in a couple of different parts due to changes in the GNSS constellations

- 1995-2009: GPS only using 200 stations
- 2009-2015: GPS + GLONASS using 175 stations
- 2015-2016: GPS + GLONASS + GALILEO using 175 stations
- 2016-today: GPS + GLONASS + GALILEO using 150 stations

For this 3rd reprocessing the new "long" names will be used. So our products will be easily recognisabel with from the "ESA" label.

3 Other ESA IGS Contributions

- Dr Loukis Agrotis is the Real-Time Analysis Centre Coordinator and a voting member of the IGS GB since 2013
- Dr Florian Dilssner is involved in the antenna working group for the estimation and validation of the GNSS PCO and PCVs.Also contributes significantly to the estimation and validation of the GNSS attitude modes, in particular during the eclipse phases.
- Dr Werner Enderle is a voting member of the IGS Governing Board since 2015 (?)
- Dr Joachim Feltens is active in the ionosphere working group
- Dr Ignacio (Nacho) Romero is the Chairman of the Infrastructure Committee since 2009 ensuring the IGS data requirements and standards are observed across the IGS Station Network, Data Centers, etc to meet the demanding needs of all IGS Analysis Centers and users
- Dr Tim Springer is the Chairman of the IGMA and the Satellite Dynamics Working Groups

4 GNSS Sensor Station Network Upgrade

ESA/ESOC continues to provide worldwide data for all GNSS constellations to the IGS via its 10 public stations, and to expand its total station network EGON (ESA's GNSS Observation Network), currently operating 23 stations. This expansion is accomplished by focusing on the establishment of collaborations with third parties to install new stations at various locations around the world such as in South Africa, Mexico, Argentina, Brazil, Russia, Canada, Malaysia, New Zealand, etc. The ESOC GNSS Reference Station network is also present at all 3 ESA Deep Space sites and other locations where ESA have satellite tracking assets around the world, Figure 1.

The ESA GNSS network operates a mixture of Septentrio PolarRx4 and PolarRx5 receivers with SEPCHOKE and SEPCHOKE_B3E6 antennas, with the exception of MGUE, MAL2, MAS1 and FAA1 where the Leica AR25.R4 antennas are installed. The station network has been expanded in 2019 with installations in Queretaro (Mexico), Cachoeira Paulista (Brazil), Cordoba (Argentina), Reykjavik (Iceland), and plans are on-going for more stations and receiver and antenna upgrades in the next months. No data is publicly available for the time being for any of the newly installed stations.

The Septentrio PolaRx5 receivers have been chosen as the next step in the station evolution as they can track the new signals at B3/E6 from Beidou and Galileo plus all the legacy signals from all GNSSs. This enhanced tracking is now available at 17 of the 23

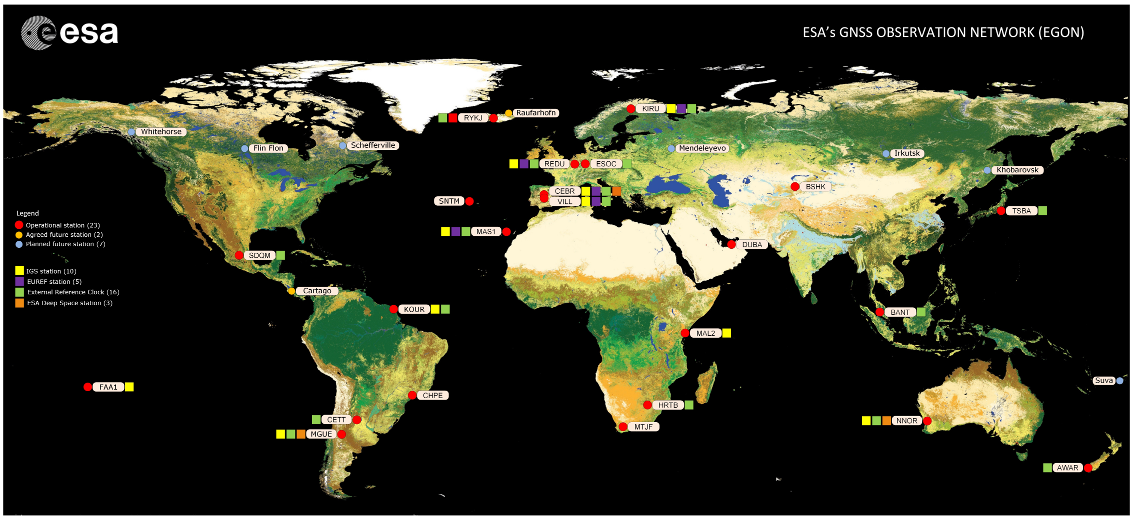


Figure 1: ESA/ESOC GNSS Station Network

EGON stations, pending upgrades of the remaining 6 stations throughout 2020. Last year ESA/ESOC has continued contributing a full complement of Rinex 2 and Rinex 3 data files in daily, hourly and high-rate modes, plus real-time data streams, to the IGS from the 10 ESA/ESOC public stations; VILL, CEBR, FAA1, KIRU, KOUR, MAS1, MAL2, NNOR, REDU and MGUE.

For 2020 worldwide coverage is planned to be enhanced considerably with on-going negotiations with third parties in Russia, Fiji, Iceland and Canada. The station map shows a projection of the impact on the global coverage for the inclusion of the 9 planned future ESA/ESOC stations – 2 of which have been agreed - enhancing worldwide GNSS satellite coverage, aiming to provide full triple station coverage for al GNSS satellites at all times.

http://navigation-office.esa.int/ESA's_GNSS_Observation_Network_(EGON).html

5 Ionosphere Modeling Activities

ESA/ESOC contributes with IONEX products to the IGS Ionosphere Working Group since its inception in 1998. Up to now, ionosphere products for the IGS are still based on a single-layer approach, where the vertical TEC is represented by spherical harmonics, in combination with an estimation of daily receiver and satellite DCBs. ESA IONEX files are delivered in final (2h time resolution) and in rapid (2h and 1h time resolution) mode to the IGS, and they are based on processing both GPS and GLONASS observations. In addition, predicted products are delivered. ESOC employs the Ionosphere Monitoring Facility (IONMON) for its ionosphere processing, which in 2013 became and integral part of ESOC's NAPEOS software.

Actual development activities focus on the implementation of 3D ionosphere modelling, which shall in the medium term replace the current 2D single-layer approach using TEC data only. The 3D ionosphere model generation will be based a 3D electron density grid, which is established with a background model describing a medium ionosphere. Into these background electron densities, different kind of ionosphere observation data will be ingested by an assimilation process. For this assimilation process, special methods were worked out, as well as dedicated algorithms, among others, for:

- Special coordinate grid for data assimilation (combination of spherical – and L-shell based coordinates)
- Efficient methods to conduct processing in this grid, e.g. dedicated point indexing method
- Definition of influence regions for the assimilation of observation data into the 3D background grid
- Efficient methods for processing observed electron densities and TEC data during the assimilation process
- Dedicated 3D electron density interpolation algorithms
- Dedicated TEC integrators
- 3D IONEX and other data formats being more efficient for 3D ionosphere model representations

3D model TEC values are then obtained by integration of electron densities through the 3D assimilation grid. Currently, the assimilation process is tested and verified with TEC data derived from GPS and GLONASS dual-frequency observables. So far, test results look promising. In a later step of development, further observation types, such as electron densities, e.g. from radio occultation data and ionosondes, or TEC data from further sources, shall be included into the 3D data assimilation too. In addition to the implementation of a 3D ionosphere modelling, some minor activities are ongoing, so to say as side activities. Of these, the following two are exemplarily mentioned here:

- Working on novel plasmasphere/plasmapause modelling strategies in collaboration with the German Aerospace Centre (DLR) in Neustrelitz, Germany
- Provision of tropospheric and ionospheric media calibrations to the ESOC Flight Dynamics Division on operational basis

6 GNSS Research Activities

6.1 BeiDou-3 Orbit Determination

We recently started generating the first centimeter-quality orbit solutions for BeiDou's third-generation series of medium Earth orbit (MEO) spacecraft. Key elements of the estimation strategy underlying these solutions are newly developed spacecraft models for antenna phase center (APC) position and a-priori solar radiation pressure (SRP). Our APC model consists of satellite-specific phase center offset (PCO) and block-averaged phase center variation (PCV) corrections for the ionosphere-free B1-B3 linear combination. Horizontal PCOs are the values measured by the spacecraft manufacturer and published by the China Satellite Navigation Office in December 2019 as part of a larger satellite metadata release (http://en.beidou.gov.cn). Vertical PCOs and PCVs were estimated from 14 month of IGS tracking data. The estimated PCVs range from -3 mm to +4 mm and are pretty much the same for all satellites regardless of the manufacturer. Differences between CAST- and SECM-built satellites are typically below 1 mm, Figure 2).

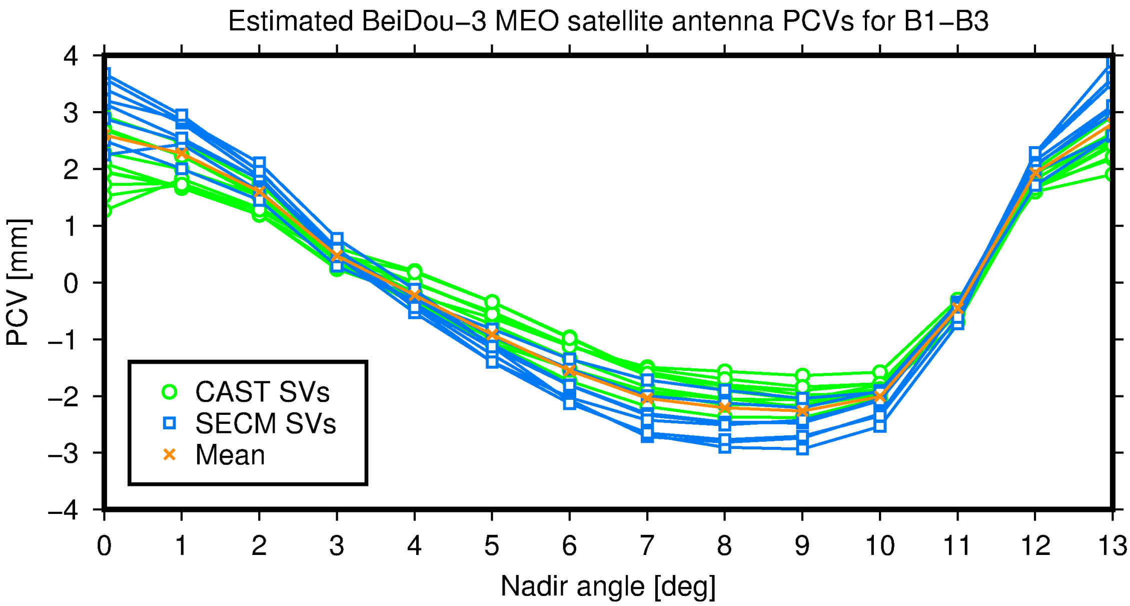
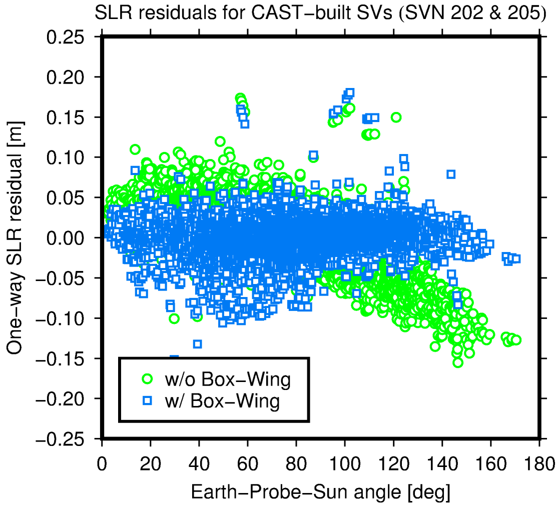
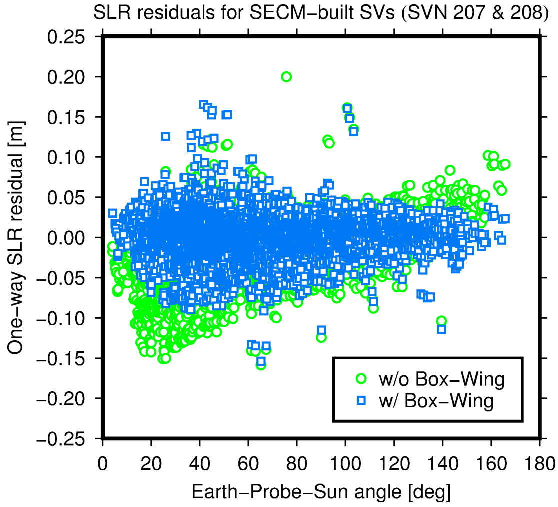


Figure 2: PCV estimates for BeiDou-3 MEO satellite antennas

The a-priori SRP models for CAST and SECM satellites are simple but very effective "box-wing" models. Surface dimensions are taken from the satellite metadata file. Optical and thermal properties of the major surfaces (+x, +z, -z) had to be "guesstimated" from looking at satellite laser ranging (SLR) and satellite clock residuals. The use of the box-wing models brings substantial improvements over the standard approach without a-priori model. Particularly striking is the reduction of the SLR residual RMS by almost a factor of



(a) CAST



(b) SECM

Figure 3: Impact of BeiDou-3 MEO box-wing models on SLR residuals

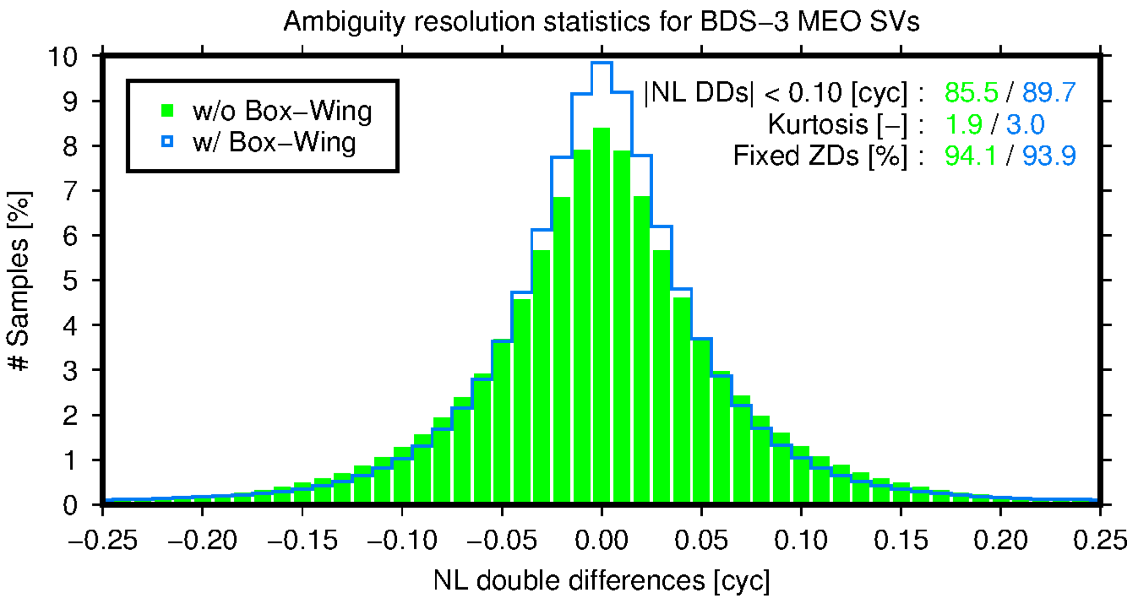


Figure 4: PCV estimates for BeiDou-3 MEO satellite antennas

two as well as the much tighter distribution of the fractional part of the double-differenced narrow-lane ambiguities (Figure 3 and 4).

Overall, laser range and overlap residuals suggest that our BeiDou-3 MEO orbits are accurate to much better than 0.04 m in all three components (Table 1). The results

Table 1: BeiDou-3 MEO orbit overlap and SLR statistics.

Satellite	Orbit overlap residual RMS [m]					One-way SLR residuals [m]			
	# Obs	Radial	Along	Cross	3D	# Obs	RMS	Sigma	Mean
CAST	794	0.024	0.036	0.023	0.049	6837	0.022	0.022	0.000
SECM	632	0.021	0.032	0.025	0.045	8378	0.026	0.026	0.002
ALL	1426	0.023	0.034	0.024	0.047	15215	0.024	0.024	0.001

are at least as good as for GLONASS and just a breath away from the accuracy we are currently obtaining for GPS and Galileo. Therefore, the new BeiDou constellation is fully integrated into our operational multi-GNSS routine, bringing the total number of daily processed GNSS satellites to more than 110 (http://navigation-office.esa.int/products/gnss-products).

6.2 SLR-based yaw attitude determination

We accidentally found when running some SLR orbit validation tests with a wrong satellite yaw attitude model, that this may cause a strong systematic signature in the time series of SLR "full-rate" range residuals. The magnitude of the effect generally depends on the location of the laser retroreflector array (LRA) with respect to the spacecraft rotation axis (z-axis) and the elevation angle under which the satellite passes over a tracking station. In case of the two LRA-equipped GPS Block IIA satellites which both have a total LRA horizontal offset of approximately 1.3 m, residual errors at decimeter level may arise, for instance, when using nominal yaw attitude during and after eclipse (Figure 5).

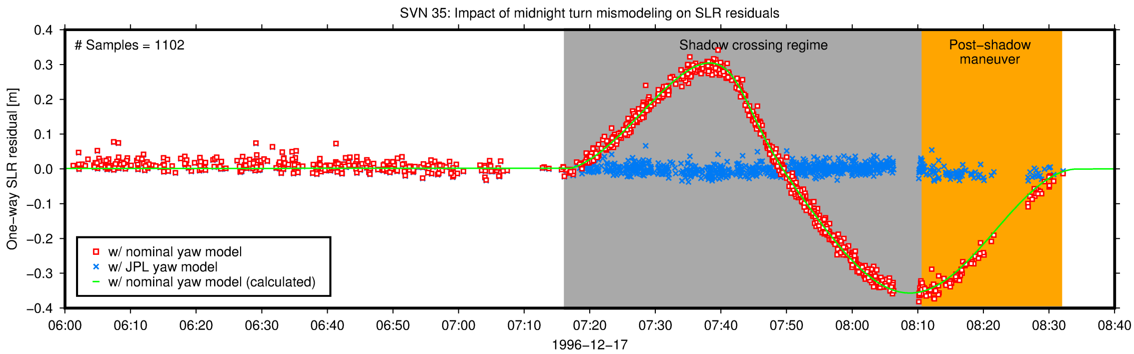


Figure 5: High-rate SLR range residuals between former ILRS tracking station HALL (Haleakala, Hawaii) and GPS Block IIA satellite SVN 35 while traveling through Earth eclipse

We concluded that, vice versa, one can take advantage of the relation between yaw angle and laser range residuals in order to reverse-engineer the "true" spacecraft attitude law. The processing of SLR kHz data from one of the ILRS stations to a Galileo satellite in a simple recursive least-squares algorithm has demonstrated that this can be done with an accuracy of a few degrees Dilssner (2019). The method may serve as an interesting alternative to reverse kinematic point positioning (RPP), particularly for LRA-equipped satellites without significant transmit antenna phase center offsets as, for example, the GPS Block III "Follow-On" satellites.

7 Summary

The European Space Operations Centre (ESOC) of the European Space Agency (ESA) Analysis Center continues to produce *best in class* products for the IGS. All products are generated using the Navigation Package for Earth Orbiting Satellites (NAPEOS) software. NAPEOS is a state of the art software that is highly accurate, very efficient, robust and reliable. It enables ESA/ESOC to deliver the high quality products as required for the IGS but also for the other space geodetic techniques DORIS and SLR. This is important because besides being an IGS Analysis Centre, ESA/ESOC is also an Analysis Centre of the IDS and the ILRS.

In the coming year our main focus will be on further improving the orbit modelling for the different GNSS constellations. We need to improve our (a priori) box-wing models for the GPS IIF, III, QZSS, BeiDou and GLONASS-K satellites. We will continue to improve and enhance our ESA tracking network. And we are looking forward to getting some first results from our ionosphere 3D modelling.

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GFZ Analysis Center Technical Report 2019

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1 Summary

During 2019, 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 2019 including GPS, GLONASS, BeiDou, Galileo, and QZSS. From April 15-17 we hosted the IGS Analysis Workshop 2019.

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 to keep the consistency concerning the repro-2 processing strategy. Significant degradation of our ultra-rapid products occurred between day 2039/1 and 2040/2. After an update of our operational data center, several ultra-rapids were processed with only a few stations due to

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
2019-02-12		w2040.2	Updated internal data paths in the ultra-rapid configuration
2019-11-26		w2081.2	Updated generation of initial orbits in the ultra-rapid configuration

misleading paths. During the year, some of our 12h and 18h submissions showed a much lower number of satelllites compared to the associated 0h and 6h jobs. This problem, caused by an issue in our automatized ultra-rapid configuration related to the generation of initial orbits, was finally solved at day 2019/330. After dedicated testings, we included the GPS block III satellite G04 (SVN 074) in our processing lines at day 2019/331.

4 Multi-GNSS data processing

The IGS rapid/ultra-rapid like style multi-GNSS processing was continued in 2019 (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

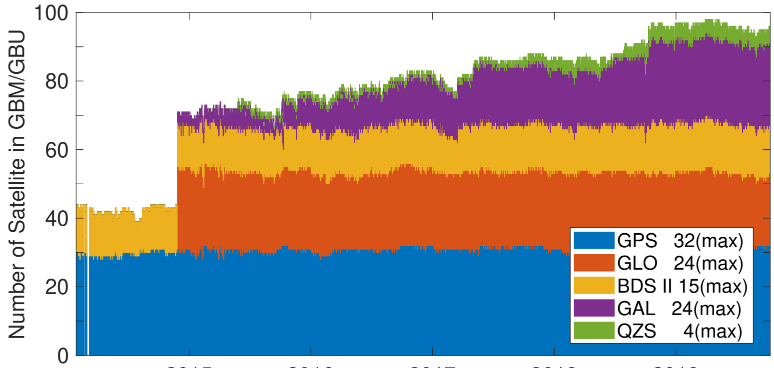

Figure 1: Total number of satellite per GNSS included in the daily multi-GNSS data processing (gbm)

per GNSS included in the gbm MGEX solution since 2014. The maximum number of GNSS satellites in gbm is 97. The gbm and gbu product are available at ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

5 Multi-GNSS Combination

During 2019, we pushed some efforts into the elaboration of an orbit and clock combination strategy compatible with a multi-GNSS environment. To do so, we use the IGS Multi-GNSS products provided within the framework of the MGEX Working group. Our investigations focused on:

- an enhancement of the legacy IGS combination software (Kouba et al. 1994), to make it compatible with the new GNSS constellations, namely Galileo, Beidou and QZSS. The RMS of combined orbit w.r.t. input ACs ones are $\sim 30 \pm 15$ mm for recent weeks of a test period from GPS week 1800 to 2000 (Figure 2). This combination is also consistent at the centimeter level with the legacy IGS final combination.
- the development of a new combination strategy that is fully consistent for all constellations. This new approach includes a reference frame alignment optimized for the MGEX products (Mansur et al. 2020), an improved satellite outlier detection, and a satellite weighting based on a Variance Component Estimation. We are also considering an SLR validation step.

6 Reprocessing activities

The GFZ Analysis Center is contributing to the IGS repro3 campaign. According to software and time restrictions we decided to process stations listed in the IGS-ACS-1235

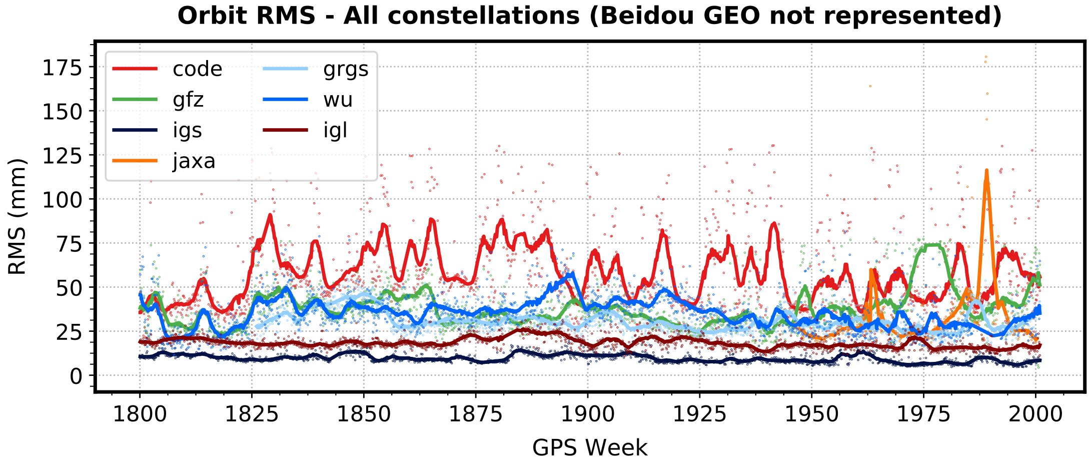

Figure 2: Orbit RMS of the different MGEX inputs w.r.t. the Multi-GNSS combination based on the legacy software. We consider in the combination the following MGEX Analysis Centers products: CODE, GFZ, GRGS, Wuhan University (WU) & JAXA. We also represented here a comparison with the IGS GPS (*igs*) and GLONASS (*igl*) final legacy orbits. Please note that the Beidou Geostationary satellites were excluded from the RMS computation.

e-mail under category 1 to 4 (i.e., IGS14 core sites, local tie stations, redundant local tie stations, and remaining IGS14 stations) as well as IGS stations operated by GFZ. The modeling and parametrization follows the decision of the IGS Analysis Workshop 2019, i.e., switch to (1) a linear mean pole model, (2) GOCO6s as time-variable gravity field, (3) applying FES2014b for ocean tides and ocean loading, and (4) the Desai and Sibois (2016) model for the high-frequent EOP variations. In 2019, we provided solutions to the two test campaigns covering 2017-2018 (solutions GPS+GLO+GAL, GPS+GLO, GPS, GAL) and 2014 (GPS+GLO+GAL). We presented the initial results of the 2017-2018 test at the 27th IUGG General Assembly in Montreal, Canada and submitted a corresponding proceeding paper to the IAG Symposia Series (Männel et al. 2019). The GFZ solution showed orbit overlaps of 28, 64, and 40 mm for GPS, GLONASS, and Galileo, respectively. SLR orbit validation showed 96 and 58 mm RMS for GLONASS and Galileo, respectively. Station coordinates determined separately for GPS and Galileo showed good agreement except for the height where a global scale parameter of 1.16 ppb was determined which was caused by different transmitter phase center offsets (PCO). Using GPS PCOs re-adjusted w.r.t. the ground calibrated Galileo PCOs the 2014 test was performed. The initial orbit and SINEX combinations revealed good results for the GFZ solution.

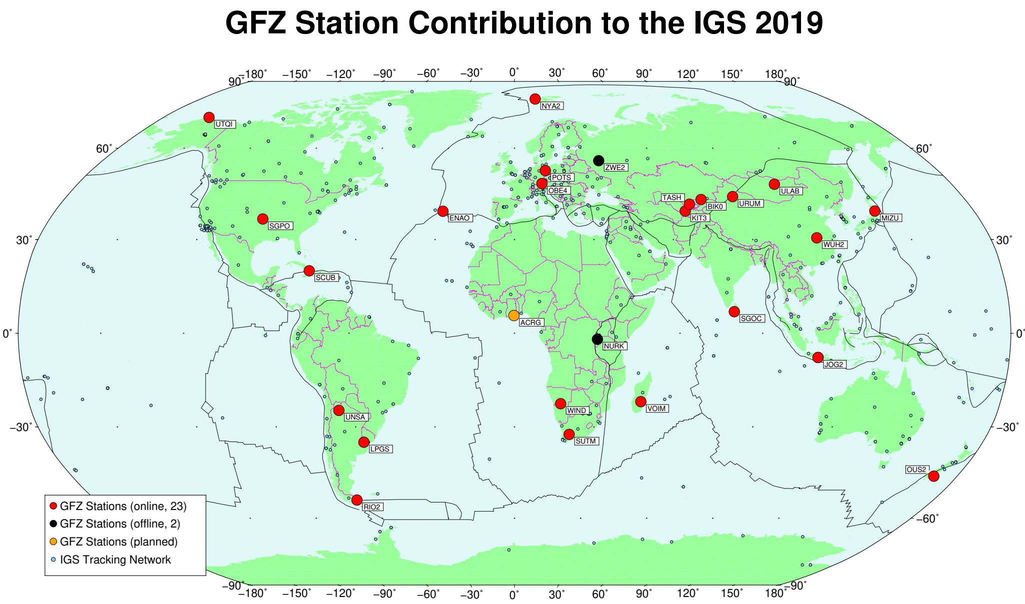

Figure 3: GNSS stations operated by GFZ (as of December 2019)

7 Operational GFZ Stations

The GFZ operated global GNSS station network comprises currently 25 GNSS stations participating in the IGS tracking network. Figure 2 shows the global distribution of these stations. In 2019, the following stations were upgraded: MIZU (Mizusawa, Japan) and OUS2 (Dunedin, New Zealand) are now equipped with SEPT ASTERX4 receivers and SEPCHOKE_B3E6 antennas, NYA2 (Ny Alesund, Spitsbergen), SUTM (Sutherland, South Africa), and WIND (Windhoek, Namibia) are now equipped with JAVAD TRE3 receivers and JAVRINGANT_G5T antennas. The receiver in Barrow, Alaska (UTQI) was replaced by the same type (JAVAD TR_G3TH). Two new stations were installed in Billings, Oklahoma (SGPO) and Graciosa Island, Acores (ENAO). Both are equipped with JAVAD TRE3 receivers and JAVRINGANT_G5T antennas. The problems for our stations NURK (Kigali, Rwanda) and ZWE2 (Zwenigorod/Russia) could not be resolved yet. Due to a time tag related bug in our data logging software associated with the GPS week rollover, all GFZ IGS stations did not provide data at 2019/090 and 2019/091. However, as the tracking was not affected all data have been resubmitted later.

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CNES-CLS
Technical Report 2019

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1 Introduction

In 2019, the CNES-CLS Analysis Center continued its contribution through the weekly delivery of final products using the GINS CNES software package. The formal "GRG" GPS-GLONASS products can be downloaded from the "gps/products/wwww" directory of any IGS archiving center while MGEX "GRM" GPS-GLONASS-Galileo products are accessible from the "gps/products/mgex/wwww" directory. The main evolutions of our processing strategy have concerned the multi-GNSS ambiguity fixing algorithm and the satellite PCO estimations and are discussed in section 2 and 3 respectively. In addition, in the framework of the REPRO3 campaign, several implementations, tests and analysis have been carried out. In particular, the Desai-Sibois sub-diurnal pole model has been implemented and updated series of ocean tide loading coefficients from the FES2014b model are now considered. Section 4 is dedicated to the C21 S21 coefficients used to follow the new mean pole IERS convention. More information can be found in the references given in section 5 as well as at: https://igsac-cnes.cls.fr/.

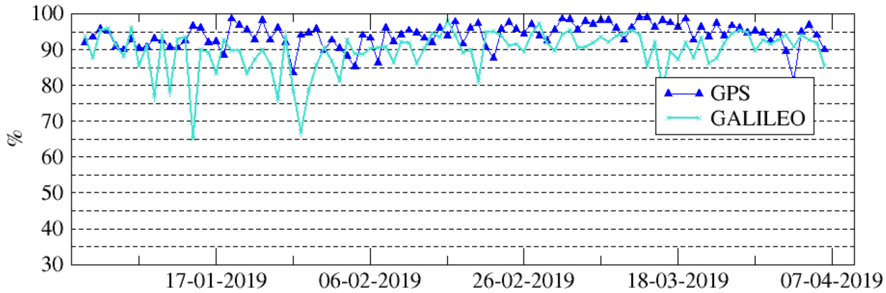

Figure 1: Ambiguity fixing success rate in a GPS+Galileo process. The implementation of an alternative algorithm the 3rd of February, significantly improved Galileo statistics.

2 Multi-GNSS ambiguity fixing

Fixing un-differenced ambiguities in a multi-GNSS GPS+Galileo processing needs to carefully manage the number of parameter to be estimated within the initialization process. In particular, if a signal interruption occurs during a given day for a given constellation (e.g. Galileo) while the other one (e.g. GPS) has continuous observations, no additional parameter for Galileo is needed as GPS brings the consistency of the parametrization on both sides of the discontinuity. In the initial version of our algorithm too many parameters were estimated in such scenario and the corresponding increasing of the degree of freedom of the problem was sometimes producing erroneous ambiguity solutions. Starting the 3rd of February 2019 (DOY 34) our algorithm has been updated. This produced a clear improvement in Galileo ambiguity fixing success rates as shown in figure 1.

We routinely produce 36 hour orbital arcs centered on noon each day, so two successive solution overlap during 12 hours. The WRMS of the 3D Galileo satellite position comparison during each overlap period before and after DOY 34 is given in figure 2. The new ambiguity fixing strategy obviously has a positive impact Galileo satellite orbit determination.

3 Satellite PCO

The capacity to provide satellite PCO information in the SINEX files have been implemented. In order to test this new capability, we used the SINEX provided to the ACCs for the period 2017-2018 in the frame of the REPRO3 test campaign.

The estimated PCO values for each GPS SVN satellite compared to the "standard" ANTEX values is shown in figure 3. In this processing the Galileo PCOs were fixed to the metadata values provided by ESA. As expected GPS values change by few centimeters mainly along the yaw Z axis.

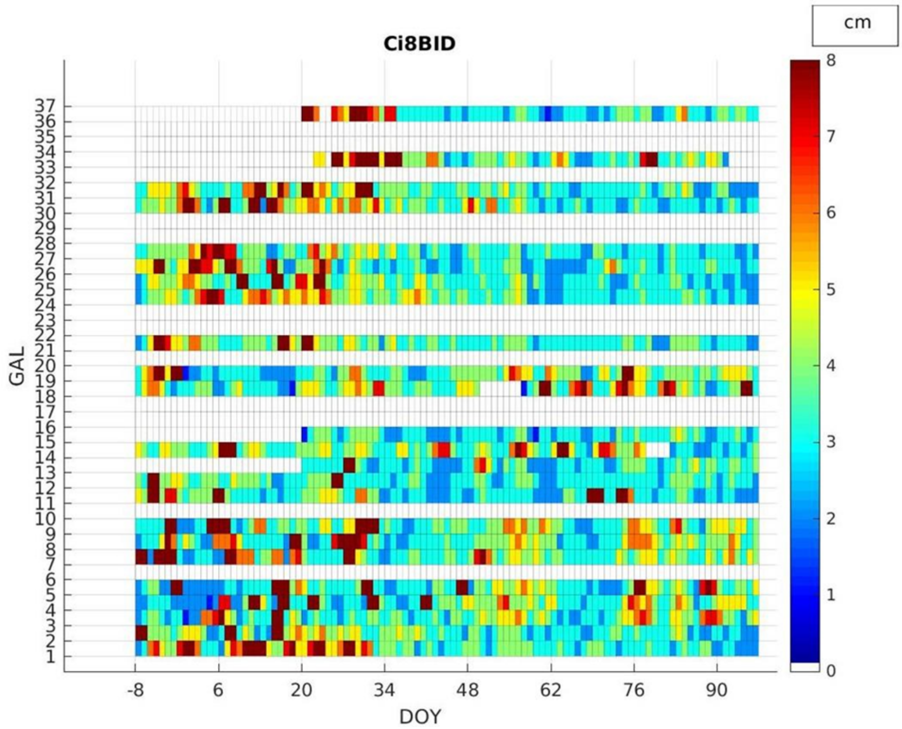

Figure 2: Galileo satellites 3D-WRMS overlaps. After the algorithm update of DOY 34, there is a significant reduction of this proxy.

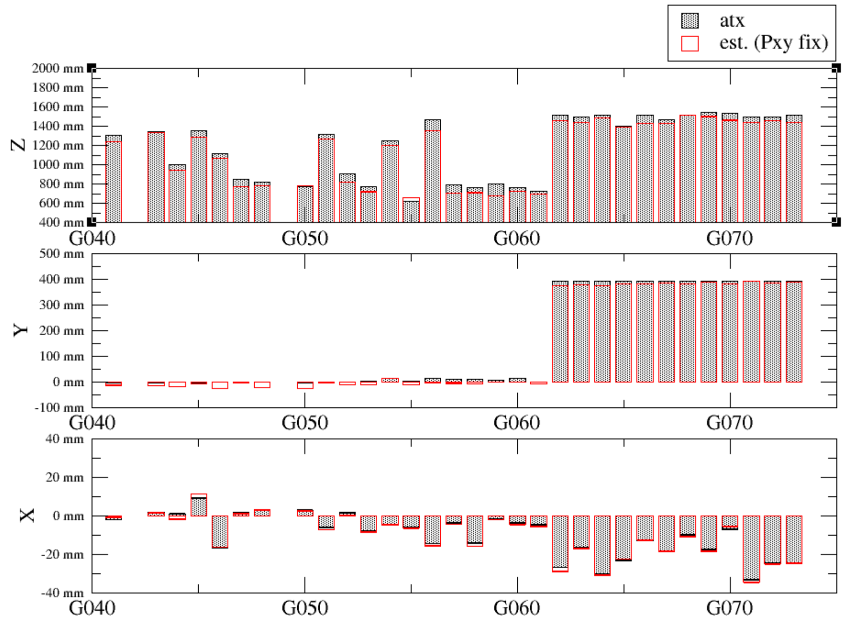

Figure 3: Estimated GPS PCO versus ANTEX "standard" values.

4 New mean pole convention implementation and C21 S21

The IERS recommandation to use a linear mean pole a priori model have been implemented into our processing package. This change impacts the values of the C21 and S21 gravity coefficient that have to be considered. We evaluated two alternative approaches based respectively on the C21 S21 model provided by the IERS and the C21 S21 coefficient series available through the EIGEN gravity field model jointly produced by GRGS.

The difference of the normalized values can reach 0.15 10-9 as illustrated in Figure 4 (deviation between the red and blue curves).

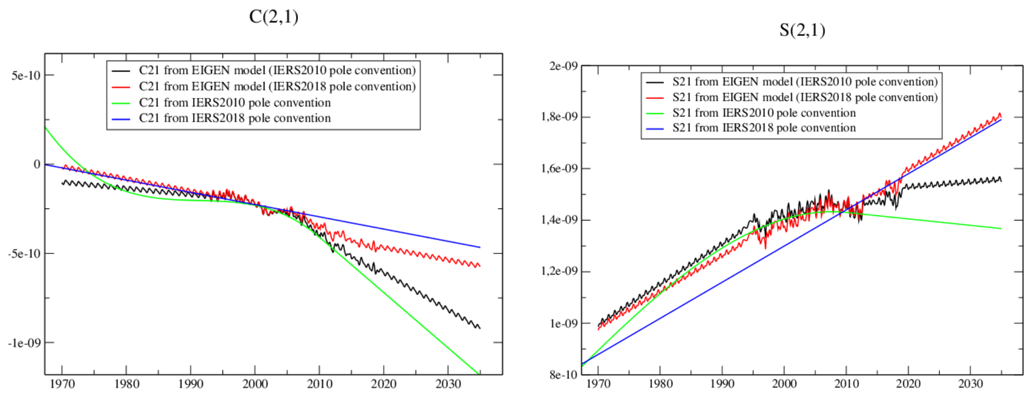

Figure 4: EIGEN normalized C21 (top) and S21 (bottom) series compared to the IERS conventional values (Courtesy Jean-Michel Lemoine, CNES)

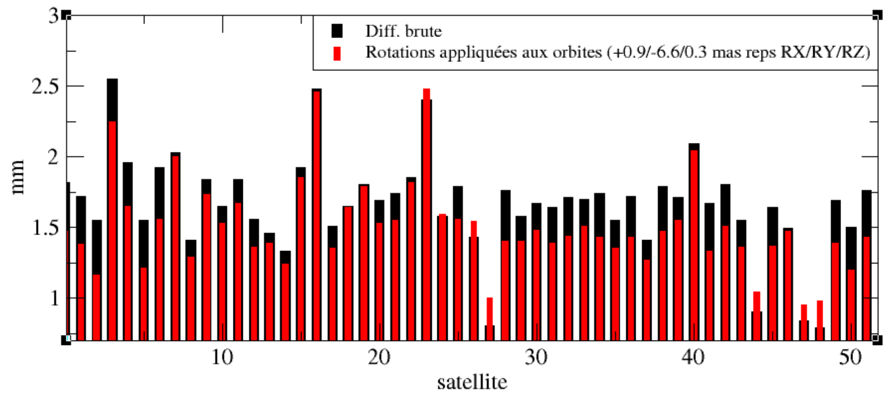

Figure 5: Orbit difference (3DRMS) between two GPS+GLONASS solutions based respectively on the IERS C21/S21 linear model associated to the linear mean pole 2018 convention and on the C21/S21 EIGEN gravity field model series.

We then wanted to check how this choice was impacting GNSS satellite orbit determination.
Figure 5 compares, on one representing day, GPS+GLONASS orbit solutions using the IERS and the EIGEN C21 values (S21 was kept similar). The effect observed is aroun 1.5 mm 3D on average and can reach up to 2.5 mm 3D for a given satellite. The global plan rotation is 7uas for this day. We have finally decided to adopt the C21 S21 EIGEN series for the REPRO3 campaign and future ITRF2020 IGS products. The corresponding files can be downloaded from:
In "gfc2" format: http://gravitegrace.get.obs-mip.fr/grgs.obs-mip.fr/data/RL04/static/EIGEN-GRGS.RL04.MEAN-FIELD.linear_mean_pole.zero_slope_extrapolation.gfc2
In GRACE format: http://gravitegrace.get.obs-mip.fr/grgs.obs-mip.fr/data/RL04/static/EIGEN-GRGS.RL04.MEAN-FIELD.linear_mean_pole.zero_slope_extrapolation

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JPL IGS Analysis Center Technical Report 2019

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1 Introduction

In 2019, 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 2019.

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 2000-05-04 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, respectively, at:

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

Note: These files are no longer available via ftp.

2 Processing Software and Standards

On 29 Jan 2017 (start of GPS week 1934) we switched from using GIPSY (version 6.4) to GipsyX to create all our orbit and clock products. As of week 2003 (2018-05-27), all IGS Finals were submitted in the IGS14 frame, and furthermore a reprocessing in the IGS14 frame has also been released back through week 658 (1992-08-16).

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. VLBI data processing is being added.
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, 2018 ILRS workshop, and 2018 Fall AGU meeting. 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)

5 Future Work

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

6 Acknowledgments

The work described in this report was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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1 Introduction

In 2019, 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 2019.

2 Core Analysis Center Products

There were no changes in the NGS analysis center rapid and final products (see Table 1) for 2019. Ultra-rapid products from NGS showed divergence from combined solutions for an unknown reason. Since the software for ultra-rapid product generation is not currently maintained, NGS stopped providing ultra-rapid products. The last day NGS ultra-rapid products were submitted was GPS week 2078 day 6. A project to write a new software with capabilities to process multi-GNSS data is currently on going within NGS and this new software will include the capability to generate ultra-rapid products. When the new software is ready, ultra-rapid product submission from NGS will resume. Please refer to the Analysis Coordinator website (http://acc.igs.org) for combination statistics of the NGS analysis center products.

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

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:

- Solar radiation pressure model has been updated to ECOM2 model for GPS satellites except Block IIF. ECOM1 continues to be used for Block IIF following IGS recommendation. Updated model has been used for rapid and final products since GPS week 2054 day 0.

4 Regional Data Center Core Products

During 2019, 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 GR30	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+GAL
GUUG	Mangilao, Guam, USA	13.43	144.80	LEICA GR50	GPS+GLO+GAL
HNPT	Cambridge, MD, USA	38.59	-76.13	LEICA GRX1200GGPRO	GPS+GLO
WES2	Westford, MA, USA	42.61	-71.49	SEPT POLARX5	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
WUHN	Wuhan, China	30.53	114.36	TRIMBLE NETR9	GPS+GLO+BDS
	The last data received from WUHN was from 2019-036.				

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 2019

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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, 2019

Figures 1-4 Figures 1-4 show the 2019 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 24 mm (24-h post-processed segment) and 39 mm (6-h predict) wrt the IGS rapid combined orbits. USNO rapid (post-processed) and Ultra-rapid 6-h predicted clocks had median 125 ps and 1128 ps RMSs wrt IGS combined rapid clocks. The rapid shows improvement from the 2018 value of 179 ps.

USNO rapid polar motion estimates had (x, y) 23 and 22 microarcsec RMS differences wrt IGS rapid combined values (a significant improvement from the 2018 values of 40 and 28, respectively). USNO Ultra-rapid polar motion estimates differed (RMS of x, y) from IGS rapid combined values by 541 and 461 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 638 and 538 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 2019, seven-parameter Helmert transformations computed between USNO and IGS Ultra-rapid GPS+GLONASS orbits had median RMSs of 35 and 64 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 376 and 311 microarcsec, respectively. USNO GPS+GLONASS Ultra-rapid 24-h predicted polar motion x and y values differed from the IGR values, RMS, by 550 and 398 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 2019.

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Table 1: Precision of USNO Rapid and Ultra-Rapid Products, 2019. 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		
1/1/2019–12/31/2019	15	24	39	23	22	541	461	638	538	125	1128

Table 2: Precision of USNO Ultra-Rapid GPS+GLONASS Test Products, 2019. 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
1/1/2019–12/31/2019	35	64	x: 376 y: 311	x: 550 y: 398

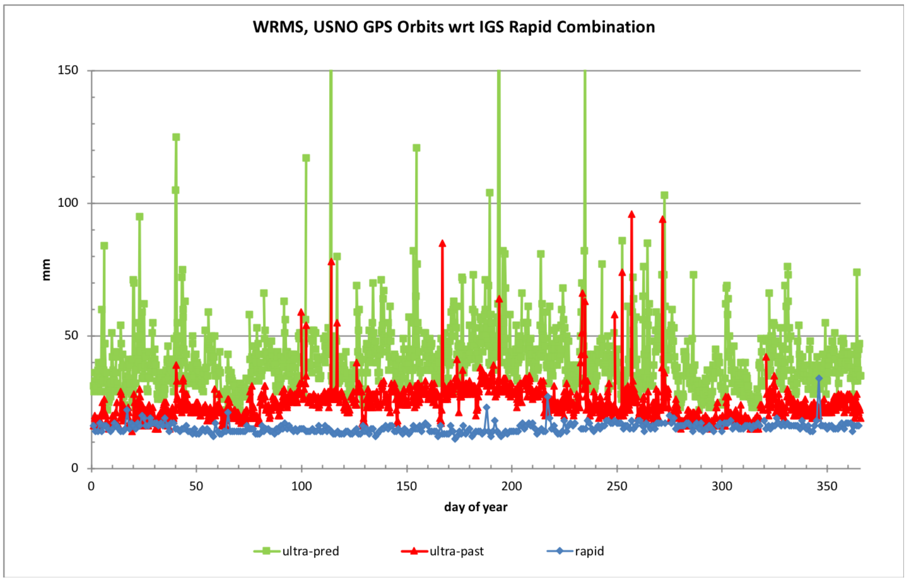

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2019. "Ultra-past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra-pred" refers to first six hours of Ultra-rapid orbit prediction.

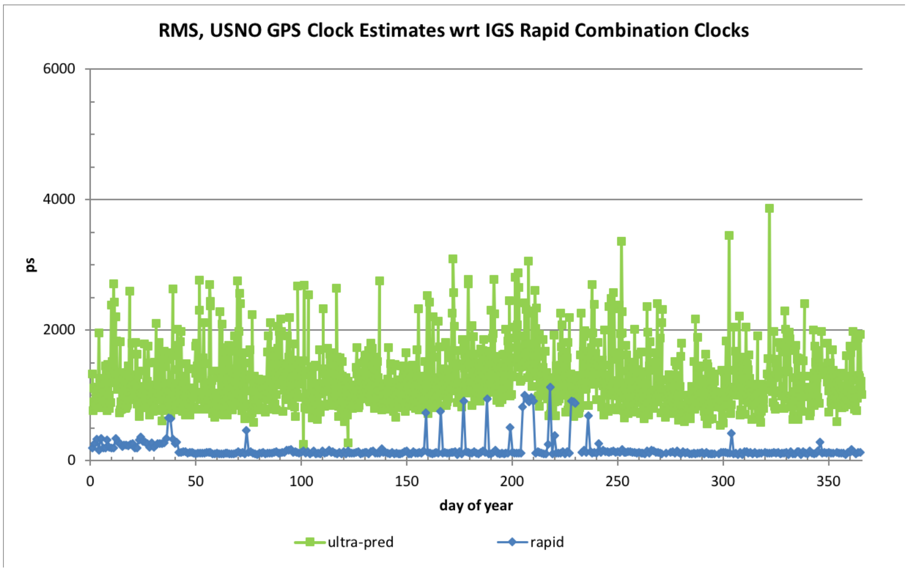

Figure 2: RMS of USNO GPS rapid clock estimates and Ultra-rapid clock predictions with respect to IGS Rapid Combination, 2019.

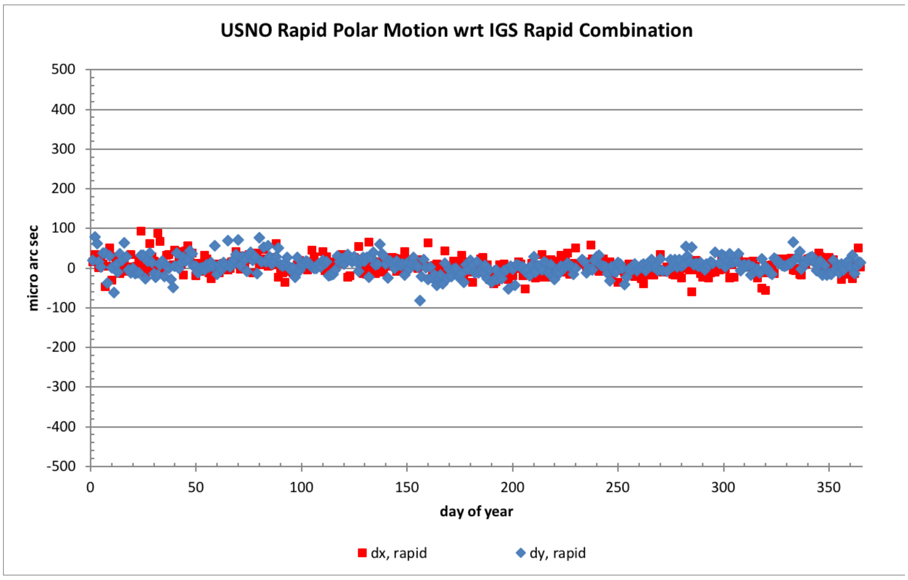

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2019. Note, scale kept same as in previous reports.

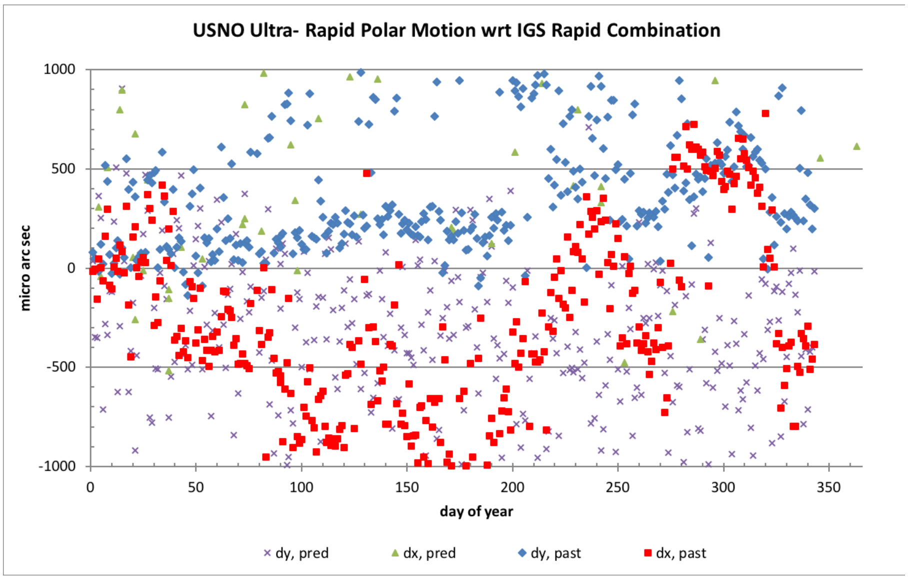

Figure 4: USNO Ultra-rapid polar motion estimates minus IGS Rapid Combination values, 2019.

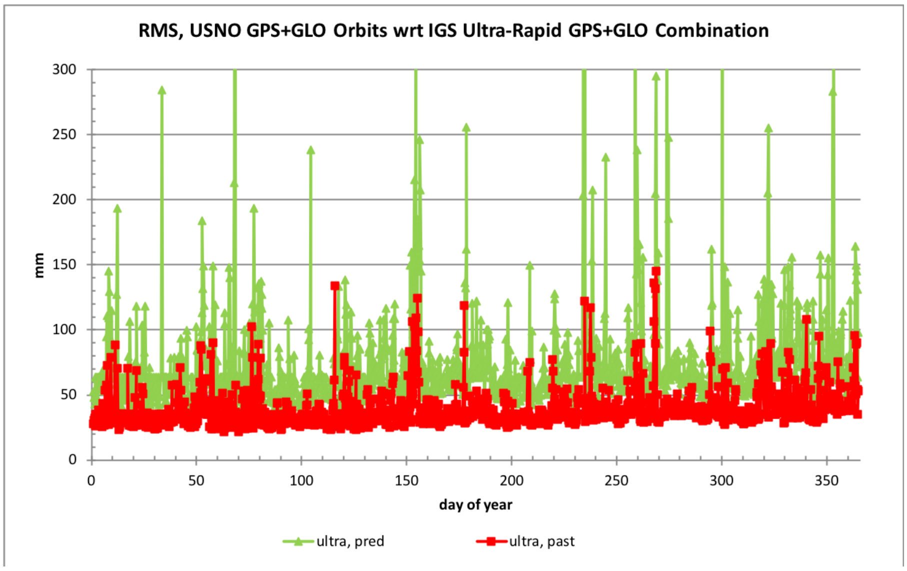

Figure 5: RMS of USNO Ultra-rapid GLONASS orbit estimates with respect to IGS Combined Ultra-rapid GLONASS orbits, 2019. "Ultra, past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra, pred" refers to first six hours of Ultra-rapid orbit prediction.

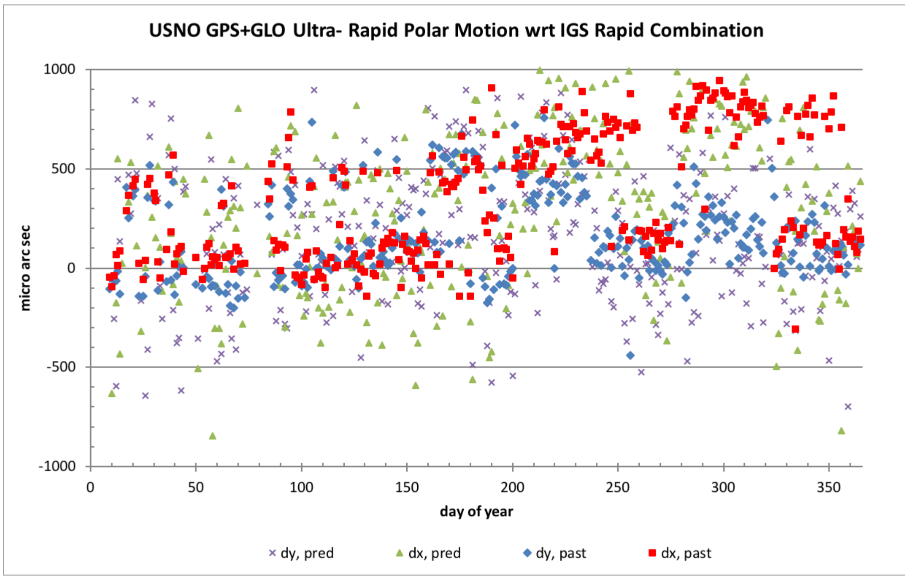

Figure 6: USNO Ultra-rapid GPS+GLONASS polar motion estimates minus IGS "IGR" GPS-only rapid solution, 2019.

WHU Analysis Center Technical Report 2019

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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).

In 2019, WHU participated in the 3rd IGS Reprocessing campaign contributing the GPS/GLONASS orbit products and agreed upon the proposed models and methods. In this report we give a summary of the IGS related activities at WHU during the year 2019.

2 WHU Analysis Products

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

3 Product Changes

In the routine operations, we have adopted the data processing approach used for our Repro3, which has the following improvements, compared to our previous data processing strategy (http://acc.igs.org/repro3/repro3.html):

1. Solar radiation pressure models (ECOM2).

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

2. Satellite Transmit Power (Antenna Thrust).
3. Earth albedo models.

Since September 2019, the product accuracy (Figure 1) and scale parameters (Figure 2) have been significantly improved, when compared with IGS rapid products of Wuhan University after GPS week 2070.

4 Reprocessing

Currently, the WHU working group on reprocessing conducts a third reprocessing campaign. In preparation of the third reprocessing, we participated in the ACC's precision orbit determination test of 2014, and the test results have shown good agreement with the combination products.

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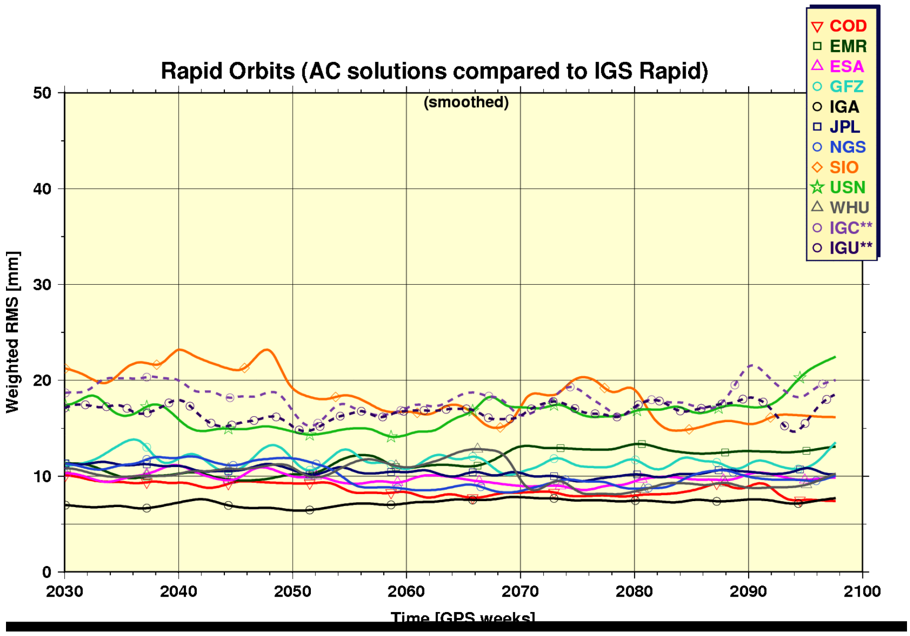

Figure 1: Improvement of WHU's rapid orbit products since GPS week 2070.

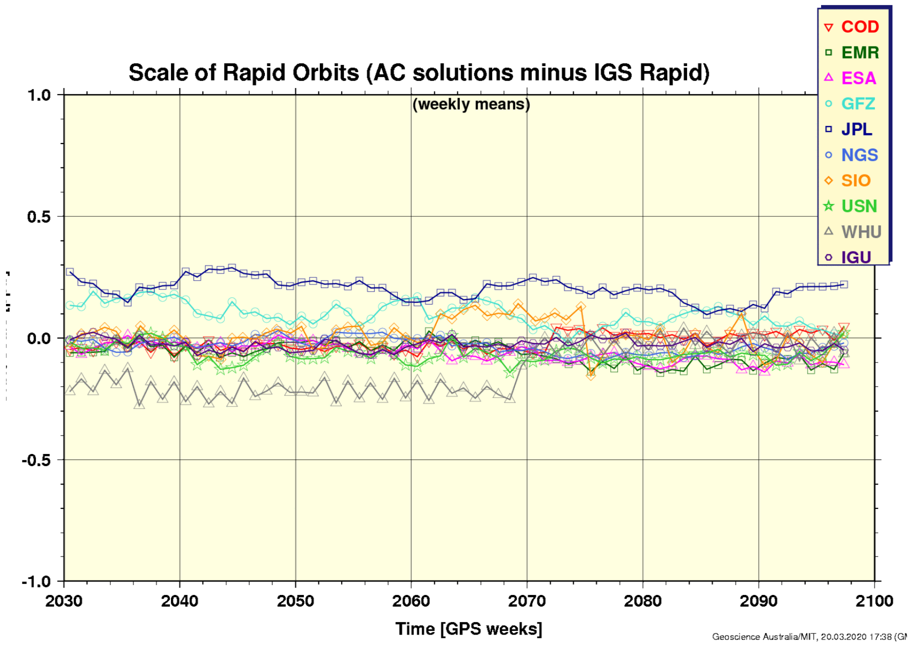

Figure 2: Improvement of the orbit scale parameters since GPS week 2070.

EUREF Permanent Network Technical Report 2019

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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 2019.

2 Analysis Centres Workshop

3 EPN Tracking Network

3.1 EPN Central Bureau

The EPN Central Bureau (CB, managed by the Royal Observatory of Belgium) continued to monitor operationally EPN station performance in terms of data availability, correctness of metadata, and data quality. To improve the monitoring of multi-GNSS data, the EPN CB analysed 23 years of historic EPN data. The results are provided in Bruynix et al. (2019a).

The development of the "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^3G, available from https://gnss-metadata.eu) continued in 2019 with the release of version 2.0 in July 2019 and version 3.0 in December 2019. More than 120 European agencies make their station site logs available through M^3G. M^3G is also designed to collect information on data licenses and Digital Object Identifiers (DOI). The system contains presently validated GNSS site logs of 2161 stations, including all EPN stations and 1595 EPN densification stations (see ftp://gnss-metadata.eu/station/logforsitelogs and ftp://gnss-metadata.eu/station/xml for GeodesyML files). All site logs of EPN and EPN densification station can also be retrieved, as usual, from the EPN Central Bureau. Since 2019, these site logs are also available using the RINEX 3 station naming conventions (see ftp://epncb.oma.be/pub/station/log_9char).

3.2 Network Changes

20 new stations were integrated in the EPN in 2019: six stations in Germany, one in Poland, one in Montenegro, three in Ukraine, three in Turkey, one in Italy, one in Austria, two in Spain, and two in Ireland (see Figure 1). The total number of EPN stations is now 348. 13 of the new stations are tracking GPS, GLONASS, and Galileo satellites (Table 1). Five stations also have individual antenna calibrations.

End of 2019, an impressive 58% (48% in 2018) of the EPN stations were providing BeiDou data and 72% (63% in 2018) provided Galileo data (Figure 2). About 250 stations provided their data in the RINEX v3 format and 230 of them were using the new RINEX v3 file naming conventions. The attempts of the EPN CB to convince all station managers to use the new RINEX v3 naming conventions have not been successful so far. In addition, about ten stations continue to report incorrectly in their site log that they provide multi-GNSS data while they do not submit RINEX 3.

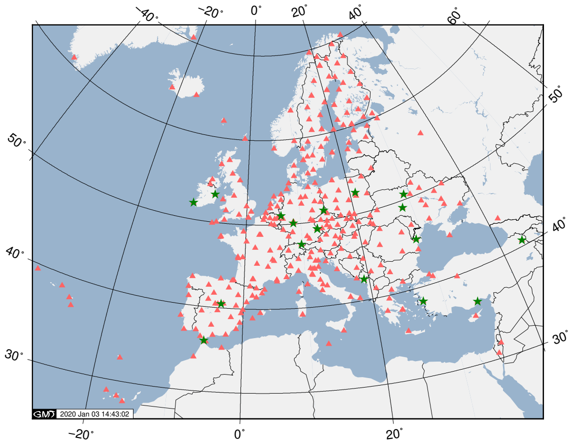

Figure 1: EPN tracking stations (status Dec. 2019). * indicates new stations included in the network in 2019

Table 1: New stations included in the EPN in 2019 (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
BAUT00DEU	Bautzen	GRECS	Y	indiv. chamber (GRECJS)
BOGE00POL	Borowa Gora	GRECS		type mean
DGOR00MNE	Podgorica	GREC		type mean
FFMJ00DEU*	Frankfurt / Main	GRECS	Y	indiv. robot (GR)**
GDRS00UKR	Gorodok	GR		type mean
IZMI00TUR*	Izmir	GR		type mean
IZRS00UKR	Izmail	GR		type mean
KRS100TUR*	Kars	GR		type mean
MAT100ITA*	Matera	GRECS		type mean
MERS00TUR*	Erdemli	GRECJS		type mean
PFA300AUT	Bregenz	GREC	Y	type mean
TAR000ESP	Tarifa	GRE	Y	type mean
TIT200DEU*	Titz	GRECS	Y	indiv. robot (GR)**
TLL100IRL	Dublin	GREC		type mean
TOR100ESP	Torrejon De Ardoz	GRS		type mean
VLN100IRL	Valentia	GREC		type mean
VNRS00UKR	Vinnytsia	GR		type mean
WTZA00DEU*	Bad Koetzting	G		type mean
WTZS00DEU*	Bad Koetzting	GREC		indiv. chamber (GRE)
WTZZ00DEU*	Bad Koetzting	GRECS		indiv. robot (GR)**

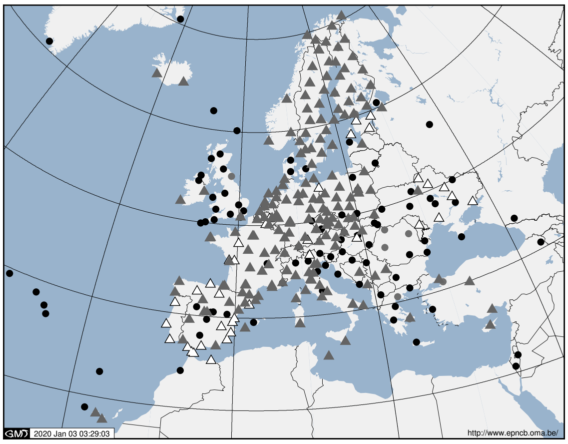

Figure 2: EPN tracking stations (status Dec. 2019). : • tracking only GPS, ●: tracking GPS+GLONASS, △: tracking GPS+GLONASS+Galileo, and ▲: tracking GPS+GLONASS+Galileo+BeiDou.

3.3 New Station Operation Guidelines

In November 2019, the EUREF Governing Board issued an update of the Guidelines for EPN stations and Operational Centres (see EUREF mail http://epncb.oma.be/ftp/mail/EUREF/eurefmail.10054). They are available from http://epncb.oma.be/_documentation/guidelines/guidelines_station_operationalcentre.pdf.

With this update, from 2020 on, stations submitting RINEX 3 data can discontinue RINEX 2 uploads. The update also clarifies that RINEX data must be generated from the raw receiver data. Concerning the real-time data, submission of RTCM 3 is preferred over RTCM 2 and station managers are asked to insert the ETRS89 coordinates released by EUREF in their real-time streams.

3.4 Individual Antenna Calibrations

In 2019, the EPN CB received new individual calibrations for several EPN receiver antennas, which were processed and included in EPN solutions using older individual calibrations (see EUREF mails no. 9670, 9971). To enable taking these recalibrated values into account, the EPN CB prepared new ANTEX files that include multiple calibrations for the same antennas to be used in specified time windows. The new files are available at the EPN Central Bureau (CB) ftp server:

- ftp://ftp.epncb.oma.be/pub/station/general/epnc_14_recalib.atx
- ftp://ftp.epncb.oma.be/pub/station/general/epn_14_WWWW_recalib.atx (where WWWW represents a GPS week). OnMay 1st, 2020, the new files will replace the

presently used files:

- ftp://ftp.epncb.oma.be/pub/station/general/epnc_14.atx
- ftp://ftp.epncb.oma.be/pub/station/general/epn_14_WWWW.atx

At the EPN ACs workshop (Section 2), the CODE analysis centre demonstrated that using GSA (European GNSS Satellite Agency) satellite Galileo E5 calibrations for Galileo E5 observations affects the scale as it is realized by the GPS and GLONASS satellite antenna offsets based on the IGS14 reference frame. This inconsistency produces biases in station heights when using Galileo measurements. At the same time, the usage of receiver GPS L2 antenna corrections for Galileo E5 signal causes also a bias in the obtained station height. It was shown that both effects compensate each other. It was therefore decided to use the IGS14 antenna model as it is and not use anymore the Galileo E5 calibrations from new individual receiver antenna calibrations provided to the EPN. As a consequence, for the new individual antenna calibrations received after mid Oct. 2019, the EPN CB includes in the EPN ANTEX files (epnc_14.atx, epn_14_WWWWW.atx, epnc_14_recalib.atx, epn_14_recalib.atx) only calibrations for GPS L1/L2 and GLONASS L1/L2 frequencies (even if the individual calibration includes more frequencies). The existing individual EPN antenna calibrations for antennas that are currently used in the EPN will not be changed. The calibrations indicated with ** in Table 2. were therefore restricted to only dual frequency GPS and GLONASS calibrations.

More details can be found in http://epncb.oma.be/ftp/mail/EUREF/eurefmail.10056.

4 Data Products

4.1 Positions

The EPN ACs operationally process GNSS observations collected at EPN stations. In 2019, all 16 ACs (Table 2) were providing final weekly and daily coordinate solutions of their subnetworks. Twelve ACs were providing also rapid daily solutions, and three ACs were providing ultra-rapid solutions. Two ACs, NKG and SUT, started providing rapid solutions in 2019. Details of the various combinations done by the Analysis Center Coordinator (ACC) are given on http://www.epnacc.wat.edu.pl.

In 2019, a test phase concerning the evaluation of the impact of adding Galileo observations on combined EPN station positions was completed. In the test phase, eight EPN ACs provided GNSS solutions based on GPS, GLONASS and Galileo observations in addition to the operational solutions based on only GPS and GLONASS observations (Bruynix et al. 2019b). The comparison between the two-system (GPS, GLONASS) operational coordinate solutions and the three-system (GPS, GLONASS, Galileo) test solutions showed that for the majority of stations mean position differences (over 44 weeks of daily solutions) were smaller than 1 mm in the horizontal components and 3 mm in the vertical component

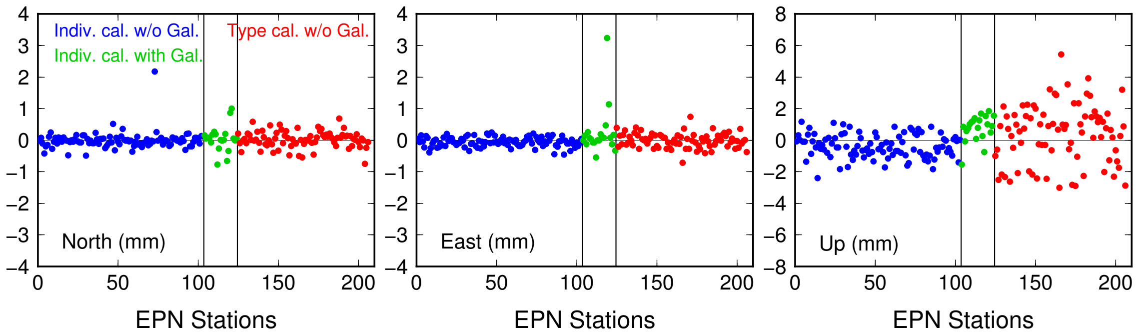

Figure 3: : Mean differences of station positions between combined three-system (GPS, GLONASS, and Galileo) test solutions and EPN combined two-system (GPS and GLONASS) operational solutions. Blue dots denote stations equipped with antennas with individual calibrations without corrections for Galileo (corrections available only for GPS and GLONASS), green dots denote stations with individual antenna calibrations with Galileo corrections, and red dots denote stations with type mean calibrations without Galileo corrections. Position differences are presented only for stations observing Galileo satellites.

(Figure 3). It was also noticed that larger differences were obtained for stations with type mean calibrated antennas than for stations with individually calibrated antennas (either with Galileo corrections or without), especially for the vertical component (Liwosz and Araszkiewicz 2019). Since March 10, 2019 (GPS week 2044), 11 ACs (Table 2) include Galileo observations in operational products (LPT AC has been using Galileo observations since 2016).

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.

So far, the EPN ACs processing Galileo observations have been using CODE MGEX (Multi-GNSS Experiment) products (GNSS orbits, clock corrections, Earth orientation parameters). However, at the EPN AC workshop, CODE announced that the IGS14 antenna model used for the generation of the MGEX products will be changed to the new antenna model (prepared for the IGS repro3 campaign), and that after this change the CODE MGEX products will no longer be consistent with the IGS14 reference frame

Table 2: 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 2019), used software (GOA – GIPSY-OASIS, BSW – Bernese GNSS Software, GG – GAMIT/GLOBK), used GNSS observations (G – GPS, R – GLONASS, E – Galileo)

AC	Analysis Centre Description	Solutions	# sites	Software	GNSS
ASI	Centro di Geodesia Spaziale G. Colombo, Italy	WDRU	73(8)	GOA 6.4	G
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	107(10)	BSW 5.2	GRE
BEV	Federal Office of Metrology and Surveying, Austria	WD	120(10)	BSW 5.2	GRE
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRU	129(12)	BSW 5.2	GRE
COE	Center for Orbit Determination in Europe, Switzerland	WD	41(0)	BSW 5.3	GR
IGE	Instituto Geografico Nacional, Spain	WDR	90(4)	BSW 5.2	GRE
IGN	Institut Géographique National de L'information Geographique et Forestiére, France	WDR	63(0)	BSW 5.2	GR
LPT	Federal Office of Topography swisstopo, Switzerland	WDRU	61(2)	BSW 5.3	GRE
MUT	Military University of Technology, Poland	WD	147(3)	GG 10.70	GE
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WDR	96(0)	BSW 5.2	GRE
RGA	Republic Geodetic Authority, Serbia	WD	54(0)	BSW 5.2	GR
ROB	Royal Observatory of Belgium, Belgium	WDR	106(7)	BSW 5.2	GRE
SGO	Lechner Knowledge Center, Hungary	WDR	41(0)	BSW 5.2	GR
SUT	Slovak University of Technology, Slovakia	WDR	59(0)	BSW 5.2	GRE
UPA	University of Padova, Italy	WDR	71(10)	BSW 5.2	GRE
WUT	Warsaw University of Technology, Poland	WDR	130(6)	BSW 5.2	GRE

(Dach et al. 2019). Therefore, to continue with the processing of Galileo observations within EPN, the EPN ACs agreed to switch (before the end of November 2019) from the CODE MGEX products to the new CODE rapid products for the generation of the EPN final solutions. This was possible because the CODE rapid products have been recently (since September 23, 2019) extended from a two-system (GPS, GLONASS) solution to a three-system (GPS, GLONASS, Galileo) solution and are consistent with the IGS14 antenna model. In addition, the accuracy of the CODE rapid solutions for the satellite orbits hardly differs from the accuracy of the CODE final solutions. The recent activities of the EPN ACC were presented at the ACs workshop in Warsaw (Liwosz and Araszkiewicz, 2019). In 2019, the EPN ACC continued the analysis of the impact of adding global stations to the EPN regional network on EPN station positions. Differences of station positions between the combined solution with global stations and the operational EPN solution (regional) mostly came from the different alignment of both solutions to the terrestrial reference frame (the position differences could be almost entirely absorbed by the 7-parameter transformation). It was verified that the differences in the reference frame alignment were mainly caused by the non-tidal loading effects (due to atmosphere and continental water). The options for a new EPN-Reprocessing campaign (Repro3) to reprocess all available data for the EPN network were discussed at the AC workshop. This activity strongly depends on the reprocessing activities of the IGS, since reprocessed orbits and earth rotation parameters are required. For the time being, the EPN reprocessing activities have been postponed and the new reprocessing results of the IGS are awaited.

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 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 releases, each 15 weeks, an update of multi-year coordinates/velocities of the EPN stations in the latest ITRS/ETRS89 realizations (Legrand and Bruynix 2019). The Reference Frame Coordinator (RFC) computes the EPN multi-

[1] European Centre for Medium-range Weather Forecasting

year solutions with the CATREF software (Altamimi et al. 2007). In 2019, four solutions have been released: C2025 (January, 2019), C2040 (April, 2019), C2055 (July, 2019) and C2070 (September, 2019).

The consistency of the EPN multi-year solutions wrt to IGS14 and weekly updates of the IGS multi-year solution IGSYYPWW is excellent. For example, 90% of the position differences between the EPN solution C2040 and the solution IGS19P08, are below 0.8 mm, 1.1 mm, 4.8 mm for resp. the North, East and Up components (at mean epoch of EPN position estimates) and 90% of the velocity differences ($>$ 3yr) are below 0.2 mm/yr, 0.2 mm/yr, 0.7 mm/yr for resp. the North, East and Up components. Most of the largest differences are explained by gaps in IGS time series (large gaps or sparse data).

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.oma.be/_productsservices/timeseries/. In addition, extended time series are updated every day by completing the EPN multi-year solution with the most recent EPN final and rapid daily combined solutions. 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.

To help users of the EPN multi-year position and velocity solution identify the best EPN reference stations, EUREF is distinguishing between Class A and Class B stations. Class A stations represent stations whose multi-year positions and velocities are reliable enough to be used as reference station for densification projects. However, this classification lacks granularity. In order to improve it, more criteria have been investigated. First, the seasonal signals and scattering of the position time series were analyzed. Then, we quantified the reliability of the velocity estimation by computing (using the Hector software, Bos et al. (2013)) more realistic velocity errors taking into account temporal correlated noise derived and also by comparing the velocity estimates from CATREF with the ones obtained with Hector software. Finally, we looked for a criterion to assess the stability of the station velocities over their full history. For this, we quantified for each station its temporal velocity variability by comparing the velocities obtained from various time spans with velocities obtained from the full time span of the station. Based on all the criteria above, thresholds have been defined in order to end up with a new station classification. A web tool will help the user to select the best reference stations in a considered area and for a given period of observation. The criteria and web tool are currently under evaluation within EUREF.

4.4 Official National Coordinates

Since 2009, EUREF is collecting the official national coordinates for the EPN sites as they are used in the countries for national reference frame densifications, mainly provided using real-time positioning services. Those coordinates are routinely compared with those provided by the RFC. 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).

5 Working Groups

5.1 EPN Densification

EPN DThe 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. 2019). 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 most recent results cover the period from November 2006 to April 2019 (GPS week 1400-2050) using inputs expressed in IGS14. Solutions based on the IGb08.atx antenna calibration model prior to GPS week 1933 had been converted to IGS14.atx using the IGS latitude-dependent models of position offsets for non-IGS stations and offsets for IGS stations (https://lists.igs.org/pipermail/igsmail/2016/001233.html). The solution includes 31 networks with positions and velocities of 3300 stations, well covering Europe. The length of the individual station position time series is shown in Figure 4. The positions and velocities are expressed in the ITRF2014 and ETRF2014 reference frames and it tied to the reference frame using minimum constraints on a selected set of ITRF2014 reference stations. The description of the EPN Densification, station metadata, and results are available from the EPN CB Densification webpages (http://epncb.oma.be_densification/).

5.2 European Dense Velocities

The velocity estimates in ETRF2000, derived by currently 30 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 (Brockmann et al.(2019). In some countries, as e.g.

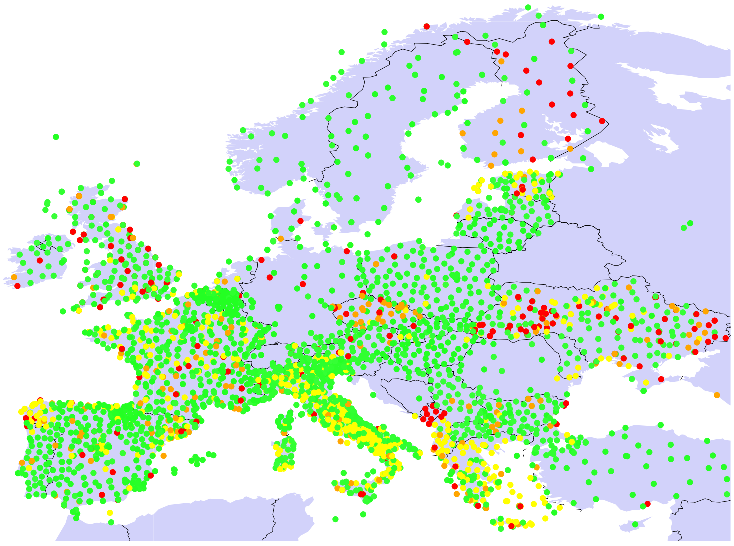

Figure 4: The distribution and length of the position SINEX series available for EPN Densification.

in the Nordic countries, velocity models are already in use. They can be integrated to indicate 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 6200 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. Figure 5 shows the horizontal velocity field in its current status. The web page was furthermore enhanced with dynamical visualizations. 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 2019, 54 % of the EPN stations provided real-time data with 188 mount-points. As can be seen from Table 1, only some of the new EPN stations are also providing real-time

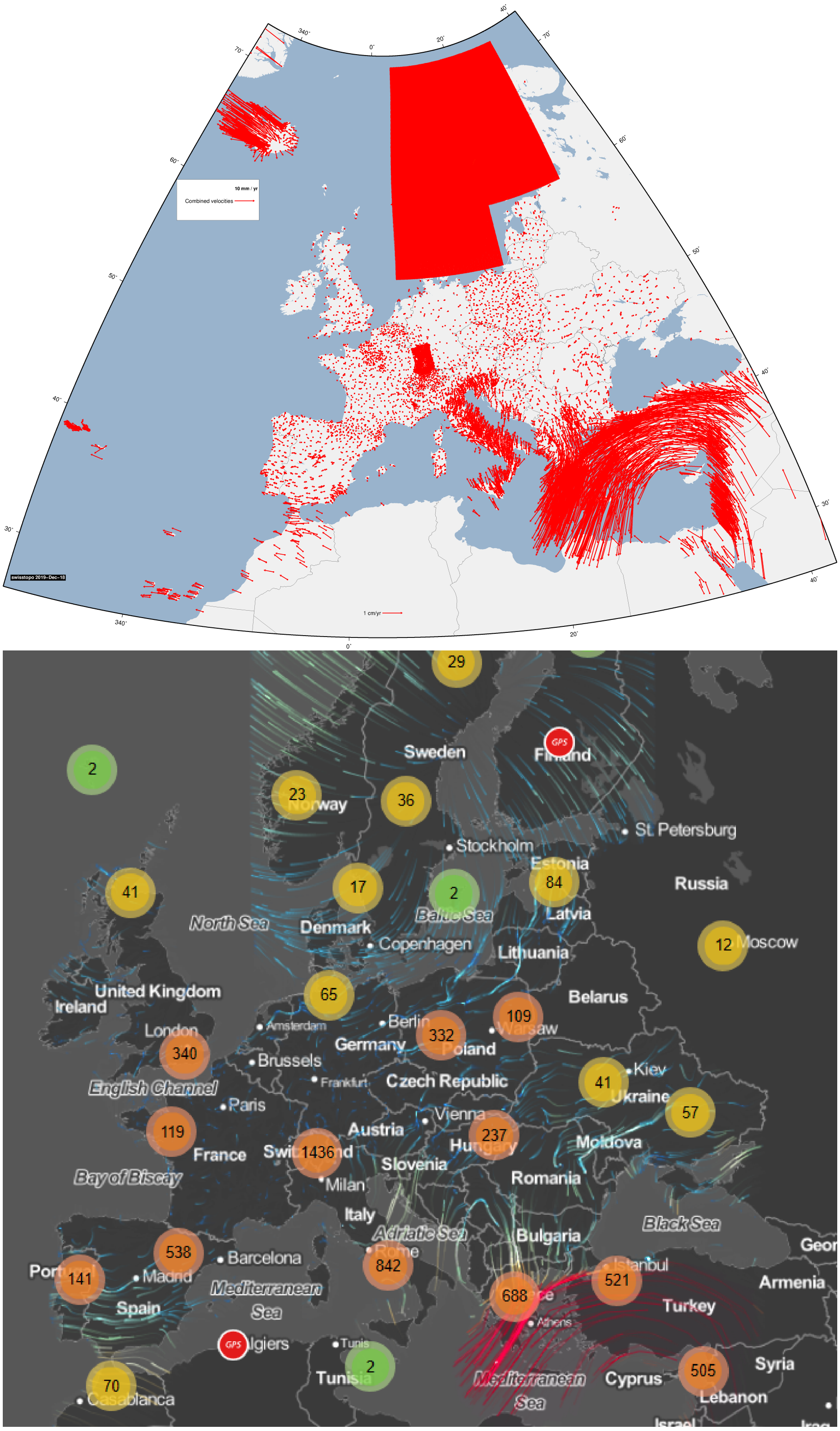

Figure 5: Horizontal velocities derived by the "European Dense Velocity" Working Group. Static plot at top, animation of velocities as a wind field (http://geolabpasaia.org/gnss/agi/maps/EU-DenseVelocities.html#4/50.04/14.99) at bottom.

data streams. The introduction of long mount-point names on the three EPN broadcasters has been completed. Almost all varieties of RTCM messages (2.x to 3.3) are available from the EPN broadcasters, with 10 stations still providing RTCM 2.x. The number of streams supporting the RTCM 3.3 Multi Signal Messages (MSM) is still growing. The number of stations providing MSM messages, which are delivering MSM4 (message type 1074 etc.) or MSM5 (message type 1075 etc.), increased to 54 whereas the MSM7 (1077 etc.) was available for 68 stations. Hence, the stations providing the "legacy" messages 1004 (GPS) and 1012 (GLONASS) significantly reduced from 95 to 50.

The visibility of the real-time data streams and the monitoring of the three EPN broadcasters at the EPN CB was extended. The availability of the data streams and in particular the latency (http://epncb.oma.be/_networkdata/stationlist.php) are important performance indicators. The updated sections on availability of data and product streams (http://epncb.oma.be/_networkdata/data_access/real_time/status.php) and on meta-data monitoring (http://epncb.oma.be/_networkdata/data_access/real_time/metadata_monitoring.php) show in a concise way a large variety of parameters, from latency over equipment to message types and satellite constellations. There are station-dependent as well as broadcaster-dependent outputs implemented. Compared to last year, the consistency between the three EPN broadcasters improved very much. In particular, the ASI caster successfully implemented a large portion of missing stations, so that 85 % of the real-time data is available at all EPN casters. For the remaining 27 real-time stations, the caster administrators have been encouraged to check the missing connectivity information.

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SIRGAS Regional Network Associate Analysis Centre Technical Report 2019

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1 Introduction

The present realisation of SIRGAS is a network of continuously operating GNSS stations distributed over Latin America (Cioce et al. 2019). 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. 2012a). 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, 2020; 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 and Drewes 2016, 2020; Sánchez et al. 2016; Sánchez and Seitz 2011).

2 SIRGAS reference network

The SIRGAS continuously operating network is at present composed of 414 continuously operating GNSS stations (Fig. 1). 70 of these stations are included in the IGS (International GNSS Service) global network (Johnston et al. 2017) and some of them are used for the datum realisation in the SIRGAS reference frame computation. 87% of the SIRGAS

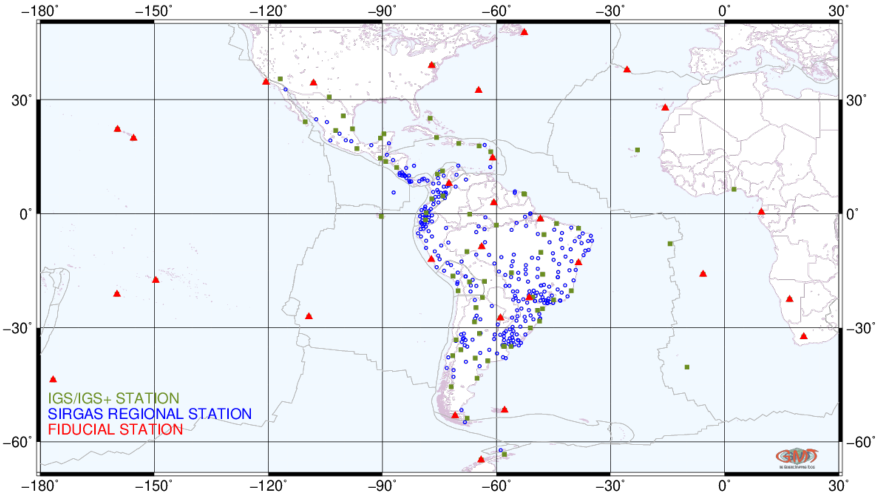


Figure 1: SIRGAS reference frame (as of Dec 2019). It is composed of 414 GNSS stations (100% GPS, 83% GLONASS, 22% Galileo, 14% Beidou). 70 of these stations (green squares) are included in the IGS global network and some of them (red triangles) are used for the datum realisation in the SIRGAS reference frame computation.

stations track GLONASS, 29% Galileo and 19% 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:

- 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

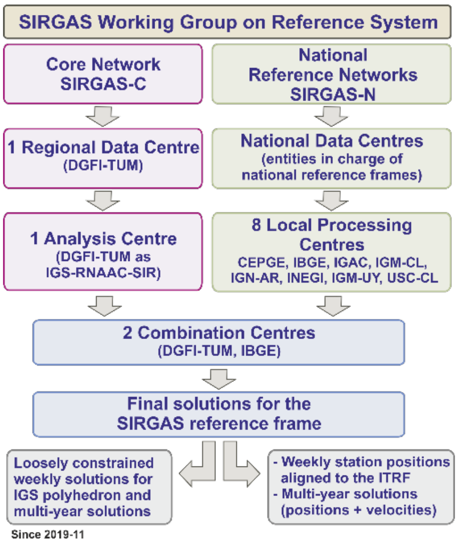


Figure 2: Data flow within the SIRGAS reference frame analysis (source www.sirgas.org)).

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)
- 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).
- IGM-Uy: Instituto Geográfico Militar (Uruguay), see Caubarrère (2018).
- USC: Universidad de Santiago de Chile: Centro de Procesamiento y Análisis Geodésico USC (Chile), see Tarrío et al. (2019).

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 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. 2.

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 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 (see Fig. 1). 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. 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.

Additionally, based on the SIRGAS weekly processing, the SIRGAS Analysis Centres for the Neutral Atmosphere and the Ionosphere generate hourly tropospheric zenith path delays and hourly maps of vertical total electron content (vTEC), respectively. The SIRGAS Analysis Centre for the Neutral Atmosphere (CIMA) is operated by the Facultad de Ingeniería of the Universidad Nacional de Cuyo (UNCuyo, Mendoza, Argentina) in cooperation with the Facultad de Ingeniería of the Universidad Juan Agustín Maza (Mendoza, Argentina) and with support of the Argentinean Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), see Mackern et al. (2019). The SIRGAS Analysis Centre for the Ionosphere is operated by the Universidad Nacional de La Plata (Argentina), see Bruini et al. (2012b).

6 Reprocessing of the SIRGAS reference frame in ITRF2014

The operational 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 determine 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 normal equations 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). In Nov 2018, DGFI-TUM (as IGS RNAAC SIRGAS) started the reprocessing of SIRGAS GNSS historical data from Jan 2000 to Dec 2019 using the IGS14. In this reprocessing, we use the model igs14.atx (`ftp://ftp.igs.org/pub/station/general/igs14.atx`) and 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 stations co-located with VLBI and SLR (Fig. 3). The main objective is to evaluate the reliability of the datum realisation (origin, orientation, scale) in the regional network. The idea is to define the geodetic datum of the regional network by combining GNSS with SLR and VLBI normal equations and to compare the station coordinates with the GNSS-only frame computations. In the combined realisation, the origin shall be obtained from SLR and the scale as a weighted mean of SLR and VLBI scale. The orientation shall be realised as it is standard, i.e., by applying a non-deforming no-net-rotation condition using a subset of selected global IGS stations as fiducial points. Today (Jan 2020), about 90% of the

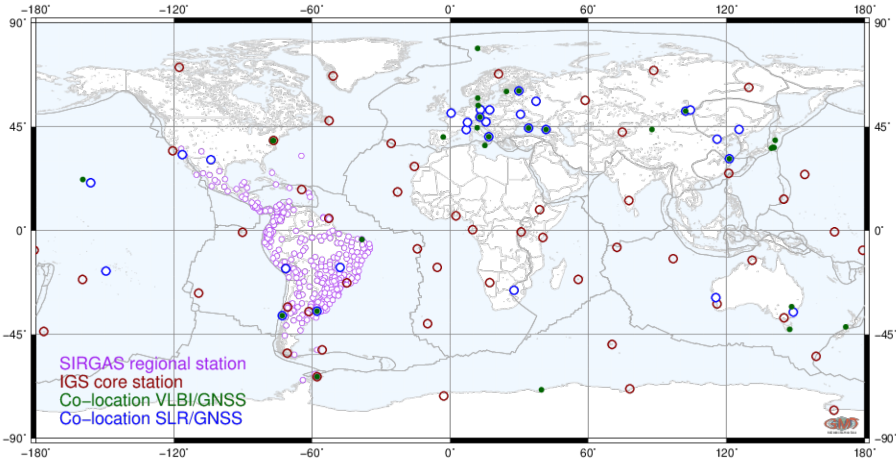


Figure 3: GNSS network configuration for the combination of GNSS, SLR and VLBI normal equations in the realisation of a global geodetic datum in the regional reference frame SIRGAS. VLBI/GNSS (green dots) and SLR/GNSS (blue circles) co-located stations are necessary for the normal equation combination. IGS core stations (red circles) are necessary for a high-quality GNSS data processing.

IGS14-based SIRGAS reprocessing is completed. Once it is finished, it would be possible to evaluate the reliability and long-term stability of the SIRGAS reference frame over 20 years and to contrast the GNSS-only frame realisation with the GNSS/SLR/VLBI-based realisation. In addition, the IGS14-based station position time series will be valuable input data for further studies focusing on the analysis of on-going geodynamic process in Latin America.

7 Reference frame kinematics and surface deformation

In the Andes region, like in any active seismic region of the Earth, there are large discontinuities in the station coordinate time series and considerable variations in the station velocities caused by strong earthquakes. The consequence is that the respective reference frames cannot be used and have to be frequently updated for geodetic purposes. In the frame of the IGS RNAAC SIRGAS activities, we regularly compute multi-year solutions for the SIRGAS reference frame to evaluate the reference frame deformation caused by recent strong earthquakes. For instance, the comparison of the last two mult-year solutions SIR15P01 (Sánchez and Drewes 2016) and SIR17P01 (Sánchez and Drewes 2020) makes evident that the present-day surface deformation in the western margin of Latin America is highly influenced by the effects of six major earthquakes (Fig. 4): Maule (Mw8.8, Feb. 27, 2010), Nicoya (Mw7.6, Sep. 5, 2012), Champerico (Mw7.4, Nov. 11, 2012), Pisagua (Mw8.2, Apr. 1, 2014), Illapel (Mw8.3, Sep. 16, 2015), and Pedernales (Mw7.8, Apr 16, 2016).

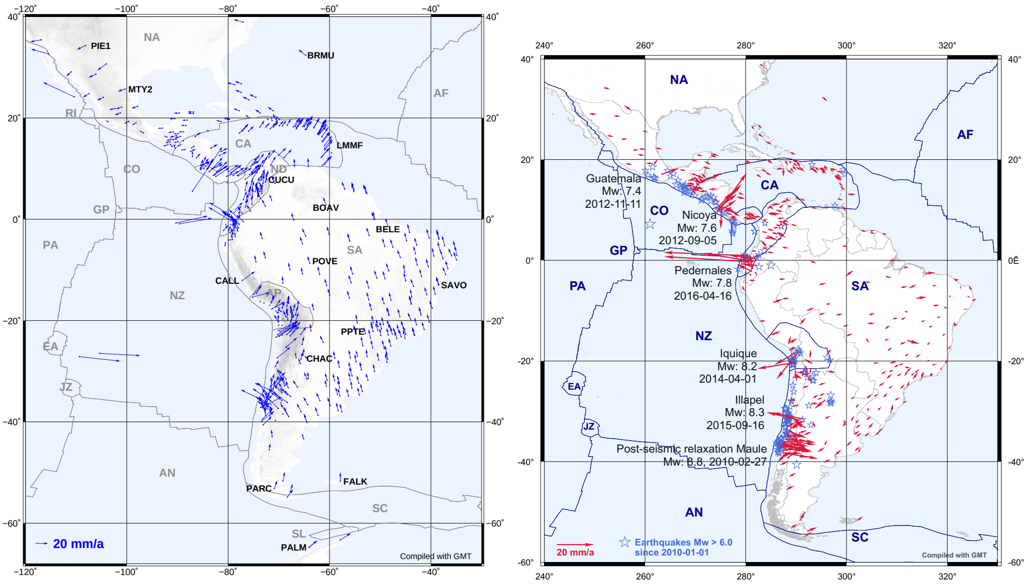
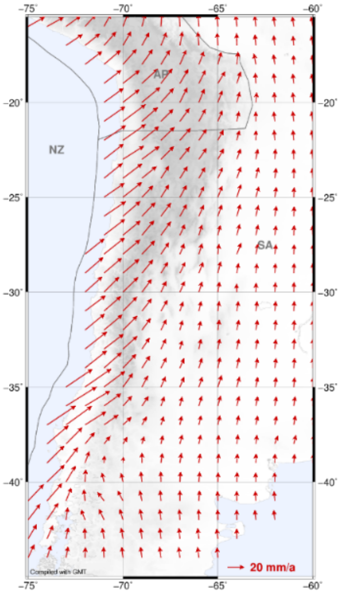


Figure 4: Horizontal velocities of the SIRGAS reference frame realization SIR17P01 (left) and differences with respect to the previous SIRGAS realization SIR15P01 (right). SIR15P01 covers the period 2010-03-14 thru 2015-04-11; SIR17P01 covers the period 2011-04-17 thru 2017-01-28. Black labels in the left identify the fiducial stations. Black labels in the right identify the earthquakes causing recent strong deformations of the SIRGAS reference frame.

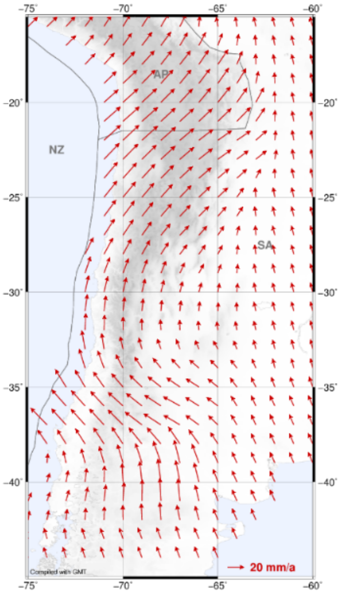
Additionally, due to the frequent occurrence of seismic events in the Andean region, the IGS RNAAC SIRGAS regularly computes updated station velocity models for SIRGAS (VEMOS) on continuous grids. These models allow the monitoring of the reference frame kinematics, the determination of transformation parameters between pre-seismic and post-seismic (deformed) coordinates, and the interpolation of surface motions arising from plate tectonics or crustal deformations in areas where no geodetic stations are established. Besides the geodetic usability of the VEMOS models, they provide a detailed view of surface deformations caused by on-going geodynamic processes. As an example, Fig.5 presents the strain components inferred in the Central and Southern Andes from the models VEMOS2009 (Drewes and Heidbach 2012), VEMOS2015 (Sánchez and Drewes 2016) and VEMOS 2017 (Sánchez and Drewes 2020).

8 SIRGAS stations included in the IGS reprocessing campaign for the ITRF2020

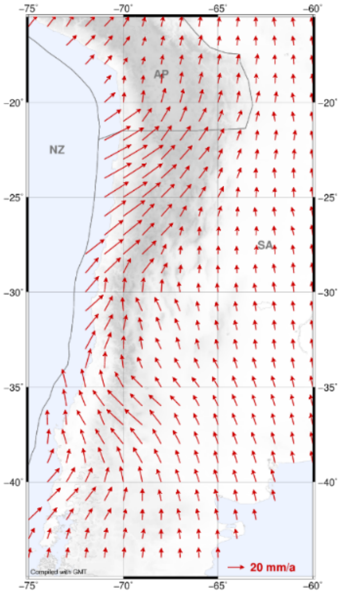
Based on the performance of the SIRGAS stations, the IGS RNAAC SIRGAS, in agreement with the IGS Reference Frame Coordinator proposed 30 additional SIRGAS stations to be included in the IGS reprocessing campaign for the ITRF2020 (Fig. 6).



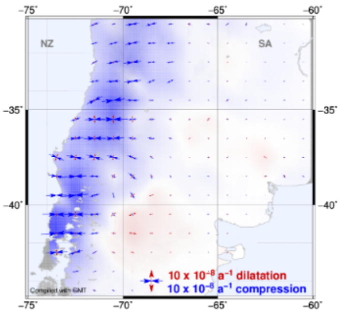
(a) Extract of VEMOS2009 (valid from 2000.0 to 2009.6) after Drewes and Heidbach (2012)



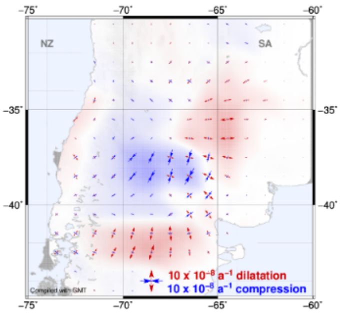
(b) Extract of VEMOS2015 (valid from 2012.2 to 2015.2) after Sánchez and Drewes (2016)



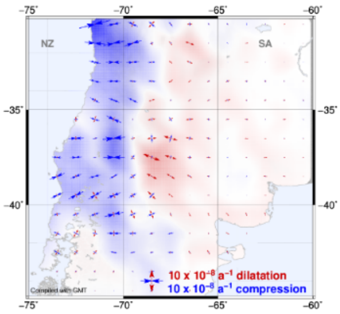
(c) Extract of VEMOS2017 (valid from 2014.0 to 2017.1), after Sánchez and Drewes (2020)



(d) Strain field inferred from VEMOS2009 (valid from 2000.0 to 2009.6)



(e) Strain field inferred from VEMOS2015 (valid from 2012.2 to 2015.2)



(f) Strain field inferred from VEMOS2017 (valid from 2014.0 to 2017.1)

Figure 5: Deformation model and strain field series in the Central and South Andes inferred from VEMOS2009 (left), VEMOS2015 (centre), and VEMOS2017 (right). Blue shades represent compression; red shades represent dilatation.

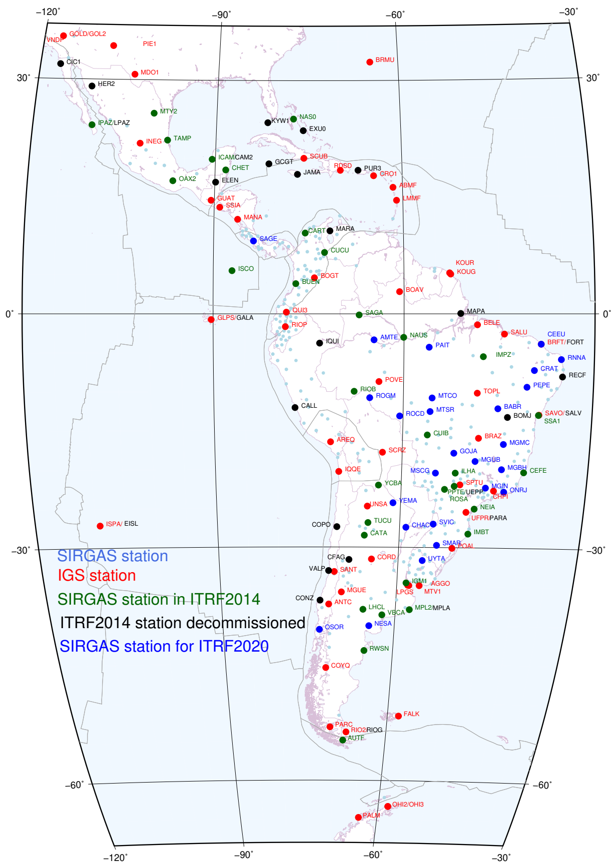


Figure 6: SIRGAS stations included in the IGS reprocessing campaign for the ITRF2020

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Part III

Data Centers

Infrastructure Committee Technical Report 2019

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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.

Current Members: renewed on Dec, 2017 for terms up to Dec 2019;

- Carine Bruyninx (ROB)
- Nicholas Brown (GA)
- Nacho Romero – Chairman – (ESOC)
- Brian Donahue (NRCan)
- Wolfgang Soehne (BKG)

Ex–officio Members:

- Mayra Oyola – Central Bureau
- David Maggert – Network Coordinator
- Michael Moore – Analysis Coordinator
- Tom Herring – Analysis Coordinator
- Andre Hauschild – Real-Time Working Group Chair
- Bruno Garayt – Reference Frame Coordinator
- Carey Noll – Data Center Coordinator
- Michael Coleman – Clock Products Coordinator

Member changes since last Report:

- Lou Estey (UNAVCO) – Retired
- Steve Fisher (CB) – replaced
- Axel Ruelke (RT WG) - replaced

2 Summary of Activities in 20189

Over 2019 the IC has supported the Network Coordinator on answering questions from IGS product and data users, plus;

- Adding 12 stations to the Station Network,
- Consulting in the removal 18 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 Chair has participated in several Working Group teleconferences over the year to ensure there is coordination in terms of station needs and infrastructure across all the different IGS activities. Additionally, the IC Chair gave the IGS infrastructure status presentation at the Unified Analysis Workshop 2019 in Paris, France.

Work continues in coordination with the different working groups for all the IGS products to accept the station long names into the products. The MGEX Analysis Centers all now use long product names for their submissions. For the 3rd reprocessing campaign at the IGS “repro3”, all Analysis Centers have agreed to use the long product names.

Over 2019 the IC, in response to recommendation 2018-2 of the 2018 IGS Workshop, proposed detailed plans for the creation of a single data tar file from the 96 daily 15 min 1Hz data RINEX files, with a 6-month delay, the effort is being led by CDDIS. Additionally, in response to recommendation 2018-4, a plan was created and refined to transition at the DC level to gzip for all IGS files (Data and products), the effort led by GA. Finally, in response to recommendation 2018-3, the IC & DC worked with the IGS GB to create the new Data Center Coordinator position in the IGS Terms of Reference (TOR) and started on the new IC Charter to formally reflect the folding in of the DC WG into the IC.

3 Planned 2020 Activities

During 2020 the IC will strive to complete the implementation of the remaining recommendations still outstanding from the 2017 & 2018 IGS Workshops and to create a representative programme for the 2020 IGS Workshop in Boulder, Colorado.

CDDIS Global Data Center Technical Report 2019

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1 Introduction

The Crustal Dynamics Data Information System (CDDIS) is NASA's active archive 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), in particular, the system has supported the International GNSS Service (IGS) as a global data center since 1992. The CDDIS activities within the IGS during 2019 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 globally accessible through anonymous ftp (address: cddis.nasa.gov) and through web-based archive access (https://cddis.nasa.gov/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 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. 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 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.

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 Ingest Software

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. 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).

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

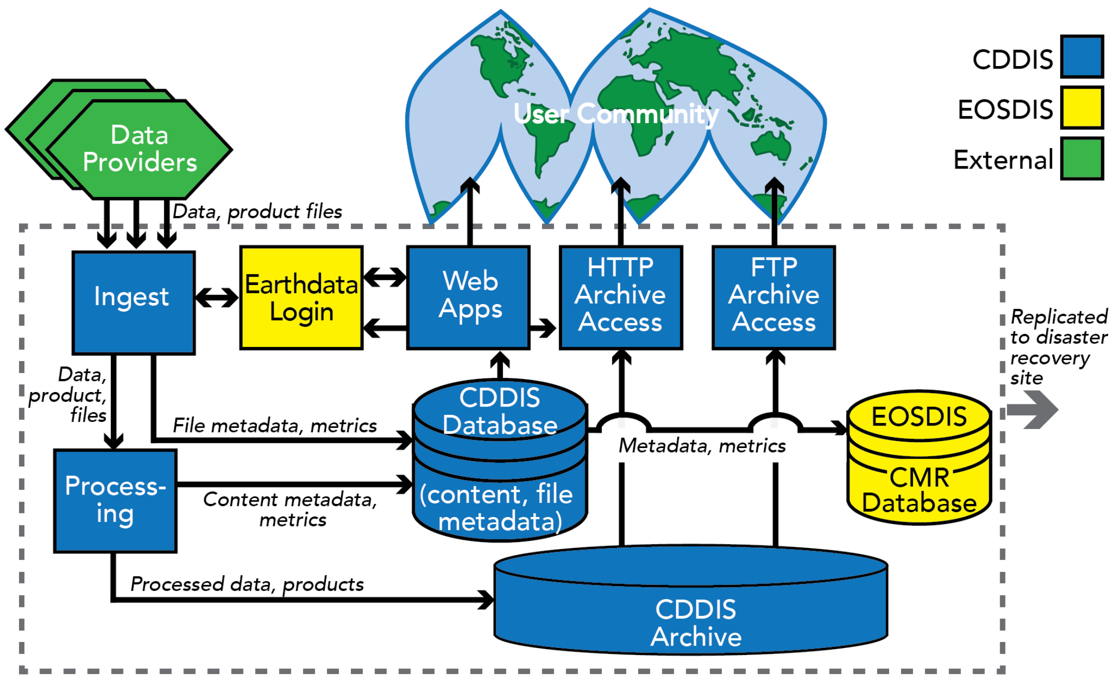

Figure 1: System architecture overview diagram for the CDDIS facility installation within the EOSDIS infrastructure.

activities. The CDDIS archive is approximately 27 TBytes in size (over 260 million files) of which over 95% is devoted to GNSS data (30 TBytes) and GNSS products (1.7 TBytes). All these GNSS data and products are accessible through subdirectories of ftp://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. Nearly 50 operational and regional IGS data centers and station operators make data 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) to retrieve (or receive) data holdings not routinely transmitted to the CDDIS by an operational or regional data center. Table 1 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/archive/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 availability 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 287K daily station days from 602 distinct GNSS receivers were archived at the CDDIS during 2019; of these sites, 294 sites supplied both RINEX V2 and V3 data (see Table 2). A complete list of daily, hourly, and high-

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

Table 2: GNSS Data Archive Summary for 2018.

	Number of sites						
Data type	V2	V3	V2&V3	Unique	Vol.	#file	Directory
Daily	552	344	294	602	892 GB	1.3 M	`/gnss/data/daily`
Hourly	378	255	222	411	948 GB	15.1 M	`/gnss/data/hourly`
High-rate	270	101	64	307	3,900 GB	20.0 M	`/gnss/data/highrate`

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 on-line, 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 411 unique hourly sites (over 15 million files) were archived during 2019; 222 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

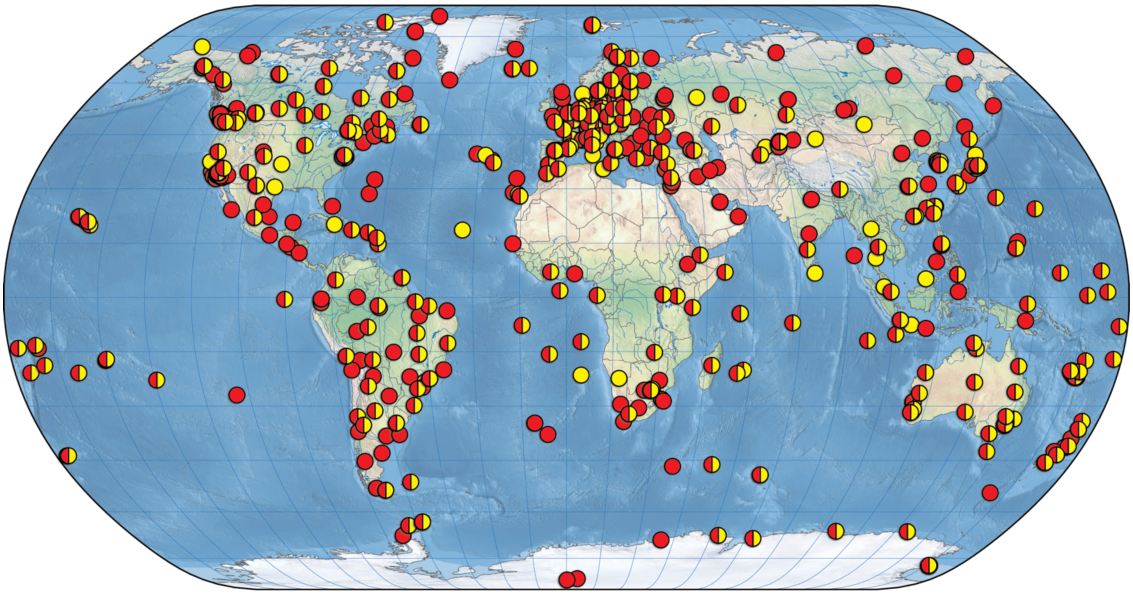

Figure 2: The main, operational archive at CDDIS now includes data in RINEX V2 format using the 8.3.Z filename specification (red) and RINEX V3 format using the V3 filename specification (yellow); sites providing both RINEX V2 and V3 formatted data are shown with the red+yellow icon.

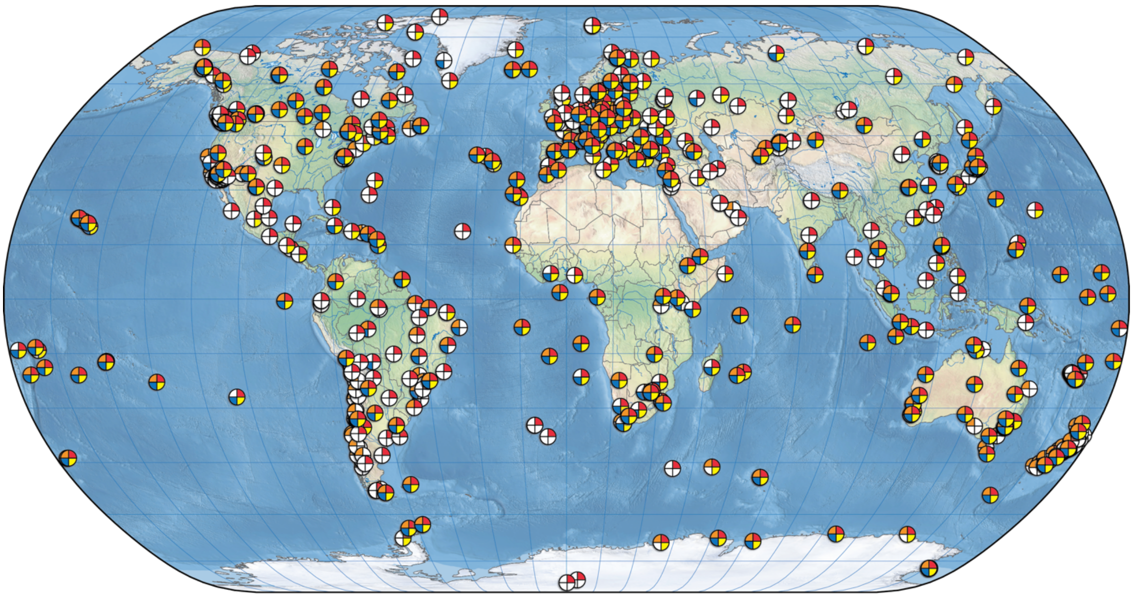

Figure 3: CDDIS GNSS archive includes data in daily (red), hourly (yellow), sub-hourly (blue), and/or real-time (orange) increments. Hourly, sub-hourly, and real-time data allow analysts to generate products for applications needing more frequent updates.

of these data files are created from real-time streams. As shown in Table 2, data from 307 unique high-rate sites (over 20 million files) were archived in the CDDIS in 2019; 64 high-rate sites provided data in both RINEX V2 and V3 formats.

3.2 Broadcast Navigation Files

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/archive/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 also archives 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) from real-time streams, contains all the unique broadcast navigation messages for the day. The file, named `BRDM00DLR_S_YYYYDDD0000_01D_MN.rnx.gz`, is stored in daily subdirectories within the archive (`/gnss/data//daily/YYYY/DDD/YYp`) and in a yearly top level subdirectory (`/gnss/data/daily/YYYY/brdc`). In addition, the TUM/DLR team provides a merged GPS/QZSS LNAV and CNAV navigation file generated from real-time streams; these files use the naming convention `BRDX00DLR_S_YYYYDDD0000_01D_MN.rnx.gz`.

For the near term, the CDDIS continues to archive a daily merged multi-GNSS broadcast ephemeris file and GPS/QZSS CNAV file using the RINEX V2 naming convention and archived in the MGEX campaign directories: (/gnss/data/campaign/mgex/daily/rinex3/YYYY/DDD/YYp/brdmDDD0.YYp.Z and /gnss/data/campaign/mgex/daily/rinex3/YYYY/cnav/brdxDDD0.YYx.Z respectively. The archive of these files will discontinue in the near future as the IGS moves to complete the integration of the campaign directory contents into the main GNSS data archive.

3.2.1 Supporting Information

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

3.2.2 RINEX V3 (MGEX) Campaign Archive

During 2019, 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).

3.3 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 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.

Table 3: GNSS Product Summary for 2019.

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, 1.8 GB/year	`/gnss/products/ionosphere/YYYY`
Real–time	Combination	28 MB/week	`/gnss/products/rtpp/WWWW`
MGEX	7	500 MB/week	`/gnss/products/mgex/WWWWY`

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

Seven AACs (CODE, GFZ, GRGS, JAXA, TUM, SHAO, and Wuhan) generated weekly products (orbits, ERP, clocks, and others) in support of MGEX; these AACs now 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.

3.4 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 2019, the CDDIS caster broadcasts 39 product and more than 600 data streams in real-time. The caster runs the NTRIP (Network Transport of RTCM via Internet Protocol) format. Figure 44 shows the distribution of stations providing real-time streams to the CDDIS caster by source. 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

Table 4: CDDIS Caster Stream Availability.

Acronym	Agency/Country	Approximate Number of Streams*
Data		
ASI	Italian Space Agency (Italy)	9
BKG	Bundesamt für Kartographie und Geodäsie (Germany)	106
CNES REGINA	Centre National d'Etudes Spatiales Reseau GNSS pour l'IGS et la Navigation (France)	27
CNS	Centro Sismológico Nacional, University of Chile (CNS, Chile)	62
FinnRef	National Land Survey of Finland (Finland)	1
GA	Geoscience Australia (Australia)	88
GDGPS	Global Differential GPS, Jet Propulsion Laboratory (USA)	98
GFZ	GeoForschungsZentrum (Germany)	21
GSI	Geospatial Information Authority of Japan (Japan)	6
IBGE	Instituto Brasileiro de Geografia e Estatística (Brazil)	30
ICGC	Institut Cartográfic i Geològic de Catalunya (Spain)	2
IGN	Institut Geographique National (France)	20
LINZ	Land Information New Zealand (New Zealand)	98
NRCan	Natural Resources Canada (Canada)	21
ROB	Royal Observatory Belgium (Belgium)	2
TrigNet	TrigNet (South Africa)	4
UNAVCO	UNAVCO (USA)	16
Total Data:		611
Product	Multiple	39
Total Streams		650

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

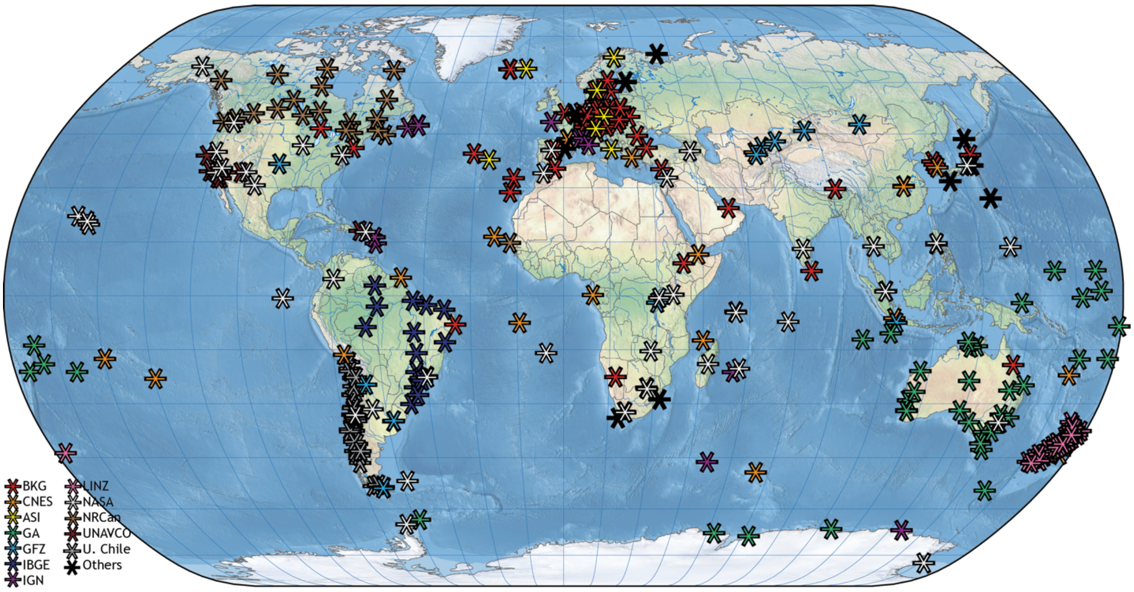

Figure 4: CDDIS is operationally supporting the dissemination of data from over 650 real-time GNSS sites as well as near real-time products derived from these data.

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 2019, over 330 users from 47 countries have registered to use the CDDIS caster; approximately 65 users were added in 2019. More information about the CDDIS caster is available at https://cddis.nasa.gov/Data_and_Derived_Products/Data_caster_description.html.

The CDDIS staff updated the caster to provide new 10 character mount point names as per direction of the IGS Real-Time Working Group (RTWG). The expanded mount point names align with the RINEX V3 naming convention utilized within the IGS to accommodate multi-constellation data.

As stated previously, the CDDIS utilizes the EOSDIS Earthdata Login, for authenticating file uploads to its incoming file server. 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, 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.

3.5 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 2019. 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 1.5 billion files (nearly 286 TBytes) were transferred in 2019.

As for real-time system usage, an average of 15 users consistently accessed the CDDIS real-time caster on a daily basis in 2019, with on average 9,000 stream connections to over 500 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; nearly 300K unique hosts accessed the system in 2019. 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. Starting in 2018, as per U.S. Government and NASA directives, the CDDIS began 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. Access to data in the CDDIS archive using anonymous ftp will continue until October 2020; users are strongly encouraged to implement procedures to use the https

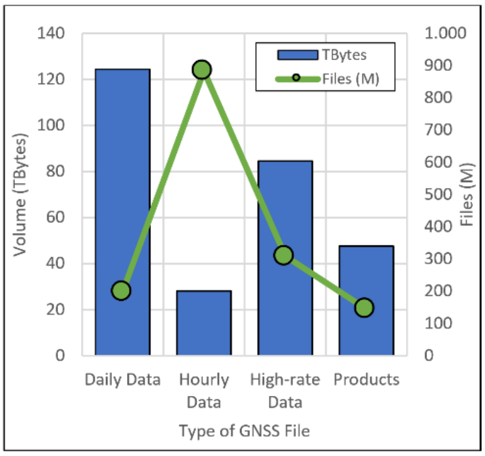

Figure 5: Number and volume of GNSS files downloaded from the CDDIS in 2019.

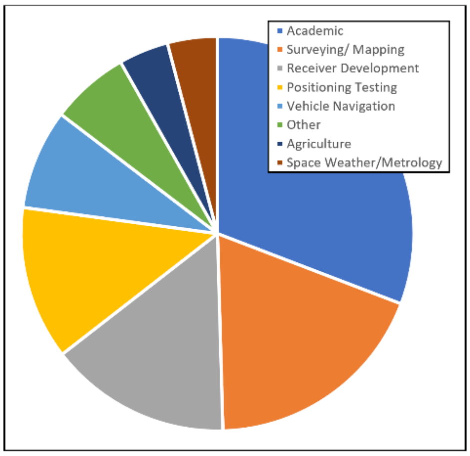

Figure 6: Primary applications supported by CDDIS real-time caster streams.

(address: https://cddis.nasa.gov/archive) 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 and examples documentation at: https://cddis.nasa.gov/Data_and_Derived_Products/CDDIS_Archive_Access.html. Various presentations on these updates to the CDDIS archive access are also available (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 have now been assigned to the majority of GNSS data and product sets archived at CDDIS.

5.3 Real-time Caster Updates

By the end of 2019, the CDDIS real-time caster was configured to stream data from over 600 GNSS data mount points and 39 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 August 2020.

6 Future Plans

6.1 Archive Access

As discussed in Section 5 above, the CDDIS cannot continue to support of non-encrypted anonymous ftp access to its archive; access to the archive through https and ftp-ssl have already been implemented. The schedule for terminating anonymous ftp access is as follows:

- July 01, 2020 – all anonymous ftp service will be bandwidth limited to 1MB/s
- August 10, 2020 – all anonymous ftp service will be bandwidth limited to 250KB/s
- October 01, 2020 – all anonymous ftp service will be bandwidth limited to 50KB/s
- October 31, 2020 – all anonymous ftp service will be permanently discontinued at CDDIS

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 continue to investigate the use of 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 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 procured new systems, storage, and network hardware for its next hardware refresh. Staff members have begun the integration of this next system; plans are to have the upgraded system installed by mid-2020. 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.

6.6 Repro3 Support

The CDDIS provided support through the upload of files from the ACs and online archive of the IGS repro1 and repro2 campaigns (`/gnss/products/WWWW/repro[1,2]` and `/gnss/products/repro[1,2]/WWWW`). As the ACs work on solutions for the next reprocessing campaign (repro3), CDDIS will try to provide archive support; initial size requirements, however, may not be sufficient to allow for a complete upload of files. The CDDIS staff continues to work with the ACC and ACs on possible solutions.

7 Publications

The CDDIS staff attended several conferences during 2019 and presented, or contributed to, papers on their activities within the IGS, including:

M. Pearlman et al. GGOS: Current Activities and Plans of the Bureau of Networks and Observations (poster), presented at the EGU General Assembly, Vienna, Austria, April 07-12, 2019. https://ilrs.gsfc.nasa.gov/docs/2019/GGOSEGU201904.pdf

C. Noll, P. Michael. The Crustal Dynamics Data Information System: NASA's Active Archive of Geodetic Observations Supporting Research in Understanding our Dynamic Earth, presented at the 27th IUGG General Assembly, Montreal Canada, July 08-18, 2019. https://cddis.nasa.gov/docs/2019/CDDISposter_IUGG2019_v3.pdf

C. Noll. Role and function of the SLR Data Centers, presented at the First SLR School, Stuttgart, Germany, October 20, 2019. https://cddis.nasa.gov/2019_Technical_Workshop/docs/2019/presentations/SLRschool/Session2/SLRschool_session2_Noll_presentation.pdf

C. Noll, M. Pearlman. ILRS: Recent Developments, presented at the 2019 ILRS Technical Workshop, Stuttgart, Germany, October 21-25, 2019. https://cddis.nasa.gov/2019_Technical_Workshop/docs/2019/presentations/Session1/session1_Noll_presentation.pdf

T. Otsubo, Y. Aoyama, A. Hattori, K. Doi, M. Pearlman, C. Noll. The Final Frontier for Satellite Laser Ranging: Antarctica, , presented at theTenth Symposium on Polar Science, Tokyo, Japan, December 03-05, 2019. https://ilrs.gsfc.nasa.gov/docs/2019/PolarSci10-otsubo-finalfrontier-s.pdf

P. Michael, C. Noll. NASA CDDIS: Supporting Global Geodetic and Geophysical Research and Applications, presented at the 2019 Fall AGU meeting, San Francisco, CA, USA, December 09-13, 2019. https://cddis.nasa.gov/docs/2019/CDDISposterAGU201912v0.pdf

S. Blevins, N. Pollack, P. Michael, C. Noll. Enhancements to the GNSS Real-time System

at CDDIS, presented at the 2019 Fall AGU meeting, San Francisco, CA, USA, December 09-13, 2019. https://cddis.nasa.gov/docs/2019/SMBlevins_AGU2019_final.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:

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Manager, CDDIS	Fax:	(301) 614-6015
Code 61A	E-mail:	Patrick.Michael@nasa.gov
NASA GSFC	WWW:	https://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 authors would like to acknowledge the entire CDDIS staff. 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.

"Access NASA Earth Science Data", from Earthdata website, https://earthdata.nasa.gov.

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 2019

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1 Introduction

The GNSS Science Support Centre (GSSC) is an initiative led by ESA's Galileo Science Office to consolidate a GNSS Preservation and Exploitation Environment in support of IGS and the GNSS scientific community at-large.

Among other goals, GSSC activities aim to secure overall IGS data mirroring and dissemination. Hence, as an IGS Global Data Center (GDC), the GSSC collaborates with all GDCs and specially with CDDIS, making available all lGS data and products via anonymous FTP.

2 Description

Since 2018, the GSSC, hosted at ESA's European Space Astronomy Centre (ESAC) near Madrid, integrates a wide range of GNSS assets including data, products and tools in a single environment to promote innovation in GNSS Earth Sciences, Space Science, Metrology and Fundamental Physics domains.

The core of the GSSC is a large repository which currently holds all IGS data and products. The GSSC is also one of the original providers of data and products generated by ESA's Navigation Support Office at European Space operations Centre near Frankfurt.

Moreover, GSSC is to play a key role in ESA efforts to ensure long term access to GNSS resources produced by ESA throughout its different research programmes. Along these lines, upcoming upgrades to GSSC IT infrastructure will provide storage and on-site processing capabilities to support ESA projects carrying out scientific innovation based on GNSS resources.

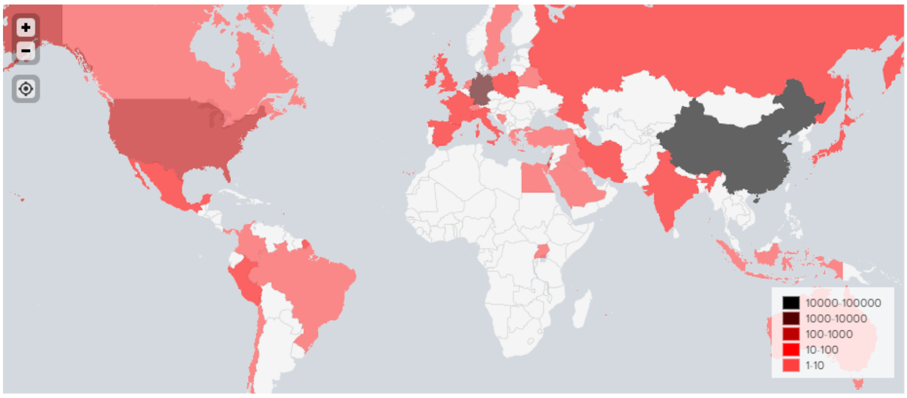

Figure 1: Worldwide Number of IGS File Downloads in 2019

3 2019 Developments

2019 has represented the consolidation of GSSC (gssc.esa.int) as a new reference point for GNSS resources supported by following developmens:

- Web-portal improvements with new content and better accessibility ergonomics.
- Repository extension with new data collections for ESA projects (GREAT, PULCHRON . . .) and GNSS In-Space (Swarm, Goce . . .).
- Initial file based services over FTP and HTTP, in charge of distributing IGS data and products, have undergone multiple upgrades to improve their resilience and.
- New monitoring capabilities to support the definition of dashboards with real-time information on alarms and KPIs.

Additionally, during 2019, GSSC developments have focused on extending aforementioned file based services with advanced APIs leading to the implementation of a new platform for users to search and analyse data using keywords, worldwide maps, filters and notebooks. These developments leverage on mainstream Big Data, Cloud, Virtualisation and Container technologies to implement GSSC's GNSS Science Exploitation and Preservation Platform. This platform evolves GSSC's repository with state-of-the-art discovery and analysis services to enable a paradigm shift characterised by the move of processing components close to the data.

As shown in the heat-map picture in Fig. 1

In the second half of 2019, derived from GSSC's consolidation in the community, a sustained increase in the level of access has triggered the introduction of hardware and network upgrades. This effect is shown in the snippets in Fig. 2 – 4 below comparing volume and number of IGS files downloads between October and 2019

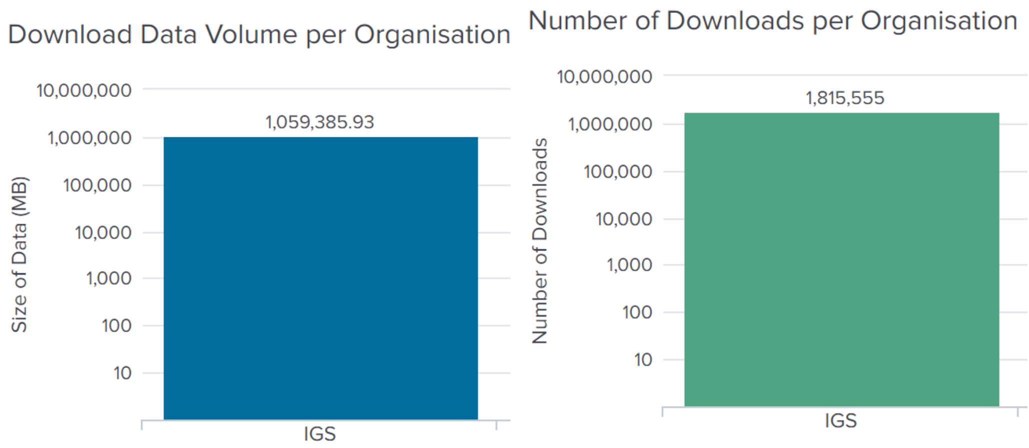

Figure 2: Volume and Number of IGS File Downloads in October 2019

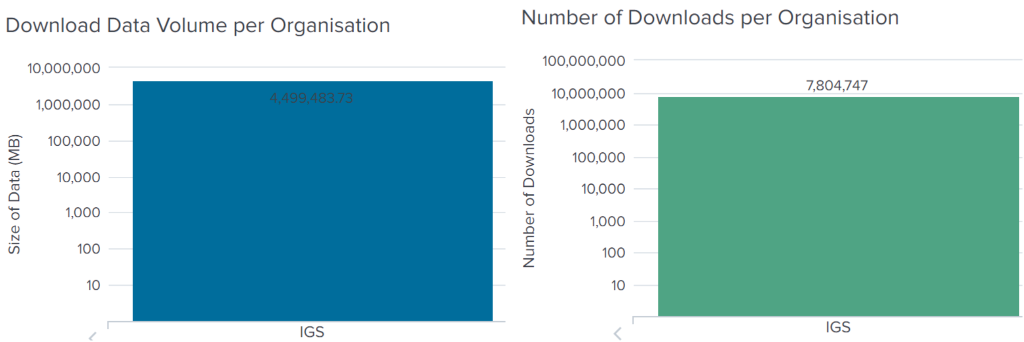

Figure 3: Volume and Number of IGS File Downloads in 2019

Figure 4: Volume and Number of IGS File Downloads per Collection in 2019

4 Planned 2020 Activities

Due for its first release into public operations during Q2-2019, GSSC's GNSS Science Exploitation and Preservation Platform has the potential to redefine delivery of GNSS data and services, enabling novel research and collaboration opportunities. Hence GSSC activities during 2020 will pivot around this first release and its successive enhancements in order to deliver:

- Advanced Data Discovery services.
- Advanced Data Analysis services based on JupyterLab.
- Advanced Workspace services.
- Evolution of GSSC's logging and monitoring systems.
- Evolution of GSSC's collections.
- Evolution of GSSC's experimental archive for GNSS Space Users Data.

WHU Data Center
Technical Report 2019

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1 Introduction

Wuhan University has joined as an IGS Global Data Center since 2015. The IGS Data Center from WHU has been established with the aim of providing services 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 accessible at WHU Data Center.

The activities of WHU Data Center within the IGS during 2019 are summarized in this report, which also includes recent changes or enhancements made to the WHU Data Center.

2 Access of WHU Data Center

In order to ensure 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/).

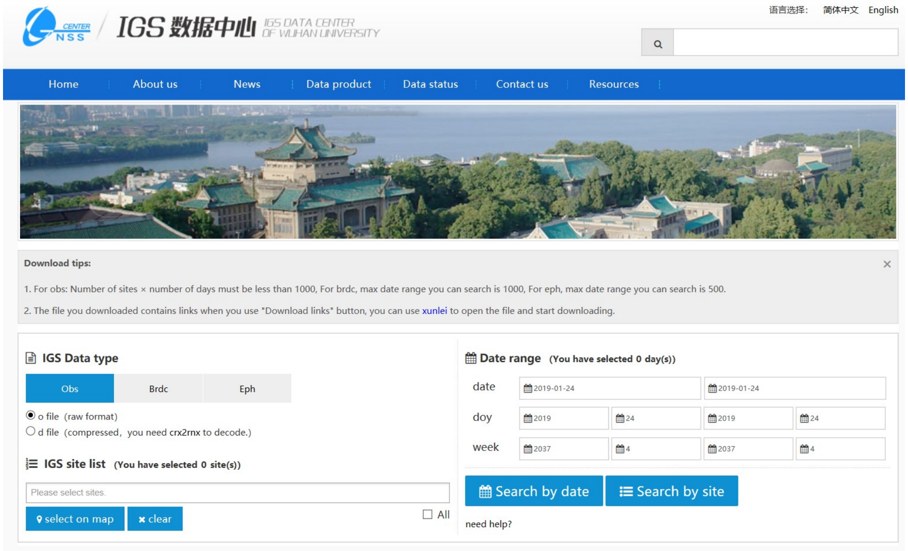

Figure 1: A snapshot of the website of WHU data center for data and products provision.

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

- 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: orbits, 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 has released 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 significant improvement of orbit predictions and error reduction for user applications.

4 Monitoring of WHU Data Center

WHU Data Center provides data monitoring function to display log information such as online user status, the arrival status of data and products, and the status of user

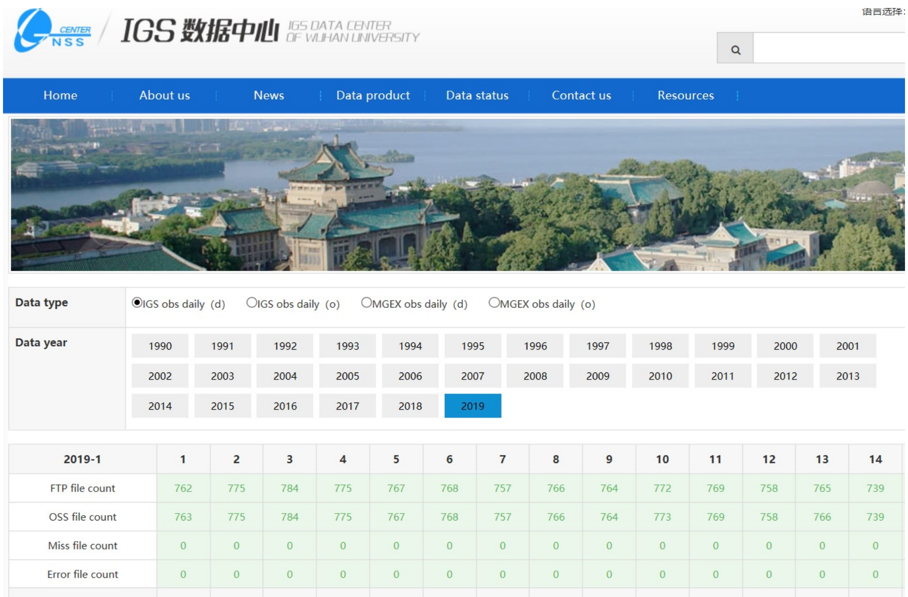

Figure 2: Data and products monitoring of WHU data center.

downloading in real time. It can display real-time data downloading and data analysis related products graphically, 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 routinely compare the daily data, hourly data and products with those in CDDIS. If one data file is missing, we will redownload it from CDDISs. Figure 2 shows the status of daily observation.

BKG Regional Data Center Technical Report 2019

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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 which is part of the EUREF or GREF network.

A basic 'REST Web Service' is provided for retrieving metadata on files or stations (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 17.5 million files are stored in the GDC with approx. 6.5 TByte of storage needed. We are facing with approx. 100000 uploads and 1000000 downloads per day. There was an increase in number of downloaded files of 30% with respect to 2018. The volume of downloads increased from 110 GB to 130 GB also. The percentage of correct downloads is stable at 90% in 2019. The full number of users may reach 24000 per hour, with approx. 140 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 (Weber et al. 2005). Since 2008, BKG is offering the so-called Professional Ntrip Caster which is used by many organizations and companies around the globe and which is updated and improved when necessary. BKG is maintaining various broadcasters for global, regional and national purposes (IGS, EUREF, GREF). BKG's caster are not running 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. For example, 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 2019):

- On the mgex-ip caster (http://mgex.igs-ip.net) we are providing real-time data of approx. 118 streams. Almost half of the streams, 53, 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. On the MGEX caster, only two RTCM streams are coming directly from the receiver.
- On the euref-ip caster (http://www.euref-ip.net) we are providing approx. 178 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. 244 data streams (compared to 216 last year) in RTCM3.0/1/2/3 format. Meanwhile, 188 MSM streams are coming directly from the receiver. 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. 54 data streams in RTCM3.0/1/2 format. These streams divide in 46 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

BKG is monitoring the availability of the data streams of its casters using a dedicated web page (https://bkgmonitor.gnssonline.eu). Color-coded, the monitor shows the availability of each stream, the duration since the last interruption, the percentage of outages per day and month as well as the number of connections per day and month. In addition, one can investigate a table for each data stream showing the history of outages, interesting for users looking for data streams with as much as possible un-interrupted availability.

Besides the monitoring of the orbit and clock correction streams which is mainly done by the IGS Real-Time Coordinator during his 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 almost unchanged on a high level of approx. 600 requests per year. 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 3000 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 1). Since several streams have been moved from the experimental MGEX to the operational IGS caster (see section 3.3), there is an increase for download from the latter one and a decrease in usage of the mgex-ip caster. In 2019 there was a remarkable increase in listening to the igs-ip caster, almost doubling the bandwidth for the usage of the IGS real-time streams. To keep the number of listeners and the amount of downloading almost constant, requests for registration coming from a region where other IGS casters are running, are redirected to the respective providers.

For the EUREF, IGS and MGEX caster we have a mean upload of 15, 20 and 20 GB per day for each caster and a download of 90, 300 and 120 GB per day, resp. The reduction of sent data of the MGEX caster, however, is much smaller than the increase from 150 GB to more than 300 GB per day for the IGS caster. For the PRODUCTS caster, finally, we have a smaller upload of 1 GB per day and a download of 50 GB per day. This sums up to a traffic of more than 630 GB per day for the four caster – compared to 450 GB at the end of last 2018.

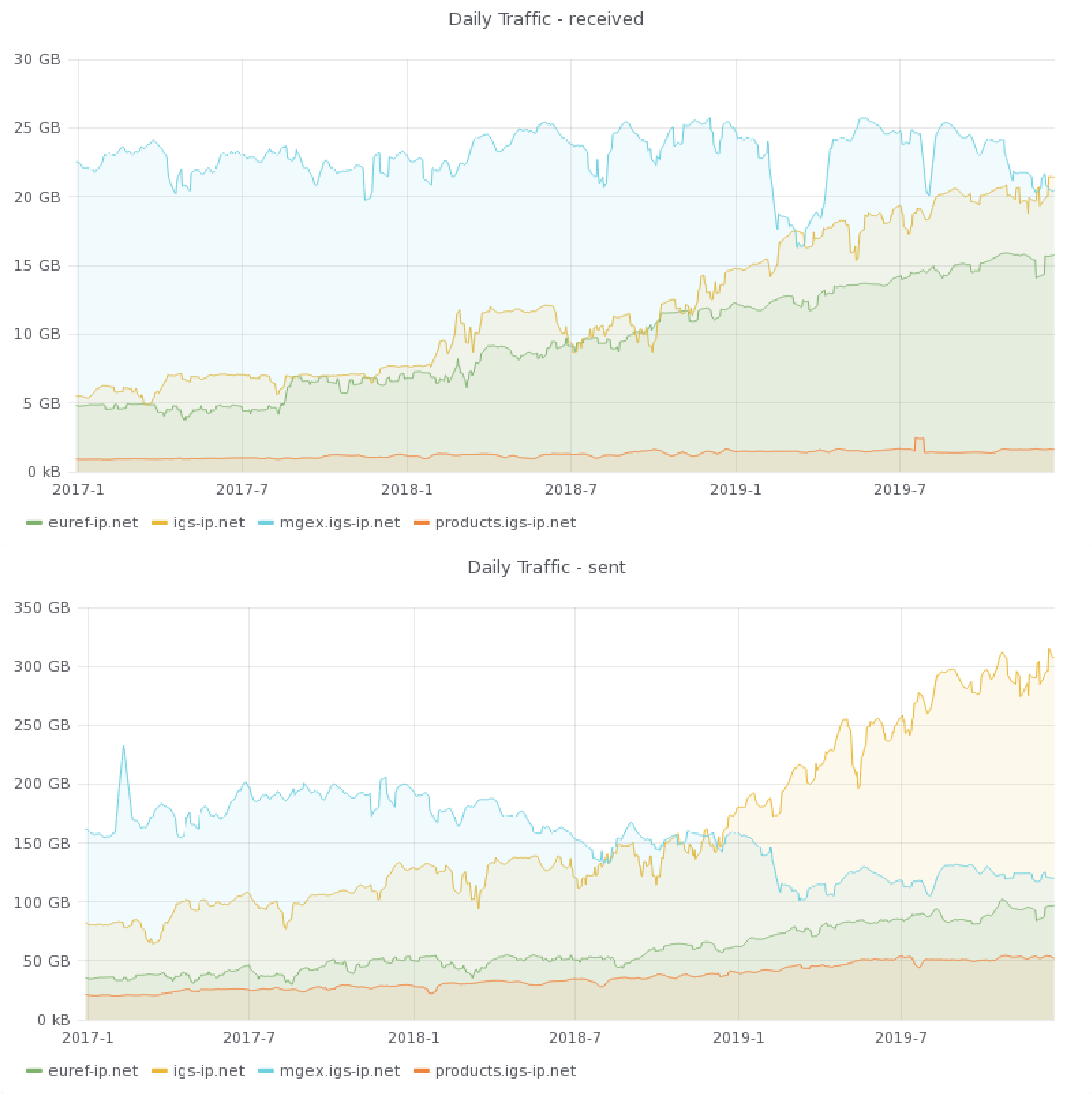

Figure 1: Daily received (i.e., upload to BKG, top) and sent (i.e., download from BKG) data volume at the BKG Broadcasters from 2017 to 2019.

4 Future Plans

In the IGS Real-Time WG the discussion on changes regarding the naming of the product streams is ongoing. Although the running system with the five character names in the form ‘CLKmn’ allows an easy and quick access for the experienced user, 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. Therefore, a new scheme with ten characters is under discussion. It will be introduced in early 2020 and for a certain time span the old names will be still available. End of the year the first product streams with long names were introduced for the new IGS RT Analysis Centre CAS, named SSRA00CAS0 and SSRC00CAS0.

To ensure an as much as possible correct download (see section 2.5), the number of simultaneous users of the GDC was limited to 190. A la longue, this number might not be sufficient. An improved mechanism to fulfil the user's need is under investigation.

The fundamental IT consolidation process within the German federal government which has been described in reports of the last two years, has been further delayed and, therefore, not been finalized in 2019. The impact on almost all activities of BKG is still not fully foreseeable.

5 Publications

M. Goltz, E. Wiesensarter, W. Söhne, 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)

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Horváth T. Alberding GNSS solutions supporting Galileo 3rd EuroGeographics PosKEN Meeting, Prague, Czech Republic 2016

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

RTCM Standard 10403.3 Differential GNSS (Global Navigation Satellite Systems) Services – Version 3 RTCM Paper 141-2016-SC104-STD

GA Regional Data Centre IGS Technical Report 2019

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1 Introduction

Geoscience Australia (GA) is a regional data centre for the IGS and the primary data centre for the Asia-Pacific Reference Frame (APREF) project. The data centre consists of a GNSS data repository, real-time broadcaster and a site metadata database.

The aim of the data centre is to deliver instant, accurate and reliable positioning information to users across the Asia-Pacific region. To achieve this the data centre team have been working to improve data access, data accuracy and data automation.

During 2019 the data centre team continued the migration of the systems and services on to Amazon Web Services (AWS). This transition has so far improved how users access the datasets through the introduction of secure end-points and a web UI, streamlined data workflows through reducing duplication and improved availability through scalable infrastructure.

2 GNSS Data Repository

2.1 Description

The GA GNSS data repository contains RINEX data from over 1000 continuously operating GNSS reference stations. The dataset is made up of the standard IGS daily, hourly and high-rate RINEX files, including navigation and meteorological RINEX files for most stations. The dataset stretchs from 1992 until present day and is growing by approximately 28,000 RINEX files per day.

The GA GNSS data repository is built on a highly-available event-optimised database. The event-database stores data as an append-only series of immutable events. The stored events are all the interactions the system makes with the RINEX files, such as submission, normalisation, metadata validation and correction. Using immutable and append-only events system integrity is enforced and a reproducible ledger for each RINEX file provided. All data files are stored in AWS Simple Storage Service (S3) and archived for prosperity at GA.

2.2 Access and Usage

All RINEX files are available online. Access to the GA GNSS data repository is possible via FTP, API and web user interface. Access is free and does not require a user account.

1. FTP access is via `ftp.ga.gov.au/geodesy-outgoing/gnss/data/`.
2. Information on the secure API can be found at `data.gnss.ga.gov.au/docs/`.
3. The web user interface can be viewed at `data.gnss.ga.gov.au`.

3 Real-Time Broadcaster

3.1 Description

GA oeparates the AUSCORS real-time broadcaster. The broadcaster runs on AWS, where the load is balanced across two identical high-availability servers. Both servers are running the latest version of the BKG Professional NTRIP Caster software.

The AUSCORS broadcaster provides access to 230 data mountpoints and 26 product mountpoints. Data streams are broadcast in either RTCM 3.1 or RTCM 3.2 format over NTRIP. Information on the data streams is available via the sourcetable and station metadata through the site metadata database `gnss-site-manager.geodesy.ga.gov.au`.

3.2 Access and Usage

Access to the AUSCORS broadcaster requires a user account. Accounts are provided free of charge and at the moment allow unrestricted access to all data and product streams. Data and product streams can be accessed and decoded by all common NTRIP clients and GNSS receivers. During 2019 we saw access from over 200 different NTRIP clients.

1. To register for an account visit `auscors.ga.gov.au/registration`.
2. To access data and product streams connect to `auscors.ga.gov.au:2101`.

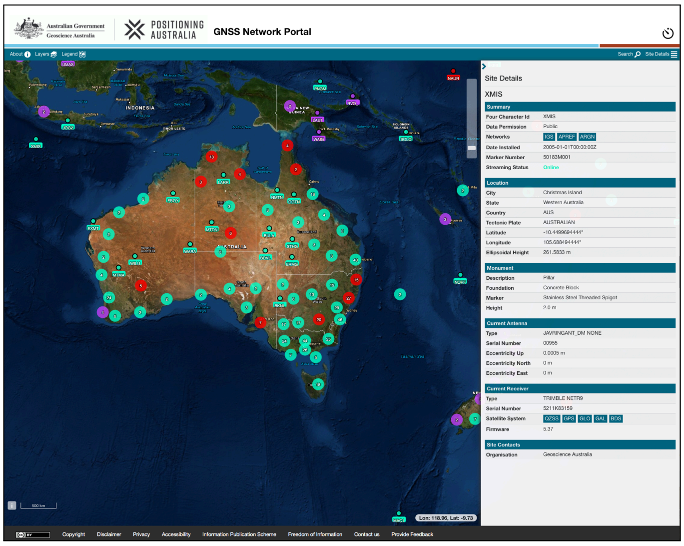

Figure 1: The GA GNSS network web portal (portal.gnss.ga.gov.au) indicates the status of the real-time data streams and provides links to station metadata and data products.

At the end of 2019 there were 1170 registered users to the AUSCORS broadcaster, this was double the number at the beginning of the year. These users equate to approximately 5000 active connections (listeners) at any point in time and over 20 Tb of data transfer per month.

4 Planned Features for 2020

Over the next 12 months the data centre team intend to:

1. Complete the migration of the GNSS data centre to AWS.
2. Usability improvements to the GNSS data portal and applications.
3. Transition from RINEX 2 to RINEX 3 as the primary data product.
4. Commence development of a new open source real-time broadcaster.
5. Setup of an experimental real-time broadcaster end-point using modern Internet of Things protocols.

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2019

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1 Introduction

The IGS Antenna Working Group (AWG) 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 Availability of antenna calibrations

The igs14.atx contains mainly robot calibrations covering GPS and GLONASS. In the last years the missing Galileo antenna pattern for the receiver antennas became a limiting factor especially taking into account that GSA disclosed meta data on the Galileo satellites including phase center corrections (PCO) and phase variations (PV) (GSA 2019). To overcome this issue the IGS AWG started in 2018 a call for multi-GNSS calibrated antenna pattern and received many contributions of chamber calibrated pattern covering all frequencies (IGSMAIL #7639 and EUREFMAIL #9309). During the preparation of the IGS repro3 campaign Geo++ made their multi-GNSS type mean antenna calibrations available leading two independent sets of antenna calibrations (Villiger 2019; Dach et al.

Table 1: IF Galileo - GPS (PCO up [mm]) from various sources

		ETH Zürich	IGS14 (L1/L2)	BONN
JAV_GRANT-G37	NONE	6.7	-1.3	
JAV_RINGANT_G3T	NONE	-10.6	+1.2	-7.6
SEPCHOKE_B3E6	SPKE	-8.0	+4.7	
TRM57971.00	NONE	-2.9	-1.7	-5.2
		Geo++	IGS14 (L1/L2)	BONN
LEIAR25.R4	LEIT	-3.6	+1.09	-2.45

Table 2: Difference of the Z-PCO of between robot and chamber calibrations (IF, GPS: L1/L2, GLONASS: L1/L2, Galileo: E1/E5a) in mm. Datum: Zero-mean condition over PV and constant term removed. ROB: Robot calibrations, CHA: chamber calibrations

Antenna		GPS	GLONASS	Galileo
ASH701945C_M	NONE	5.28	-2.32	**6.86**
JAVRINGANT_DM	NONE	-2.63	-3.31	-1.46
..				
LEIAR20	LEIM	5.04	**5.49**	3.69
LEIAR20	NONE	3.41	4.92	3.32
LEIAR25.R3	LEIT	**9.03**	3.20	6.03
TRM55971.00	TZGD	-2.55	-4.95	-2.63
TRM59800.00	NONE	1.88	1.55	-0.85
Mean value		**0.53**	**-0.65**	**0.43**

2019). In addition to the two main sources, ETH Zürich published multi-GNSS antenna calibrations for four individual antennas (Willi and Rothacher 2019).

Table 1 shows a comparison of the PCOs between the three antenna calibration provider made before the IGS AC Workshop 2019 in Potsdam. For the comparison all antenna calibrations have been aligned to a common datum (zero-mean condition over the PV and removal of a constant term in the PV). At that time Geo++ made a first antenna calibration available for first tests. Later Geo++ provided then the full set of multi-GNSS antenna calibrations which were then used for a successful preliminary test to address the feasibility and potential extend the IGS repro3 from GPS and GLONASS to a triple-system solution including Galileo (Rebischung et al. 2019).

Table 2 lists the IF PCO differences between the complete robot and chamber calibrations for selected antenna types covering all three systems (GPS, GLONASS, and Galileo). On average the PCO's vary around 1 mm, however, this depending on the antenna type. In addition, Fig. 1 shows the PV differences for the IF for GPS and Galileo for two selected antennas.

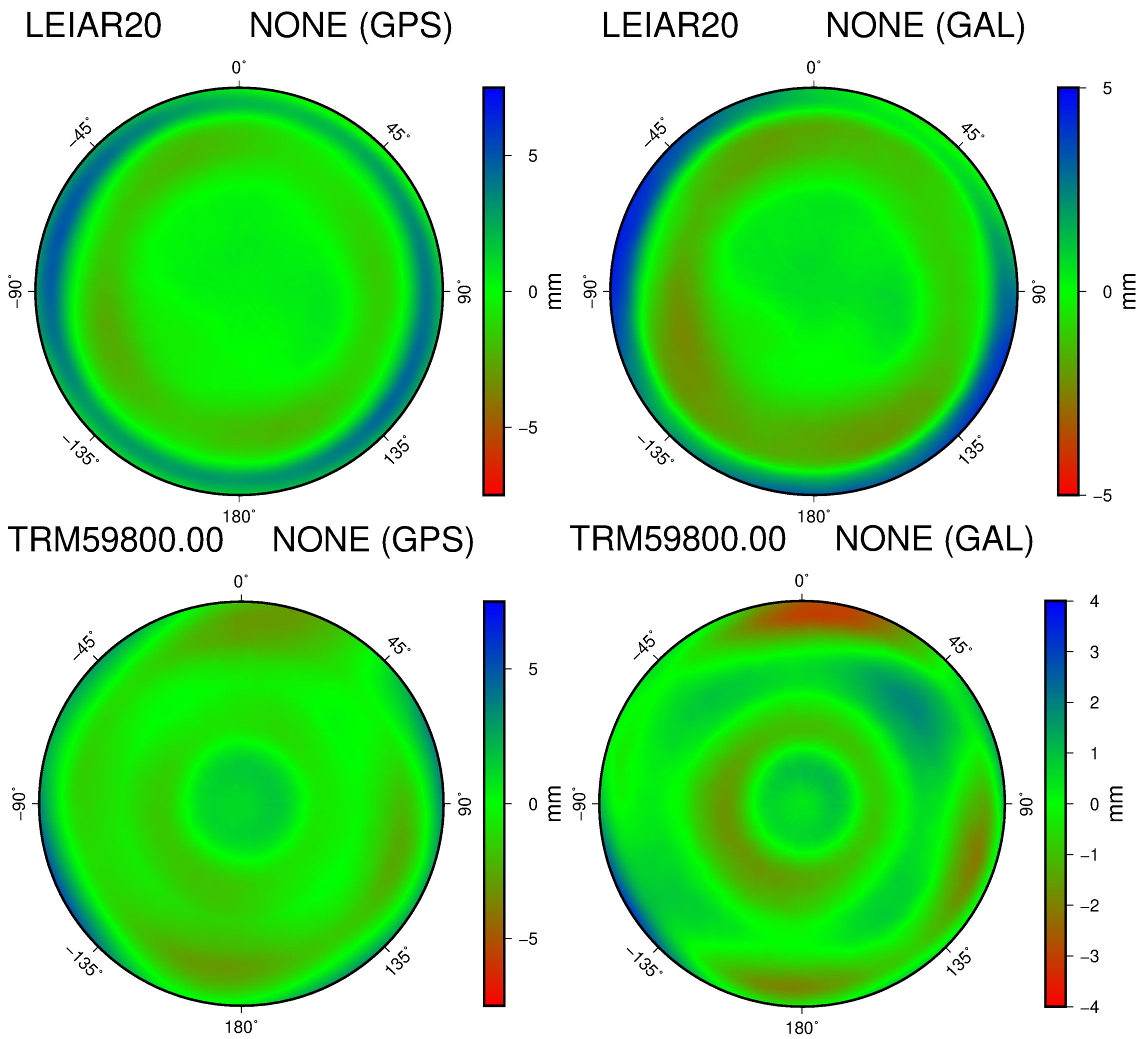

Figure 1: IF-PV differences between robot and chamber calibrations for the LEIAR20 and TRM59800 antenna without dome (robot-chamber). The datum definition of the pattern have been aligned (zero-mean condition and removal of a constant offset).

3 Antenna calibrations for repro3

For the repro effort of the IGS it was essential to assess the consistency of the antenna calibrations for Galileo measurements in order to include this system as well. Changing the IGS contribution for the next ITRF solution from a GPS and GLONASS to a triple-system solution adding Galileo would potentially allow GNSS contribute to the ITRF scale determination (Villiger et al. 2020). Galileo has meanwhile reached its full constellation and, compared to GPS and GLONASS, their satellite antenna calibrations were disclosed by GSA (phase center offset (PCO) and phase variations (PV). With the availability of receiver antenna calibrations for the Galileo frequencies from chamber and robot calibrations the situation was quite promising. Before the final decision could be made five ACs processed a two year test (2017-2018) to validate the feasibility of including Galileo and testing compatibility of the Galileo calibrations with the GPS and GLONASS ones (Rebischung et al. 2019; Rebischung 2020).

Introducing calibrated patterns for the ground and space segment allows to estimate a GNSS scale. Because only calibrations for Galileo satellite antennas are available, the GPS and GLONASS PCOs had to adjusted accordingly. In the IGS14 ANTEX file the PCO were estimated using the scale introduced by the ITRF2014. By estimating a system-wise scale offset for the PCOs of GPS and GLONASS it is possible to align those to GNSS to the scale induced by Galileo.

3.1 Satellite calibrations

The test period 2017-2018 was processed by five ACs (CODE, ESA, GFZ, GRG, TUM) and submitted to the IGS Reference Frame Coordinator. The results was presented during IGS AC teleconference (September 10. 2019) and it was decided to use the Galileo chamber calibrations and realign the PCOs for GPS and GLONASS to the scale induced by the Galileo PCOs. Therefore, a common PCO offset in z direction for all GPS and for all GLONASS satellite were estimated and their values accordingly adjusted. The IGSR3 ANTEX file reflects the Galileo induced scale.

3.1.1 GPS

Changes w.r.t. IGS14 ANTEX file:

- Adjustment w.r.t. the Galileo scale: Δz = -16.0cm
- PV and PCO have been verified using the latest data sets available

3.1.2 GLONASS

The PCO of the GLONASS satellites have been revised and jumps in the time series bigger than 10cm in the z-component taken into account. In addition, PCO jumps in x and y ($>$ 10cm) have been considered (Dach et al. 2019): Following modification have been made

- Adjustment w.r.t. the Galileo scale: Δz = -15.7cm
- Update of z-PCO based on COD/ESA/GFZ for SVN R852, R853, R854, R855, R856, and R857
- Jumps in the x- and y-PCO component: R701, R714, R723, R725, R736, R737

3.1.3 Galileo

For Galileo the chamber calibrated values, released by GSA (GSA 2019), have been used. Note that for satellite E102 the chamber calibrated values had big differences during the tests and has been adjusted accordingly (Rebischung 2020).

3.2 Receiver calibrations

The IGS was by mid of 2019 in the comfortable position to have to sets of multi-GNSS calibrations available to chose from for the IGS-repro3. The first set, provided by the University of Bonn, of chamber calibrated receiver antenna patterns was made available to the IGS in 2018 and was hence used to analyze the potential of the disclosed Galileo satellite antenna PCO and PVs. After encouraging results of the test scenarios processed by CODE, ESA, and GFZ in preparation of the IGS AC Workshop 2019 in Potsdam Geo++ announced and released their multi-GNSS calibrations for the Rerpro3. Finally, the ACs concluded that the usage of the robot calibrations as the main source shall be kept as, in particular for older antennas, only robot calibrations are available. Nevertheless, chamber calibrations may be used to add additional Galileo calibrations to the repro3 data set (igsR3.atx). Figure 2 shows the network of Galileo tracking stations with and without available E5 calibrations. The repro3 includes 503 sites tracking Galileo out of which 384 are equipped with antennas with available multi-GNSS calibrations. For more than 75% of the Galileo tracking sites corresponding Galileo antenna patterns are available. Therefore, Galileo observations from sites without the corresponding calibrations can be omitted for the reprocessing.

503 and with calibrations: 384

The multi-GNSS calibrations included in the repro3-ANTEX file are listed in Tab. 3.

Table 3: New multi-GNSS calibration pattern and number of station tracking Galileo with the corresponding antenna as of mid 2019

Antenna / Radom	Number of sites	Provided by
ASH700936D_M SCIS	1	Geo++
ASH701945C_M NONE	7	Geo++
ASH701945E_M NONE	7	Geo++
ASH701945E_M SCIS	0	Geo++
ASH701945E_M SCIT	1	Geo++
CHCC220GR2 CHCD	1	Geo++
JAVRINGANT_DM NONE	23	Geo++
JAVRINGANT_DM SCIS	30	Geo++
JAVRINGANT_G5T NONE	9	Geo++
JAVRINGANT_G5T JAVC	0	Geo++
JAV_GRANT-G3T NONE	2	Geo++
LEIAR10 NONE	13	Geo++
LEIAR20 NONE	7	Geo++
LEIAR20 LEIM	4	Geo++
LEIAR25.R2 NONE	0	Geo++
LEIAR25.R3 NONE	12	Geo++
LEIAR25.R3 LEIT	42	Geo++
LEIAR25.R4 NONE	12	Geo++
LEIAR25.R4 LEIT	35	Geo++
LEIAT504 NONE	2	Geo++
LEIAT504GG NONE	5	Geo++
SEPCHOKE_B3E6 NONE	5	Geo++
SEPCHOKE_B3E6 SPKE	1	Geo++
TPSCR.G3 NONE	5	Geo++
TPSCR.G3 SCIS	4	Geo++
TPSCR.G3 TPSH	2	Geo++
TPSCR.G5 TPSH	4	Geo++
TPSCR.G5C NONE	1	Geo++
TRM115000.00 NONE	17	Geo++
TRM29659.00 NONE	4	Geo++
TRM55971.00 NONE	14	Uni Bonn
TRM55971.00 TZGD	0	Geo++
TRM57971.00 NONE	44	Geo++
TRM57971.00 TZGD	3	Geo++
TRM59800.00 NONE	47	Geo++
TRM59800.00 SCIS	32	Geo++
TRM59900.00 SCIS	2	Geo++

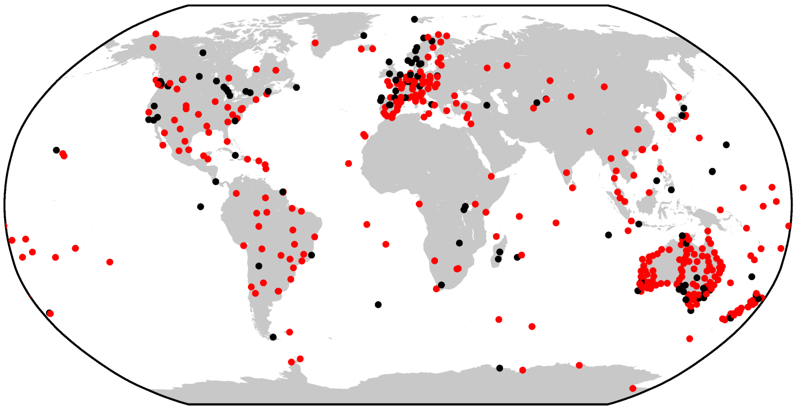

Figure 2: Repro-3 stations tracking Galileo (as of mid 2019). Red dots denotes sites with Galileo calibrations for their antennas and black dots antennas without Galileo pattern.

4 Updates and content of the antenna phase center model

Table 4 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 4: Updates of the phase center model `igs14_wwww.atx` in 2019 (`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
2086	31-Dec-2019	7879	`Added R859 (R04)`
			`Decommission date: R742 (R04)`
			`Added SLGAT45101CP SLGZ`
2082	10-Dec-2019	7871	`PRN/SVN assignment modified:`
			`C45 (C222 to C223)`
			`C46 (C223 to C222)`
			`Added AERAT1675_542E NEVE`
			`JAVTRIUMPH_3A NONE`
2080	22-Nov-2019	7860	`Added C224 (C40)`
			`Added AOAD/M_T_RFI_T NONE`
			`AOAD/M_T_RFI_T SCIS`
2076	24-Oct-2019	7843	`Added G074 (G04), R716 (R27), C104 (C59),`
			`C020 (C18),C220 (C38), C221 (C39),`
			`C222 (C45), C223 (C46)`
			`Decommission date: G036 (G04), C104 (C18)`
2074	09-Oct-2019	7836	`Added R723 (R10)`
			`Decommission date: R717 (R10)`
2073	03-Oct-2019		`Added CNTT30 CNTS`

			CNTT300+ CNTS
			CNTAT340 CNTS
2072	24-Sep-2019		Added GINCYF90 NONE
			TRM59800.99 NONE
			TRM59800.99 SCIT
2070	13-Sep-2019		Modified radom from NONE to CNTS:
			CNTT300 CNTS
			CNTAT350 CNTS
			CNTAT500 CNTS
2062	17-Jul-2019	7803	Added G036 (G04)
			Decommission date: G074 (G04)
2061	11-Jul-2019	7798	Adjusted ending time for C104 (C32)
			Added CNTT300 NONE
			CNTAT350 NONE
			CNTAT500 NONE
2060	03-Jul-2019	7792	Added R858 (R12)
			Decommission date: 723 (R12)
			Updated PCO/PV for E215-E222 with
			chamber calibrations
			Adjusted starting and endig times: BEIDOU
			Added JAVGRANT_G5T+GP JVSD
			JAV_GRANT-G3T+G JVSD
			STXSA1500 STXG
			STXSA1800 STXS
			TRM115000.00+S SCIT
			TRM159800.00 SCIT
2056	06-Jun-2019	7782	Update of Beidou-2 PCOs
			Beidou-3 satellites added
			Added C018 (C03), C101 (C31), C102 (C19,C33),
			C102 (C57), C103 (C28,C58), C103 (C58),
			C104 (C32), C201 (C19,C47), C202 (C20),
			C203 (C27), C204 (C48), C205 (C22),
			C206 (C21), C207 (C29), C208 (C30),
			C209 (C23), C210 (C24), C211 (C26),
			C212 (C25), C214 (C33), C215 (C35),
			C216 (C34), C217 (C59), C218 (C36),
			C219 (C37)
			Added TWIVC6150 NONE
			TWIVC6150 SCIS
2045	21-Mar-2019		Added GMXZENITH40 NONE
			LEIGG04 NONE
2038	30-Jan-2019	7753	Updated PCO and PV for G074 (G04)
			Added HITAT45101CP HITZ
2035	11-Jan-2019	7724	Added G074 (G04)
			Decommision date: G036 (G04)

Table 5: Calibration status of 509 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%
JAN 2020	**igs14.atx:**	**93.5%**	**1.8%**	**4.7%**

5 Calibration status of the IGS network

Table 5 shows the percentage of IGS tracking stations with respect to certain calibration types. For this analysis, 509 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general/`) were considered. At that time, 97 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 2019. The overall situation regarding the stations with state-of-the-art robot-based calibrations is similar to the one from 2018. After an increasment of 6% from igs08 to igs14 in 2017 another 2% of the IGS stations are covered by robot calibrations. In 2019 the situation has slightly improved but is very similar to the situation a year before.

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Bias and Calibration Working Group Technical Report 2019

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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 other already well established GNSS, such as 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 2019

- 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 (Villiger et al. 2019a). As part of this major revision, processing steps relevant to bias handling and retrieval were reviewed and completely redesigned. In 2017,

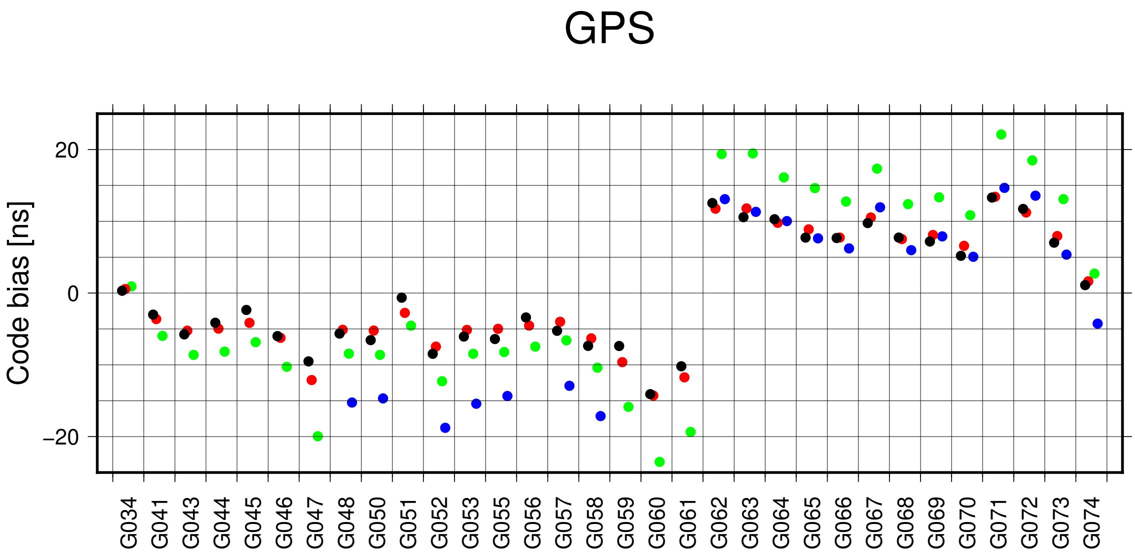

Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2020. Note that G034 corresponds to a Block IIA; G041–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations and G074 corresponds to the first Block IIIA. Legend: C1C (black), C1W (red), C2W (green), "C2" (blue).

further refinements could be achieved concerning bias processing and combination of the daily bias results at NEQ level. Daily updated 30-day sliding averages for GPS and GLONASS code bias (OSB) values coming from a rigorous combination of ionosphere and clock analysis are 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`

- Starting with GPS week 2072, CODE has extended its rapid and ultra-rapid solutions from a two-system to a three-system processing: GPS, GLONASS, and Galileo (as announced in (Villiger et al. 2019b)). Galileo is also considered in the rapid clock analysis (with fixed ambiguities for GPS and Galileo) as well as in the rapid ionosphere analysis at CODE. As a consequence of this, corresponding Galileo bias results (combined OSB results from clock and ionosphere analysis) could be incorporated into to the CODE.BIA product.
- CODE monthly OSB values for GPS C1W and C1C (that are recommended to be used for repro-3) are made available in Bias-SINEX V1.00 at
`ftp://ftp.aiub.unibe.ch/CODE/CODE_MONTHLY.BIA`
`ftp://cddis.gsfc.nasa.gov/gnss/products/bias/code_monthly.bia`
Note that the 1994-1999 period is not yet covered in this file.
- It should be mentioned that the current GPS C1W-C1C DSB (P1-C1 DCB) prod-

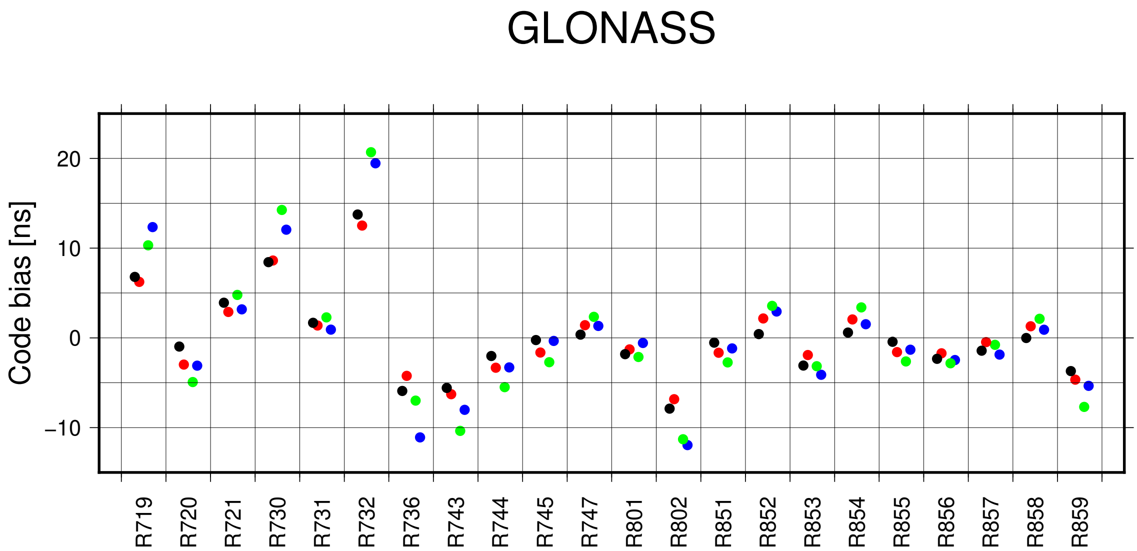

Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2020. Note that R719–R747 and R851–R859 correspond to GLONASS-M; R801–R802 correspond to GLONASS-K1 satellite generations. Legend: C1C (black), C1P (red), C2P (green), C2C (blue).

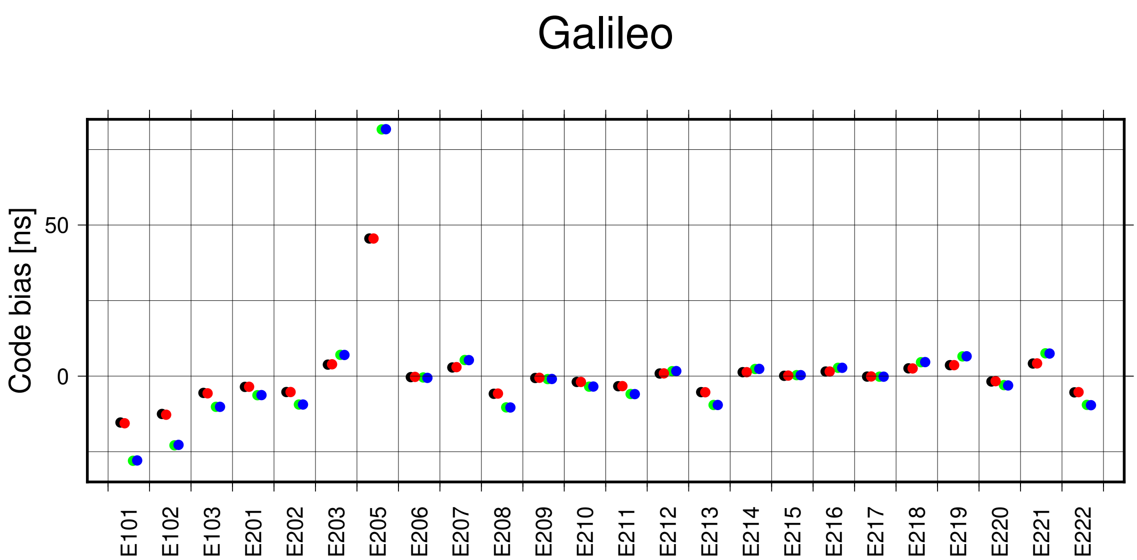

Figure 3: Observable-specific code bias (OSB) estimates for Galileo code observable types (using the RINEX3 nomenclature) and Galileo SV numbers, computed at CODE, for January 2020. Legend: C1X (black), C1C (red), C5Q (green), C5X (blue).

uct 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.
- 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 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 inter-system 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/y2019/odata2_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata2_d335_sat.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_gnss_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_gps_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_glonass_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_galileo_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_beidou_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_qzss_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2019/odata3_sbas_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

Code 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
```

Phase biases

```
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.

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 Bias-SINEX Format Version 1.00

The latest Bias-SINEX format description document (Schaer 2018) may be found at `ftp://igs.org/pub/data/format/sinex_bias_100.pdf`

Schaer et al. (2018, 2019) 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. 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/Galileo clock product) for all involved code and phase observations (and accordingly derived linear combinations, such as the Melbourne-Wübbena or the ionosphere-free LC).

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Schaer, S., A. Villiger, 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.

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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. Journal of Geodesy, Springer Berlin Heidelberg, first online 10 May 2019. DOI 10.1007/s00190-019-01262-w.

Villiger, A. et al. (2019): IGSMAIL-7832: Announcement CODE IGS RAPID/ULTRA products including Galileo. https://lists.igs.org/pipermail/igsmail/2019/007828.html.

Clock Products Working Group Technical Report 2019

M. J. Coleman, Chair

1 Introduction

Recently, there are several activities that have taken place or are ongoing in the Clock Products Working Group (CPWG). These include working towards a multi-GNSS clock combination for the IGS core products which is expected to involve contributions from other working groups and IGS coordinators. The Clock Products will also see the release of the IGS v2.2 timescale with the repro3 production that is on-going for the ITRF2020. There have been some updates to this working group's charter which entails additional membership. Details regarding the status of the existing products are also outlined in the contained report.

2 Working Group Charter Update

The CPWG came to an agreement for a number of updates to its charter this year. The key objectives for these updates were: (1) expand the mission of the WG to include multi-GNSS clock solutions and analysis; (2) widen and renew AC membership to the CPWG; and, (3) clarify the Clock Product Coordinator role. The following summaries explain each update in further detail.

2.1 Multi GNSS Clock Products

The core IGS product clock combined solutions continue to provide only GPS among the satellite clocks. A multi-GNSS combination will require multi-GNSS clock solutions from analysis centers and developments in this arena are already progressing. The CPWG has therefore added this mission to its charter as it assembles both the main providers and users of the core clock products.

The charter update includes a new statement recommending that “the CPWG should also keep close contact of its activities with other relevant IGS WGs. This communication should include, but is not limited to: the Bias and Calibration WG and the PPP–AR WG. If possible, the CPWG membership should include members of these WGs." Issues arising in biases, clocks and PPP can certainly affect one another but this will likely gain even more importance for solutions in a multi-GNSS context.

2.2 Membership

This WG consists of ex–officio members (those holding other roles within the IGS); representative members (specifically from Analysis Centers or IGS Timing Sites); and at-large members. Representative members are often appointed by the Analysis Center or IGS site to be representatives to the working group. The collection of at–large members is intended to fill or expand the expertise base of the group based on current or on-going activities. The group also strives to maintain a diverse membership both academically and geopolitically.

Table 1 shows the current membership as of December 2019. New members are identified with a dagger symbol. There are a few important points to note.

- Maorong Ge was formerly the representative from GFZ but his work is no longer commensurate with that of this WG. We anticipate a new candidate from GFZ this year.
- Daniele Rovera is an outgoing member of this WG as he has retired from the Paris Observatory (IGS site OPMT) in February 2020.

2.3 Clock Products Coordinator

There was some confusion about the Clock Products Coordinator role and its distinction from the CPWG chair. This coordinator is responsible for ensuring continuous publication of the IGS’s core clock products in tandem with the Analysis Center Coordinator. This coordinator is appointed by the IGS Governing Board (GB) and is a voting member on the GB. The Clock Products coordinator also serves as the CPWG chair. Hence, the chair of this WG is determined by the Clock Products Coordinator appointment.

Updates to some official IGS documents will be required to eliminate the designation of *Timing Coordinator*. The Timing Coordinator and Clock Products Coordinator are the same role, but both of these phrases appear throughout IGS documents (most notably in the Term of Reference) and cause confusion. It was concluded by the WG and the Central Bureau (CB) that the name *Clock Product Coordinator* is the more appropriate name to keep.

Table 1: CPWG membership as of December 2019; † represents new member.

Member		Representing	Affiliation
Michael Coleman		Chair	US Naval Research Laboratory
Ken Senior		Previous Chair	US Naval Research Laboratory
Michael Moore		IGS ACC	Geoscience Australia
Gérard Petit		BIPM Rep to GB	BIPM Time Department
Allison Craddock	†	IGS Central Bureau Rep	Jet Propulsion Laboratory
Rolf Dach		AC Rep // COD	Astronomical Institute – Univ of Bern (AIUB)
Simon Banville	†	AC Rep // EMR	Natural Resources Canada
Igancio Romero		AC Rep // ESA	ESA / European Space Operations Center
Flavien Mercier	†	AC Rep // GRG	Centre National D'Etudes Spatiales (CNES)
Paul Ries	†	AC Rep // JPL	Jet Propulsion Laboratory
Thomas Herring		AC Rep // MIT	Massachusetts Institute of Technology
Sharyl Byram	†	AC Rep // USN	US Naval Observatory
Li Min	†	AC Rep // WHU	Wuhan University
Pascale Defraigne		IGS Site Rep // BRUX	Royal Observatory of Belgium
Ilaria Sesia		IGS Site Rep // IENG	INRiM
Daniele Rovera		IGS Site Rep // OPMT	Paris Observatory
Shinn Yan Lin		IGS Site Rep // TWTF	Chungwa Telecommunications
Stephen Mitchell	†	IGS Site Rep // USNO	US Naval Observatory
Patrizia Tavella		At Large Member	BIPM Time Department

3 Product Status

The IGS core clock products consist of combined solutions of clocks from all active GPS satellites and a collection of the IGS's ground network clocks. Deviations of the solutions remain under 30 ps across most ACs as noted in Table 2. Although the core products are presently GPS only, we endeavor to extend these to multi–GNSS over the coming years.

3.1 Analysis Center Solutions

The IGS final and rapid clock products are combinations of solutions from contributing IGS Analysis Centers. The RMS and standard deviation statistics as well as weight of each of Analysis Center (AC) solution is contained in Table 2. These statistics are determined daily by the IGS clock combination routine. The numbers presented here are an average over the years 2018 and 2019.

A number of observations has been cited in regards to these contributions and was discussed at the December 2019 splinter meeting. In particular, it was noted that:

Table 2: Quality of clock solution contributions from IGS Analysis Centers. Average RMS and Standard Deviation statistics over the 2018 and 2019 calendar years.

AC	Rapid Clock Product			Final Clock Product		
	Avg Daily RMS (ps)	Avg Daily StDev (ps)	Avg Daily Weight	Final RMS (ps)	Final Stdev (ps)	Final Weight
COD	125.7	10.5	24.8 %	103.7	7.0	22.7 %
EMR	104.2	19.9	11.7 %	122.6	16.2	10.3 %
ESA	197.2	11.1	22.6 %	201.6	8.3	21.6 %
GFZ	123.1	13.7	18.1 %	155.7	11.2	15.1 %
GRG				162.3	9.9	15.3 %
JPL	105.1	10.4	22.8 %	122.7	16.2	15.0 %
MIT				718.4	69.9	0.0 %
NGS	2166.2	976.6	0.0 %	2162.2	983.6	0.0 %
USN	164.9	77.3	0.0 %			
WHU	600.0	66.5	0.0 %			

- Scripps Institute (SIO) no longer contributes clock solutions.
- Wuhan University's (WHU) rapid solution was observed to cause instability in the rapid clock combination. That issue needs to be addressed over the next year so that the WHU rapid clock solution can help improve the weighted combination.
- CNES (GRG) is considering adding a rapid clock solution.

At the WG meeting in December, these was some discussion about progress towards multi–GNSS clock solutions from analysis centers. Each AC had a different response with GFZ, ESA, EMR, COD and WHU already committing GPS and GLO to their rapid solutions. It is expected that GAL clock will appear shortly among many solutions. Beidou solutions may take longer as its constellation has different orbit models that need to be considered. JPL informed the WG that its solution will remain GPS only until it is ready to commit all four global constellations in a multi-GNSS solution.

3.2 IGS Reference Timescales

The IGS timescale reference for both the rapid and final products maintain a continuous reference time for the IGS core products. These are computed daily with a Kalman Filter based timescale and processed in conjunction with the daily combination of the IGS AC solutions.

The timescales are steered to a median average of observable UTC stations each day. This entails utilizing IGS sites that participate in UTC and provide a timing signal to the designated IGS receiver that is consistent with the calibrated signal provided as its realization of UTC(k). Calibration measurements between the antenna phase center and clock on–time point are needed to ensure the correct offset is observed in the steering control. Table 3 contains a selection of stations that are regularly used for this purpose in both the rapid and final solutions. Calibration values can change from time to time as infrastructure is updated and replaced; those presented in Table 3 are current as of April 2020.

Table 3: IGS Sites serving as UTC(k) references for IGST reference.

Station ID		Calibration Value		No. Days in Combination	
IGS	BIPM	t_c / ns	BIPM CAL ID	2019 Rapids	2019 Finals
BRUX00BEL	OR5Z	203.36	1018–2017	365	365
IENG00ITA	IT10	-298.92	1014–2019	345	357
OPMT00FRA	OP02	290.83	1001–2018	52	361
WAB200CHE	CH04	216.06	1012–2016	355	344
PTBB00DEU	PT13	184.95	1001–2018	122	347
USN700USA	US07	210.96	1001–2018	348	364

The calibration reports and notices associated with the CAL IDs in Table 3 can be found in the BIPM database at the following website.

`https://webtai.bipm.org/database/calid_gnss.html`.

Figure 1 shows the estimated offset of the two IGS timescales with respect to UTC. These estimates are obtained using GPST as a pivot and assume that the broadcast GPST is near to the estimated GPST offset from UTC as published in CircularT.

4 Clock Rinex 3.04

Providers and users of the IGS clock products are all encouraged to utilize the Clock Rinex 3.04 format. This format was adopted by the IGS governing board at the 2017 Workshop in Paris. The key differences between version 3.04 and the more commonly used 3.00 version are:

- Additional characters added to site ID field allowing for A9 formatted names.
- Expanded definitions for GNSS system reference times and vehicle IDs;
- Modification of LEAP SECOND field and addition of LEAP SECOND GNSS field.

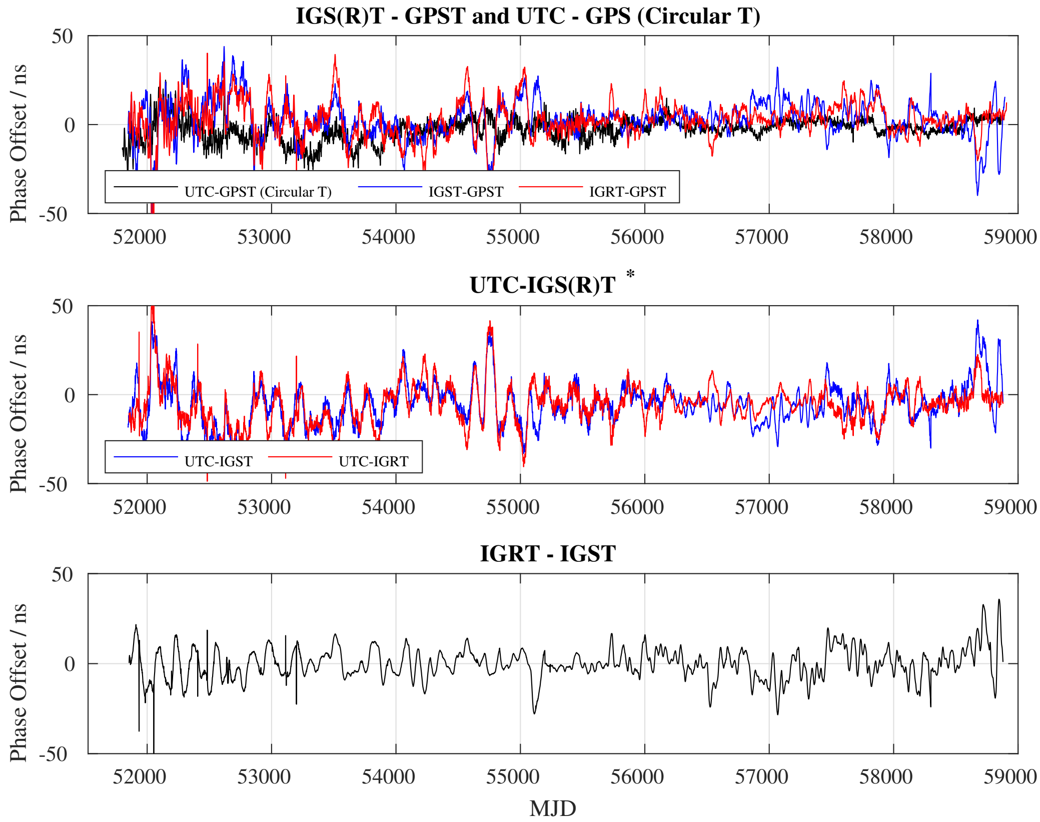

Figure 1: Estimated offset of IGS(R)T from UTC using GPST as a pivot reference.

4.1 Long Format Site IDs

With the adoption of 9-character site IDs (`YELL00CAN` versus `YELL`, for example), the Clock Rinex 3.04 format now has 85 characters across the file, as opposed to 80 in all previous versions. This format of Clock Rinex allows for both A4 and A9 site IDs, but use of A9 IDs is recommended for consistency among other product files. The expansion of the clock rinex record is detailed by the excerpt found in Figure 2. Note that satellite vehicles will remain in A3 format (G22, E05, C11, for example).

4.2 Leap Seconds

As the IGS's primary mission is the publication of GNSS data and computed products, it is most sensible that it incorporate leap seconds in a manner consistent with GNSS systems. Not all GNSS, however, have consistent architectures concerning leap seconds. The GPS program chose to align its timescale with UTC at the start of its service on 6 January 1980. As a result, GPST contains the 19 leap seconds that were installed up to that time, but

```
+-------------+-------------------------------------------------------+------------+
|TYP/EPOCH/CLK| - Clock data type (AR, AS, CR, DR, MS)                |  A2,1X,    |
|             |                                                       |            |
|             | - Receiver or satellite name                          |  A9,1X,    |
|             |   - Receiver name is the IGS 9-character or IGS       |    or      |
|             |     4-character designator                            |  A4,6X,    |
|             |   - Satellite name is the 3-character string as       |    or      |
|             |     defined in the documentation for file format      |  A3,7X,    |
|             |     Rinex v3.03 -- Section 3.5.                       |            |
|             |                                                       |            |
|             | - Epoch in specified system time (not local time!):   |            |
|             |     year (4 digits),                                  | I4,1X,     |
|             |     month,day,hour,min,                               | 4(I2,1X)   |
|             |     second                                            | F9.6,1X    |
|             |                                                       |            |
|             | - Number of data values to follow                     | I2,3X,     |
|             | - Clock data in the following sequence:               |            |
|             |   - Clock bias (seconds)                              | E19.12,2X  |
|             |   - Clock bias sigma [optional] (seconds)             | E19.12     |
+-------------+-------------------------------------------------------+------------+
```

Figure 2: Excerpt from Clock Rinex 3.04: format for a single record.

none of the leap seconds thereafter. The Galileo and QZSS programs chose to align their timescales (GALT and QZST, respectively) with GPST for consistency between systems. The Beidou program chose to align its timescale (BDST) with UTC at that start of its service, which came when 33 leap seconds existed. This approach echoed the methodology of the GPS program, but put GPST and BDST at different times. Further, GLONASS has a system time (GLOT) that incorporates all leap seconds, but aligns its timescale with local time in Moscow which puts its timescale in alignment with the UTC realization UTC(SU) + 3 hours.

For the history of its service, the IGS's clock rinex data records have been time-stamped in alignment with TAI – 19 sec (consistent with GPST). As multi-GNSS files become more prevalent and possibly clock product files from Beidou or GLONASS are created, much more attention will be needed to ensure the correct system time ID is documented. Figure 3 shows an excerpt from the IGS's Clock Rinex 3.04 Format document of the instructions for indicating the system reference for the data file.

Prior to version 3.04 of the Clock Rinex format, leap seconds were defined as the integer number of seconds in GPST – UTC. In version 3.04, the `LEAP SECONDS` field is defined as the integer number of seconds TAI – UTC. A new field `LEAP SECONDS GNSS` was introduced

```
+--------------------+----------------------------------------------+------------+
|TIME SYSTEM ID      | Time system used for time tags.              |   3X,A3    |
|                    |  - GPS = GPS system time                     |            |
|                    |      aligned to TAI - 19 sec                 |            |
|                    |  - GAL = Galileo system time                 |            |
|                    |      aligned to TAI - 19 sec                 |            |
|                    |  - QZS = QZSS system time                    |            |
|                    |      aligned to TAI - 19 sec                 |            |
|                    |  - IRN = IRNSS system time                   |            |
|                    |      aligned to TAI - 19 sec                 |            |
|                    |  - BDS = BeiDou system time                  |            |
|                    |      aligned to TAI - 33 sec                 |            |
|                    |  - GLO = GLONASS system time                 |            |
|                    |      aligned to UTC(SU) + 3 hours            |            |
|                    |  - UTC = Coordinated Universal Time          |            |
|                    |  - TAI = International Atomic Time           |            |
|                    |                                              |            |
+--------------------+----------------------------------------------+------------+
```

Figure 3: Excerpt from Clock Rinex 3.04 on Time System ID.

to reflect the existing tabulation of GPST – UTC. Figure 4 is an excerpt from the Clock Rinex 3.04 format that documents these two header fields.

5 Current Activities

The current activities for this year include supporting the repro3 effort and updating the timescale software. Unification of the two reference times to form one IGS time will also be considered, assuming no substantial loss of stability in the IGS final timescale.

The re-development of the IGS clock combination may be able to use work done in the PPP-AR WG as a foundation. That work has focused on the combination of satellite clock and bias products together for improved consistency and robustness; see Banville et al. (2020). Some preliminary results of clock combinations (for GPS, GAL, BDS and GLO independently) using the PPP-AR software were presented at the CPWG Meeting in December.

Continuing this work may be delayed over the coming year as the COVID–19 situation has now delayed the IGS's 2020 Workshop in Boulder, Colorado to a later date in 2021.

```
 +--------------------+----------------------------------------------+------------+
*|LEAP SECONDS        | Number of leap seconds, n, separating UTC and |     I6     |*
 |                    | TAI in the relation UTC = TAI - n.            |            |
 |                    |                                               |            |
 |                    | Recommended for mixed GNSS files.             |            |
 |                    |                                               |            |
 +--------------------+----------------------------------------------+------------+
*|LEAP SECONDS GNSS   | Number of leap seconds, n, separating UTC and |     I6     |*
 |                    | GNSS system times according to the relations  |            |
 |                    |                                               |            |
 |                    |           UTC ~ GLO                           |            |
 |                    |               ~ GPS - n                       |            |
 |                    |               ~ GAL - n                       |            |
 |                    |               ~ QZS - n                       |            |
 |                    |               ~ IRN - n                       |            |
 |                    |               ~ BDS - n + 14                  |            |
 |                    |                                               |            |
 |                    | * Note that the symbol ~ is used here to      |            |
 |                    |   indicate that these GNSS timescales have    |            |
 |                    |   epoch timestamps aligned to UTC as defined  |            |
 |                    |   in various GNSS ICDs (Interface Control     |            |
 |                    |   Documents).                                 |            |
 |                    |                                               |            |
 |                    |   The GNSS timescales are *not* equal to UTC  |            |
 |                    |   modulo 1 second. GNSS timescales are        |            |
 |                    |   generally maintained in real-time or near   |            |
 |                    |   real time while UTC is generated monthly    |            |
 |                    |   for longer term stability. GNSS timescales  |            |
 |                    |   are steered to different UTC(k) stations,   |            |
 |                    |   however, to keep the sub-second offset from |            |
 |                    |   UTC within standards set by their ICDs.     |            |
 |                    |                                               |            |
 +--------------------+----------------------------------------------+------------+
```

Figure 4: Refined definitions for leap seconds as of Clock Rinex 3.04

References

Banville, S., J. Geng, S. Loyer, S. Schaer, T. Springer, and S. Strasser On the interoperability of IGS products for precise point positioning with ambiguity resolution. *Journal of Geodesy*, 94, 10, doi 10.1007/s00190-019-01335-w, 2020.

GNSS Monitoring Working Group Technical Report 2019

T. Springer[1]

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European Space Agency

1 Introduction

The GNSS Monitoring Working Group was set up by the IGS Governing Board at its meeting in December 2016 in San Francisco in order to install, operate and further develop the IGS GNSS Monitoring and Assessment joint trial Project with the International GNSS Monitoring and Assessment (IGMA) Task Force of the of the United Nations Office of Outer Space Affairs, International Committee on GNSS (UNOOSA-ICG).

The ICG established the IGMA Task Force at the ICG-6 meeting in Tokyo in 2011, tasked to facilitate cooperation and information between providers and scientific organizations that engage in open service signal quality monitoring. The Task Force is co-chaired by ICG and IGS, members are GNSS system provider representatives. The ICG recommended at the ICG-10 meeting in Boulder 2015 that the IGMA Task Force and IGS initiate a joint Trial Project to demonstrate a global GNSS Monitoring an Assessment capability, utilizing existing resources and infrastructure and avoiding duplications.

The GNSS landscape is undergoing a fundamental transition with new satellite navigation systems being built up, existing systems being modernized and new signals and frequencies becoming available. Users will use these systems as one single system, benefiting from the enhancements contributed by the individual systems. To optimally exploit the benefits of multi-GNSS, users require homogeneous common monitoring of the performance of the individual constellation and signals, to verify service commitments are met and to ensure public confidence and trust in GNSS service provision and iteroperability.

The GNSS Monitoring Working Group invites participation from non-IGS analysis groups, networks and data centers to develop benchmarking between groups and generate analysis products, cross sharing between existing IGS functional streams and IGMA activities. Initially a limited number of parameters are proposed to be monitored to demonstrate the monitoring service and exercise it operationally. This will be followed by a broader set of parameters to be monitored as the system approaches permanent operations.

2 Tasks of the Working Group

Tasks of the IGMA-IGS joint trial pilot project are the determination of service parameters to monitor and the identification of gaps in current and planned monitoring and assessment methodologies, the proposal of an organizational approach avoiding duplication of existing activities, i.e., using existing infrastructure, and the exploration of methods to disseminate the products. With its Pilot Project IGS contributes to the joint project.

Parameters of all existing navigation sysstems, i.e., the global navigation systems GPS, GLONASS, Galileo, BeiDou and the regional systems QZSS and IRNNS shall be monitored with the same methodology. Initial set of parameters to be monitored are the broadcast orbits and clocks, the SIS User Range Error, the SIS UTC Offset Error, and the PDOP for selected sites. The monitoring is initially performed off-line with a target to near-realtime and realtime. Goal is to get a common understanding of monitoring parameters and parameters, but also to assess alternative parameters and methodologies.

The project follows IGS' open data and product policy. All provided data is publicly available, contributed stations are considered as IGS stations and included into the IGS network in cooperation with the Infractructure Committee. Products generated for the project are first exchanged and discussed within the Pilot Project contributors and published only after agreement with the IGMA Task Force.

The Pilot Project will terminate if it demonstrated the ability to monitor desired parameters and to generate publicly available useful products, if processes are defined for defining new parameters and for registering new Analysis Centers, if an organizational structure within or outside IGS is established for operating a GNSS Monitoring and Assessment Service, if IGMA or IGS is ready to implement a fully operational monitoring service, or if the project determined that such a service is not feasible.

2.1 Recent Activities

The main activities in the last year(s) were:

- Participation in the monthly IGC-IGMA teleconferences by the IGS Central Bureau and IGS-IGMA Chair/ACC
- Initial orbit and clock comparisons
  - First tests in 2018 with very divers inputs and results
  - Better defined test in 2018 with large differences between the results

  - Very simple test case defined which finally lead to a good agreement
  - Two month test in 2019 with very good orbital agreements, clock agreement still to be improved.
- Participation in the 2018 Joint ICG Performance Standards and IGMA Task Force Workshop in Noordwijk, the Netherlands
- Participation in the 2019 Joint ICG Performance Standards and IGMA Task Force Workshop in Vienna, Austria

3 More Information

More information about this IGS Working Group can be found on the IGS web-site, in particular at the following links:

- IGS Working Groups page (click on the GNSS Monitoring (IGMA)): http://www.igs.org/wg
- Call for participation and related information: https://kb.igs.org/hc/en-us/articles/226220548

Ionosphere Working Group Technical Report 2019

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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 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 OPTIMAP/Germany. Independent computation of rapid and final VTEC maps is used by the each analysis centers: Each IAACs compute the rapid and final TEC maps independently 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)

*Chair of Ionosphere Working Group

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

3 Key Issues

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

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

c 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 OPTIMAP) have been introduced to the IGS community – already present in CDDIS,

b First attempts to the IGS real-time ionospheric services have been made and first results have been obtained.

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

d 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 OPTIMAP group 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.

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 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 (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).

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 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).

The first results of RT-service performance are described by Zishen Li, Ningbo Wang, Manuel Hernández-Pajares, Yunbin Yuan, Andrzej Krankowski, Ang Liu, Jiuping Zha, Alberto García-Rigo, David Roma, Heng Yang, Denis Laurichesse, Denis Alexis Blot in IGS real-time service for global ionospheric total electron content modelling (2020) Journal of Geodesy 94 (3), 32, doi: 10.1007/s00190-020-01360-0.

The authors present well performance of the RT-GIMs and indicate few directions in further development, including the use of more dense and homogenous station network, shorter prediction time-span and including multi-layer ionospheric model, that would be more suitable in low-latitude ionosphere observations.

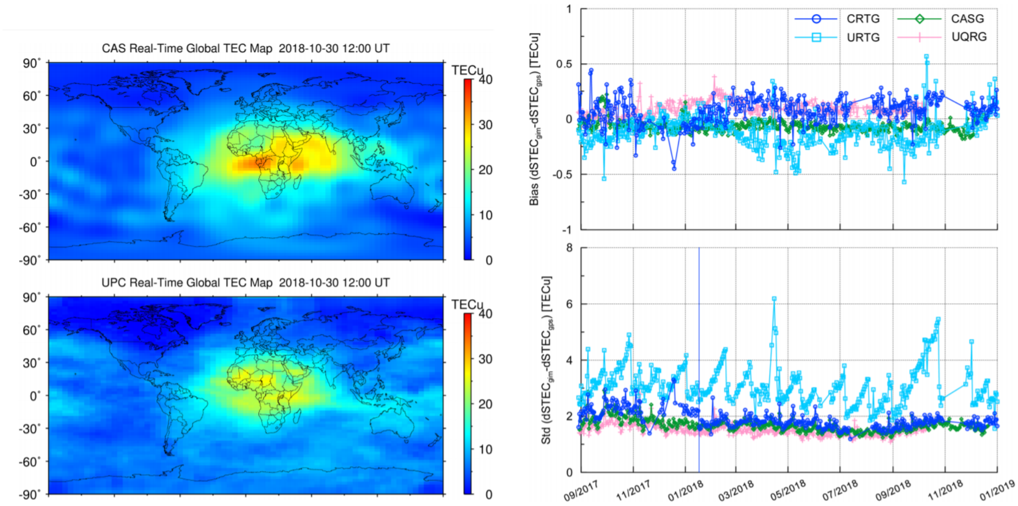

Figure 1: Examples of CAS and UPC real-time GIMs (left) and their performance in regard to UPC and CAS rapid products (right).

Multi-GNSS Working Group Technical Report 2019

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1 Introduction

The Multi-GNSS Pilot Project (MGEX) is the main activity of the IGS Multi-GNSS Working Group (MGWG). The membership of the MGWG has not changed in 2019. Altogether 13 GNSS satellites as well as a GNSS augmentation payload onboard a host satellite have been launched in 2019. The evolving systems Galileo and BeiDou are close to full operational capability and the renewal of the GPS and GLONASS constellation continues.

2 GNSS Evolution

The GNSS satellites launched in 2019 are listed in Table 1. In January 2019, the first GPS III satellite started signal transmission including the new civil L1C signal (Thoelert et al. 2019). The second GPS III satellite nicknamed Magellan was launched in August 2019 but has not yet started signal transmission within the PRN range trackable by commercial geodetic GPS receivers (G01 – G32). For all healthy Block IIR-M and IIF satellites, flex power operations (Steigenberger et al. 2019b) were observed on June 20 and 21, 2019. The most obvious effect was an increase of the carrier-to-noise density ratio of the P(Y)-code tracking by roughly 10 dB.

In 2019, two satellites of the GLONASS constellation (R723/R12 and later R10; R733/R06) suffered from single-frequency transmission on L1 only. The lack of L2 observations prohibits the precise orbit and clock determination of these satellites. Transmission outages of several weeks occurred for the GLONASS PRNs R04, R10, and R24 resulting in an

Table 1: GNSS satellite launches in 2019.

Date	Satellite	Type
20 Apr 2019	BeiDou-3 IGSO-1	IGSO
17 May 2019	BeiDou-2 GEO-8	GEO
27 May 2019	GLONASS-M+	MEO
24 Jun 2019	BeiDou-3 IGSO-2	IGSO
22 Aug 2019	GPS III-2	MEO
22 Sep 2019	BeiDou-3 MEO-23 and MEO-24	MEO
09 Oct 2019	EUTELSAT 5 West B (EGNOS)	GEO
04 Nov 2019	BeiDou-3 IGSO-3	IGSO
23 Nov 2019	BeiDou-3 MEO-21 and MEO-22	MEO
11 Dec 2019	GLONASS-M+	MEO
16 Dec 2019	BeiDou-3 MEO-19 and MEO-20	MEO

incomplete GLONASS constellation of less than 24 healthy satellites. R723/R12 and R742/R04 were replaced by the newly launched GLONASS-M+ satellites R858 and R859 in June and December 2019, respectively. Despite its single-frequency limitation, R723 continued signal transmission with PRN R10. Further GLONASS launches including the last GLONASS-M satellite as well as GLONASS-K1 and -K2 satellites are planned for 2020.

With the launch of three IGSO and six MEO satellites, BeiDou made a large step towards

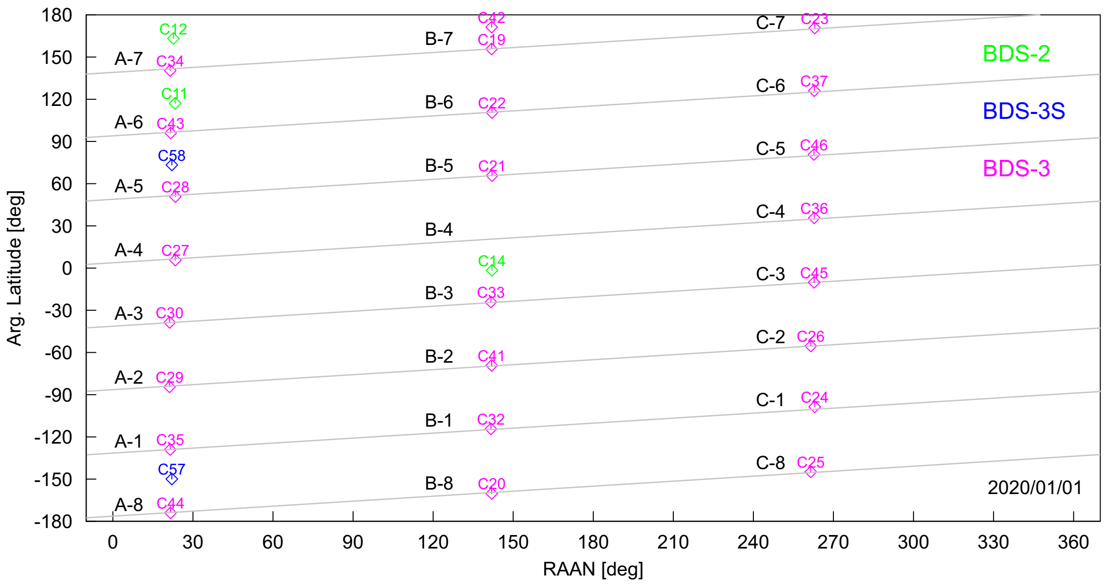

Figure 1: Constellation of BeiDou MEO satellites as of January 2020. C42 is drifting to its designated slot B-4.

the completion of the BDS-3 constellation. Whereas the nominal number of 24 MEO and three IGSO satellites has already been reached by the end of 2019, two GEO launches are expected for 2020. Figure 1 shows the constellation of BDS-2, BDS-3S, and BDS-3 MEO satellites as of January 2020. As orbital plane A is already fully populated with BDS-3 MEO satellites, two BDS-2 MEO satellites (C11 and C12) and two BDS-3S MEO satellites (C57 and C58) are placed in between the official orbital slots. The same is true for the BDS-2 satellite C14 in orbital plane B.

EUTELSAT 5 West B, located at 5° West, is a communication satellite hosting a payload for the European Geostationary Navigation Overlay System (EGNOS). The spacecraft suffers from an incident on one of the two solar panels (EUTELSAT 2019) but the impact on the EGNOS payload is currently unknown.

Version 3.0 of the BeiDou B1I interface control document (ICD) was published in February 2019 (China Satellite Navigation Office 2019). Compared to the previous version 2.1, of the B1I+B2I ICD, it defines the full range of BeiDou PRNs (up to 63) including the allocation of 10 PRN numbers for geostationary satellites and defines an updated scheme for transmission of the full BDS-2/3 constellation almanac. Furthermore, it introduces the BeiDou Coordinate System (BDCS) as a replacement for the earlier China Geodetic Coordinate System 2000 (CGCS2000) and defines a tighter synchronization (50 vs. 100 ns) of BeiDou System Time (BDT) with UTC. In December 2019, beta versions of the ICDs for the B2b open service signal of BeiDou-3 (CSNO 2019d) as well as the precise point positioning service (CSNO 2019e) were made available by the Chinese Satellite Navigation Office.

As an addition to the Galileo Open Service ICD, the European Union published a technical note on the E6-B/C Codes (European Union 2019a). It contains the primary and secondary codes for the E6-B and E6-C signals fostering the development of E6-capable Galileo receivers. In July 2019, Galileo suffered from a six-day service interruption. Whereas all satellites continued to transmit proper navigation signals, no broadcast ephemerides were transmitted during this time period (European Union 2019b). Most of the MGEX ACs were not affected by this issue and continued to provide high-quality Galileo orbit and clock products. The incident was analyzed by an independent inquiry board. Its recommendations are given in European Commission (2019).

For QZSS, three ICDs were updated in December 2019 (IS-QZSS-L1S-004 2019; IS-QZSS-L6-002 2019; IS-QZSS-TV-003 2019), amongst others to pave the way for the launch of the QZS-1 replacement satellite in 2020 as well as the extension to a 7-satellite constellation in 2023.

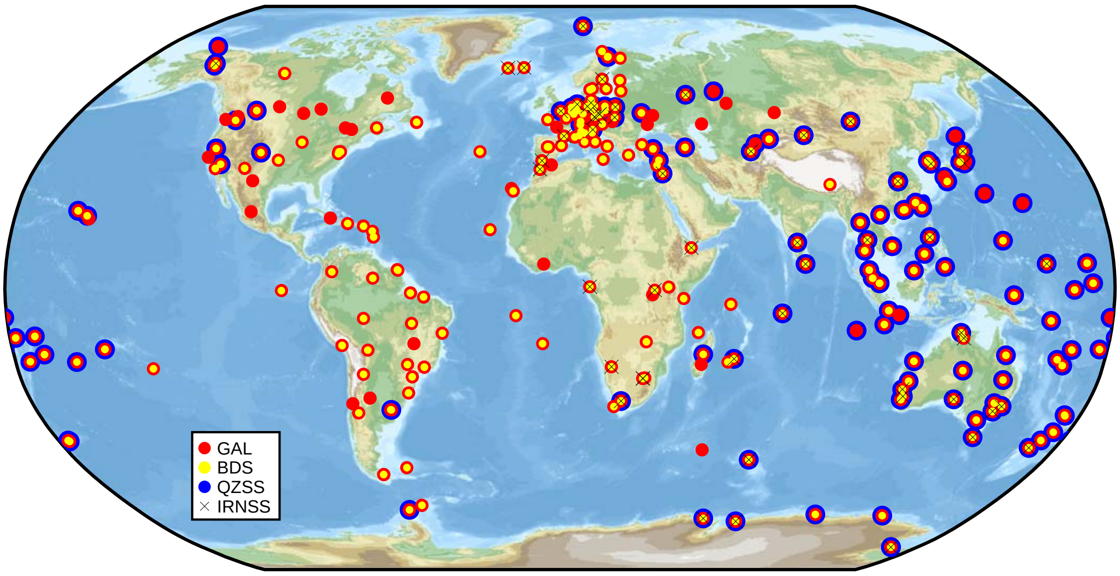

Figure 2: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2020.

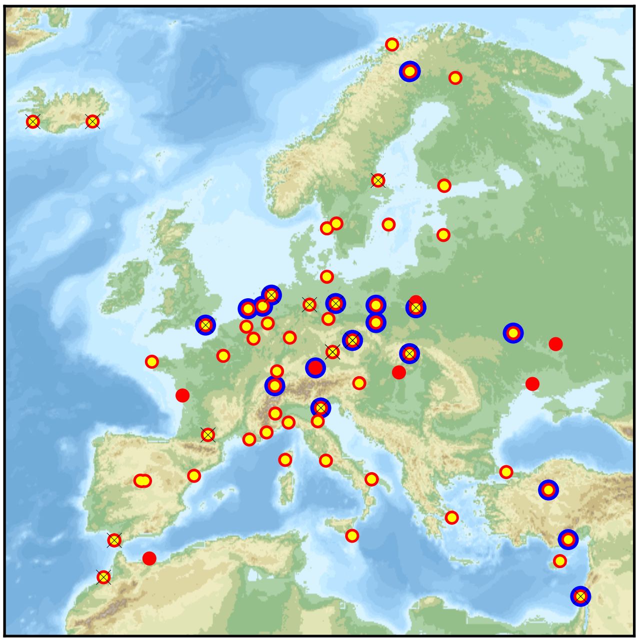

Figure 3: Distribution of IGS multi-GNSS stations in the European region as of January 2020.

Table 2: BeiDou-3 tracking capabilities of selected receivers and firmware versions. (x) indicates observables not supported by the receiver-internal RINEX converter. The second column indicates the second and third character of the RINEX 3 observation type (IGS RWG and RTCM, 2018).

Receiver		Javad TRE_3	Septentrio PolaRx 5	Trimble NetR9	Trimble Alloy
Firmware		3.7.6	5.3.0	5.42	5.42
PRN range		C01 – C37	C01 – C37	C01 – C37	C01 – C63
B1C	1P		(x)		
	1X	x			(x)
B1I	2I	x	x	x	x
B2a	5P		(x)		
	5X	x			(x)
B3I	6I	x	x	x	x
B2b	7Z	x			
B2ab	8X	x			

3 Network

As of January 2020, the IGS multi-GNSS tracking network comprises 309 stations, see Fig. 2 and 3. However, nine of these stations did not provide any RINEX 3 observation data in 2019. For seven stations in New Zealand and Antarctica operated by GNS Science (AUCK00NZL, CHTI00NZL, DUND00NZL, MQZG00NZL, SCTB00ATA, WARK00NZL, WGTN00NZL), the provision of RINEX 3 files was stopped in January 2019 due to changes in the data generation chain (IGSSTATION-7581). In late 2019, the station category 'MGEX experimental' was changed to 'IGS experimental'. As of December 2019, five stations belong to this category.

GLONASS-M+ satellites are capable of transmitting a CDMA signal on the L3 frequency. However, these signals are not fully compliant with the corresponding ICD (Sleewaegen 2020), neither the current version (Russian Space Systems 2016), nor an earlier version as stated in Urlichich et al. (2019). Several receiver manufacturers have adopted their receiver firmware in order to offer L3 capabilities for individual satellites. However, as of late 2019, very few receivers in the IGS network provide a comprehensive tracking of the most recent GLONASS-M+ satellite R859/R04.

BeiDou-3 tracking capabilities of the IGS multi-GNSS network were significantly enhanced in 2019, primarily due to receiver firmware updates but also due to receiver replacements. An overview of the BeiDou-3 signal tracking of selected receivers and firmware versions is given in Table 2. Starting with firmware version 5.42 released in August 2019, the Trimble Alloy receiver is capable of tracking BeiDou-3 PRNs up to C63. Javad released firmware 3.7.8 on December 26, 2019, supporting also PRNs up to C63 for the newest generations of Javad receivers and up to C46 for older generations. However, none of the IGS receivers utilizes this firmware as of early January 2020. Other receivers are currently limited to the BeiDou PRN range C01 – C37.

Along with the introduction of new BeiDou signals and the definition of associated RINEX observation codes, various inconsistencies in vendor or user generated RINEX observations files could be noted in the IGS data repository. RINEX files of Javad receivers with version $\leq$ 2.0.157 of the data conversion software `jps2rin` erroneously report BeiDou-3 B1C data+pilot observations (`1X`) as RINEX code `2X`. BeiDou-3 `2X` observation codes are also generated by a translation bug of the **`gfzrnx`** software prior to version 1.12-7747 (IGSSTATION-7849).

BeiDou-2 and BeiDou-3 satellites transmit different signals in the B2b band (1207.14 MHz). Whereas BeiDou-2 utilizes a BPSK(2) signal for the open service on the I-channel (RINEX code `7I`), the in-phase component of a QPSK(10) signal is used for the BeiDou-3 B2b open service (CSNO 2019d). Currently, BeiDou-3 B2b observations are obtained by Javad TRE_3 receivers in the IGS network based on combined tracking of the I- and Q-channel (RINEX code `7Z`). However, numerous RINEX files of Javad receivers contain `7I` observations for BeiDou-3 instead of `7Z` due to outdated conversion software (`jps2rin` 2.0.168 and 2.0.170; version 2.0.187 correctly reports `7Z` for BeiDou-3).

Currently, the BeiDou-3 `1P` and `5P` observables are not supported by the PolaRx5 receiver built-in RINEX converter, but can be generated with Septentrio's external conversion software `sbf2rin` version 13.4.3. The QZSS L1Sb SBAS signal of the geostationary QZS-3 satellite can be tracked by Javad TRE_3 receivers but no RINEX observation code has been defined for this signal so far.

Another problem encountered along with the rapid deployment of new GNSS satellites and signals is the limited number of tracking channels available in various stations with first-generation multi-GNSS receivers. As a result, some IGS stations provide only intermittent tracking of individual Galileo and/or BeiDou satellites. Unless those receivers can be replaced by more modern units, station-specific tracking schemes need to be developed to obtain a reasonable tracking coverage in accord with existing hardware limitations.

4 Products

The analysis centers contributing products to MGEX are listed in Table 3. Updates and changes of the MGEX orbit and clock products include:

- Inclusion of BeiDou-3 in the orbit and clock products of WU starting with day of year 1/2019.
- Long filenames: WU since 1/2019; GFZ rapid products since GPS week 2038 (27/2019, IGSMAIL-7748); TUM since 89/2019.
- Improved Galileo ambiguity resolution for CNES/CLS product since February 3, 2019 (Perosanz et al. 2019).
- Hourly orbit and clock product from Wuhan University available since 65/2019.

Table 3: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	GRGOMGXFIN	GPS+GLO+GAL
CODE	CODOMGXFIN	GPS+GLO+GAL+BDS2+QZS
GFZ	GFZOMGXRAP	GPS+GLO+GAL+BDS2+QZS
JAXA	JAXOMGXRAP	GPS+GLO+QZS
SHAO	SHAOMGXRAP	GPS+GLO+GAL+BDS2
TUM	TUMOMGXRAP	GAL+BDS2+QZS
Wuhan University	WUMOMGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS
	WUMOMGXULA	GPS+GLO+GAL+BDS2+BDS3

- Empirical thermal radiation model for Galileo satellites in CODE product since summer 2019 (Prange et al. 2019).
- Transition from conventional PCOs for BeiDou-2 to averaged estimated PCOs and inclusion of BeiDou-3 block-specific manufacturer PCOs in `igs14.atx` (GPS week 2056, IGSMAIL-7782).
- PCO and PCVs provided by GSA for the eight most recent Galileo satellites added to `igs14.atx` (GPS week 2060, IGSMAIL-7792).
- PCOs for the BeiDou-3 IGSO satellites added to `igs14.atx` (GPS week 2076, IGSMAIL-7843).

Since September 23, 2019, Galileo is also included in the CODE operational rapid and ultra-rapid orbit and clock products (IGSMAIL-7832).

Steigenberger and Montenbruck (2019) assessed the consistency of the MGEX orbit and clock products for the first term of 2018. They found a clock consistency of 2 cm for GPS, 5 cm for Galileo and GLONASS, and 10 cm for BeiDou-2. The mean combined orbit and clock consistency evaluated by the 95th percentile of the signal-in-space ranging error (SISRE) is 2 cm for GPS, 8 cm for GLONASS, 6 cm for Galileo, and 14 cm for BeiDou-2. More recent analysis of the December 2019 MGEX orbits and clocks gives a similar value for GPS and GLONASS but a significantly improved consistency of 4 cm for Galileo.

A prototype for an MGEX final orbit combination was developed by Geoscience Australia. Details on these activities are given in the ACC section of this report.

Multi-GNSS differential code bias (DCB) products are generated by CAS (daily rapid product) and DLR (quarterly final product). In the DLR product, additional BeiDou-3 DCB types were included as soon as a sufficient number of IGS receivers provided these observations:

- B1-2(I)/B2a(Data+Pilot), RINEX code `C2I-C5X`, January 2019
- B1-2(I)/B1(Data+Pilot), RINEX code `C2I-C1X`, March 2019
- B1-2(I)/B2b(Data+Pilot), RINEX code `C2I-C7Z`, August 2019

The CAS product includes additional BeiDou-3 DCBs currently not accessible with the

IGS network due to lacking tracking data (C1D-C5D and C1D-C6I) or sparse tracking data (C1P-C5P, C1P-C6I, C1X-C8X).

DLR's broadcast ephemerides product is provided with long filenames (prefix BRDM00DLR) starting with November 25, 2019 (day of year 329/2019). The same applies for the CNAV product with prefix BRDX00DLR. Both files are available in the default data directories of the IGS data centers. The provision of the products with short filenames (brdm/brdx) in the dedicated MGEX data directories will be stopped in the first months of 2020.

5 Satellite Metadata

Several new satellite metadata were published in 2019. Lockheed Martin released satellite antenna phase center offsets, group delay, and inter-signal corrections for GPS III SV01 (Lockheed Martin 2019). The Cabinet Office published additional metadata for the QZSS satellites:

QZS-1: optical properties for all surfaces; approximated shape of the L-ANT antenna cover (Cabinet Office 2019a)
QZS-2: approximated shape of the L-ANT antenna cover (Cabinet Office 2019b)
QZS-3: dimensions and optical properties of a reflector antenna on the −X side of the satellite (Cabinet Office 2019c)
QZS-4: approximated shape of the L-ANT antenna cover (Cabinet Office 2019d)

The European GNSS Agency made available mass, center of mass, antenna reference point location, antenna phase center offsets, and laser retroreflector offsets for the latest eight Galileo FOC satellites in April 2019 (GSA 2019). Corresponding antenna phase center variations were published in June 2019.

Satellite metadata for BeiDou-2 and BeiDou-3 were released by the Chinese Satellite Navigation Office (CSNO) in December 2019 (CSNO 2019a, b). This dataset includes PRN/SVN assignment, frequency-specific satellite antenna phase center offsets, mass, SLR retroreflector offsets, as well as areas and absorption coefficients (specular and diffuse reflection coefficients are missing). Additional information, attitude law, and file format descriptions are given in CSNO (2019c).

DLR measured the transmit power of recently launched GLONASS satellites with its 30 m high-gain antenna (Steigenberger et al. 2019a). For the GPS III satellites, a total transmit power of 300 W is assumed based on the measured Block IIF transmit power, the additional L1C signal, and slightly increased power levels for other signals.

The impact of metadata on Galileo and QZSS orbit determination is discussed in Li et al. (2019). As an example, a box-wing model based on the areas and optical properties could improve the orbit quality by up to 14 % in terms of 3D overlap RMS.

The MGWG maintains a metadata SINEX file covering most of the published metadata.

In particular, the MGEX satellite metadata file provides

- Time-dependent PRN and frequency channel assignments
- Satellite mass and center-of-mass location
- Equipment positions (antennas, LRAs)
- Transmit power

along with detailed references of the respective data sources. The latest version of this file is available at http://mgex.igs.org/igs_metadata.snx along with a format description. The file is intended as a centralized and standardized source of satellite metadata information for MGEX analysis centers and GNSS users. Extensions to cover additional parameters, e.g. box-wing models, are under discussion. In addition, the MGWG continues its effort to promote the release of further metadata by GNSS manufacturers and providers.

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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Precise Point Positioning with Ambiguity Resolution Working Group Technical Report 2019

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1 Introduction

Since the early 1990s, the IGS has been combining satellite orbit and clock products from analysis centers (ACs). This combination allowed delivery of products with improved reliability and robustness to end users. For over a decade, several ACs have also been experimenting with techniques enabling precise point positioning with ambiguity resolution (PPP-AR). The products generated as a part of these AC solutions contain additional satellite phase and code biases that must be transmitted to users to maintain consistency with the satellite clock products and recover the integer nature of ambiguities.

The IGS clock combination process does not, at the moment, consider these additional satellite biases. As a result, the combined products do not enable AR at the user end. With PPP-AR techniques having matured significantly since their inception, the IGS is looking into modernizing its clock combination process to include such biases. For this purpose, the precise point positioning with ambiguity resolution working group (PPP-AR WG) was established at the IGS workshop 2018, held in Wuhan, China.

2 Product Interoperability

A core objective of the working group is to analyze the interoperability of orbit, clock and bias products generated by analysis centers. To verify the consistency of these products, a one-week test period (GPS week 2026) was selected and six ACs participated in this experiment:

- Center for Orbit Determination in Europe (COD)
- Natural Resources Canada (EMR)
- European Space Agency / European Space Operation Centre (ESA)
- Centre National d'Etudes Spatiales / Collecte Localisation Satellites (GRG)
- Graz University of Technology (TUG)
- Wuhan University (WHU)

2.1 Observable-specific biases

While the IGS has adopted the Bias SINEX format (Schaer 2016) for the dissemination of satellite biases, several ACs still generate bias products in internal formats since they are not part of their production line. Table 1 summarizes the products provided by each AC.

Table 1: Products provided by analysis centers.

Analysis center	Clock Interval (sec)	Biases
COD	5	Observable specific (Bias SINEX)
EMR	30	Widelane and ionosphere-free code biases
ESA	300	Widelane and narrowlane phase biases
GRG	30	Widelane biases
TUG	30	Observable specific (Bias SINEX)
WHU	30	Observable specific (Bias SINEX)

The first step towards testing interoperability is, therefore, to convert all biases into a common representation: observable-specific biases (OSBs) (Villiger et al. 2019). Transformations from linear combinations of biases to OSBs can be achieved using mathematical representations described by Banville et al. (2020).

Consistency of individual AC solutions can only be ensured by considering both satellite clock and bias corrections simultaneously. For this reason, the standard approach to the IGS clock combination must be revisited. The next sections summarize steps taken to generate combined clock and bias products.

2.2 Interoperability of geometry-free biases

The approach adopted for the modernized combination process begins by combining geometry-free biases, i.e. differential code biases (DCBs) and Melbourne-Wübbena (MWU) biases. This section focuses on the latter, where MWU biases were formed from L1W, L2W, C1W and C2W biases (signal identification follows RINEX 3 definitions). Figure 1 shows residuals from the least-squares adjustment on 4 November 2018, representing the difference between each AC biases and the combined biases.

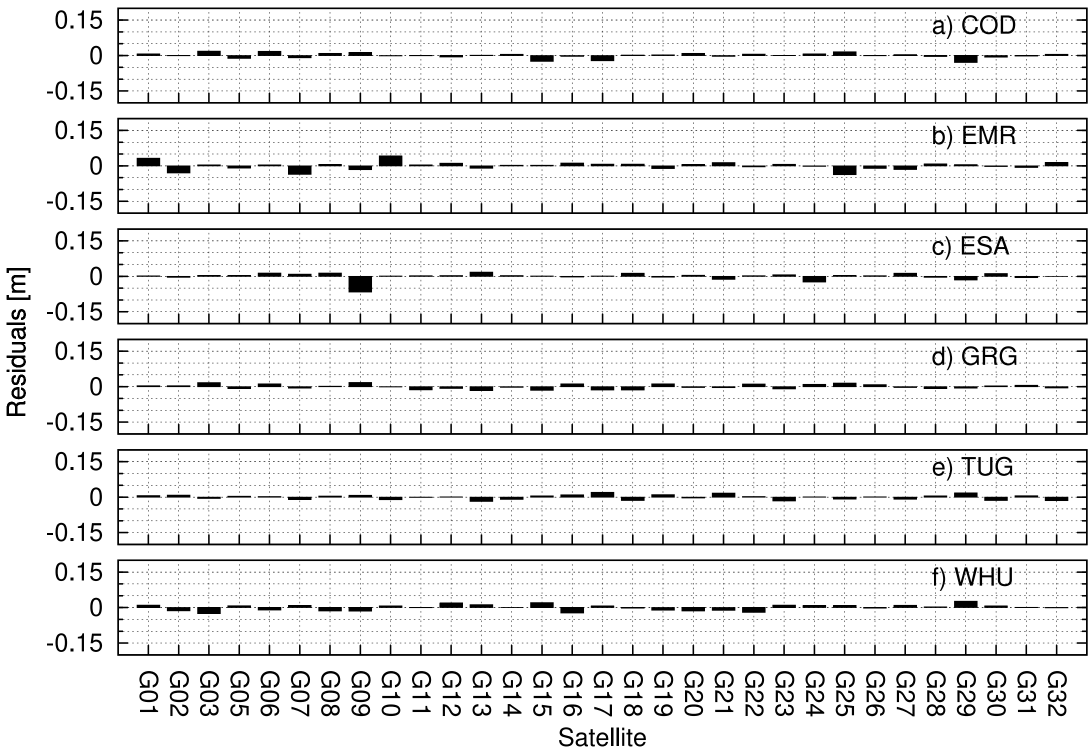

Figure 1: Residuals from ambiguity-fixed Melbourne-Wübbena biases (Banville et al. 2020).

The agreement between solutions is remarkable, with biases typically differing by less than a couple of centimeters.

2.3 Interoperability of ionosphere-free phase clocks

When considering satellite clock corrections and phase biases, one obtains "integer clocks", i.e. clocks enabling PPP-AR at the user end. An interesting property of these integer clocks is that they can be precisely aligned by shifting them by an integer multiple of the signal wavelength. As a consequence, it becomes possible to identify ambiguity-like parameters in the combination of integer clocks. These ambiguities can be resolved to integer values to ensure precise alignment of the clock among ACs. Figure 2 shows an example of this property on 4 November 2018, where ambiguity residuals are depicted. Ambiguity residuals are defined as the difference between the float estimates and their closest integer value.

Considering the standard deviation of all ambiguity residuals indicates that ionosphere-free phase clocks can be precisely aligned to better than 0.013 narrowlane cycles (< 1.3 mm). By resolving these ambiguity parameters to integers, they can be removed from the system of equations and the clock combination process can be performed. Table 2 provides a summary of the standard deviation of ionosphere-free phase-clock residuals for each AC on 4 November 2018, once all ambiguity parameters were resolved to integers. These results offer comparable values as routine processing within the IGS and confirm the consistency of the PPP-AR products generated by ACs.

2.4 Evaluation in the positioning domain

The combined satellite clock and bias products were evaluated in the positioning domain over a one-week period (GPS week 2026). A total of 209 globally distributed IGS stations were used for this test. Using the NRCan PPP software, RINEX files from these stations were processed using individual AC solutions, the standard IGS combined products (IGS) and the combined products enabling PPP-AR (IAR).

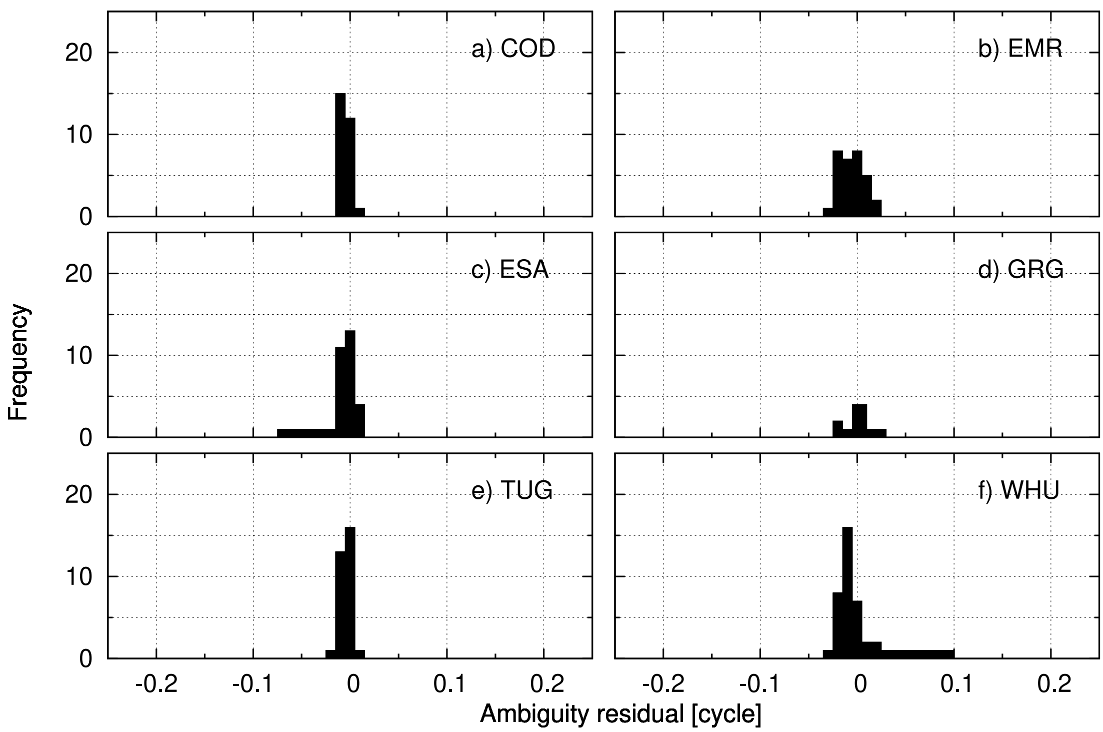

Figure 2: Ambiguity residuals from the ionosphere-free phase-clock solution(Banville et al. 2020).

Table 2: Standard deviation of ionosphere-free phase-clock residuals on 4 November 2018.

Analysis center	Clock residuals (ps)	Clock residuals (mm)
COD	4.6	1.4
EMR	14.5	4.4
ESA	8.6	2.6
GRG	5.4	1.6
TUG	5.7	1.7
WHU	5.9	1.8

The estimated daily static coordinates were compared against the coordinates contained in the daily IGS SINEX files, and a daily 7-parameter Helmert transformation was computed to account for reference frame alignment differences. The RMS errors for the north, east and up components were then computed over all solutions. The results are shown in Figure 3 for PPP (float) and PPP-AR solutions.

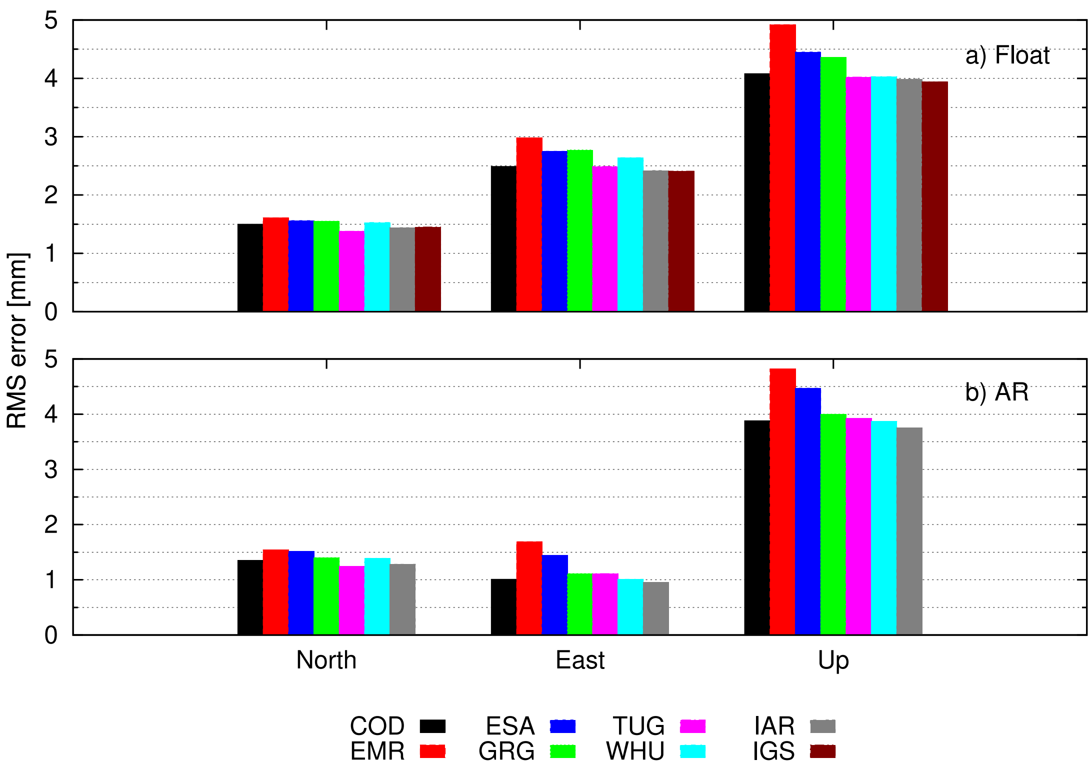

Figure 3: RMS error of static PPP (float) and PPP-AR solutions (Banville et al. 2020).

Ambiguity resolution has a clear impact on the east (longitude) component, as expected, with a RMS reduction around 60%. Since it is not possible to recover the integer nature of the ambiguities from standard IGS clock products, this solution is not included in the bottom plot of Figure 3. The combined PPP-AR products (IAR) perform very well, confirming the interoperability of the products.

3 Future Work

While interoperability of satellite clock and bias products has been confirmed, additional work is required to improve the consistency of the combined products. Various modelling strategies during satellite eclipses lead to significant discrepancies in the clock estimates. A satellite attitude exchange format has been proposed (Loyer et al. 2017) for this purpose and will be tested in 2020.

Current data formats also lack a clear means of identifying clock and bias continuity/discontinuity, for instance, at day boundaries. An extension of current data formats will then be explored to solve this issue. Once resolved, it will become possible to generate continuous satellite clock estimates over longer periods, which should be especially beneficial for the timing community.

A modernized clock combination software, implementing the concepts presented in this technical report and detailed by Banville et al. (2020), has been developed. This software will be tested and validated against the current clock combination software used by the IGS.

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Reference Frame Working Group Technical Report 2019

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After a brief overview of the operational IGS SINEX combination results in 2018 and 2019 (Section 1), this report summarizes the preparations of the third IGS reprocessing campaign (repro3) carried out in 2019, namely the preparation of the IGS repro3 ANTEX file (igsR3.atx) in collaboration with the IGS Antenna Working Group, and of the IGS repro3 reference frame (IGSR3).

1 Operational SINEX combinations

Figure 1 shows the WRMS of the AC station position residuals from the daily IGS SINEX combinations of years 2018-2019, i.e., the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed.

The WRMS of the AC station position residuals have remained at similar levels as in the previous years, with two notable exceptions:

- On GPS week 1997, GRGS brought several changes to their processing strategy (data sampling, elevation-dependent weighting of observations, cut-off angle, etc.). This had a clear positive impact of the East and Up components of their station position estimates and brought the WRMS of their East and Up residuals down to the same level as other ACs.
- On GPS week 2003, JPL switched from the IGS08/igs08.atx to the new IGS14/igs14.atx framework, which brought the WRMS of their residuals down to the same level as other ACs. JPL solutions have been included back with weight in the IGS SINEX combinations since then.

The AC Earth Orientation Parameter residuals from the IGS SINEX combinations of years 2018-2019 show similar scatters and characteristics as in the previous years. They are not shown in this report due to length limitation.

2 Preparations for repro3

The third IGS reprocessing campaign (repro3) will constitute the IGS contribution to ITRF2020. It is to be provided to the IERS by February 2021. For the first time, several ACs will process Galileo observations in their repro3 contributions in addition to GPS and GLONASS. The inclusion of Galileo required the preparation of a specific ANTEX file for repro3 (igsR3.atx) which contains:

- a set of consistent ground antenna calibrations covering the signal frequencies of the three systems (among others),
- a set of consistent satellite antenna radial phase center offsets (z-PCOs) across the three systems.

For this preparation, the Reference Frame Working Group worked in close collaboration with the Antenna Working Group and several ACs to evaluate the inter-system consistency of two candidate sets of multi-GNSS ground antenna calibrations (Section 2.1) and derive a consistent set of GPS, GLONASS and Galileo satellite z-PCOs (Section 2.2). Finally, a repro3-specific reference frame (IGSR3), consistent with igsR3.atx and the new IERS

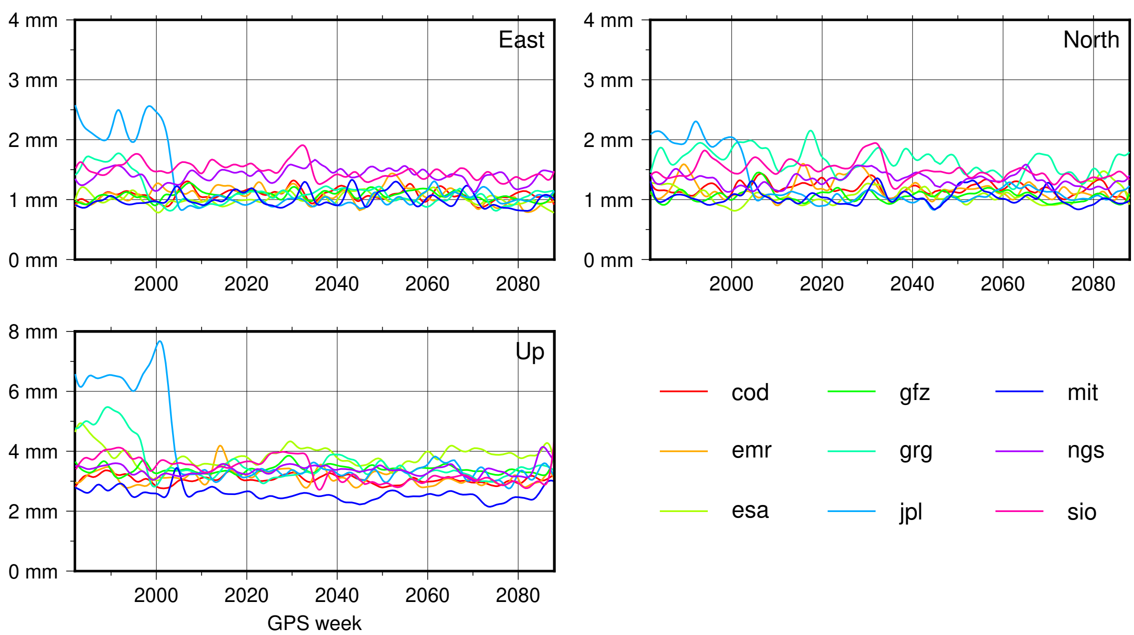

Figure 1: WRMS of AC station position residuals from the 2018-2019 daily IGS SINEX combinations. All time series were low-pass filtered with a 10 cycles per year cut-off frequency.

secular pole model, was elaborated (Section 2.3).

2.1 Evaluation of "chamber" and "robot" multi-GNSS calibrations

Two sets of multi-GNSS ground antenna calibrations were made available to the IGS in 2019: first, a set of calibrations measured in anechoic chamber and provided by Universität Bonn; then, in June, a set of calibrations provided by Geo++ and obtained with their robot. A prerequisite for the inclusion of either set in igsR3.atx was to verify that those ground antenna calibrations could yield consistent station position estimates across the three GNSS. Otherwise, i.e., in case systematic biases would exist between station positions estimated from the different GNSS, then:

- those biases would turn up between the repro3 solutions of ACs processing GPS only and those of ACs processing the three GNSS, making the combination of the AC repro3 solutions delicate and the accuracy of the IGS combined repro3 solutions questionable,
- the formation of meaningful multi-GNSS solutions would be questionable itself.

In March and April 2019, CODE and ESA provided different sets of test solutions based on the chamber calibrations provided by Universität Bonn, which allowed evaluating the inter-system consistency of those calibrations. CODE and ESA provided in particular daily GPS-only and daily Galileo-only solutions over the period 2017-2018. By forming differences between pairs of GPS-only and Galileo-only daily solutions after having brought them to a common reference frame, it was possible to assess systematic biases between GPS-derived and Galileo-derived station positions – up to an unknown 7-parameter similarity. The results revealed "Galileo – GPS" station height differences that were antenna-type-dependent and could reach nearly 1 cm in average for certain antenna types. Those systematic differences were likely indications of frequency-dependent errors in the chamber calibrations of some antenna types (Rebischung 2019).

In July 2019, five ACs (CODE, ESA, GFZ, GRGS and TUG) provided similar sets of test solutions over the period 2017-2018, but based on the multi-GNSS robot calibrations provided by Geo++. With those robot calibrations, "Galileo – GPS/GLONASS" station position differences were in particular found to be most generally smaller than 5 mm in vertical and smaller than 2 mm in horizontal. Besides, no clear antenna-type-dependent inter-system station position biases could be identified (Rebischung et al. 2019). It was concluded that the multi-GNSS robot calibrations from Geo++ could yield acceptably consistent station position estimates across the three GNSS, and decided to include those calibrations in igsR3.atx.

2.2 Re-evaluation of satellite z-PCOs

Due to the unavailability of reliable antenna calibrations for the GPS and GLONASS satellites, the IGS has until now relied on the scales of the successive ITRF releases to estimate GPS and GLONASS satellite z-PCOs (e.g., Ray et al. (2003)). The IGS products have thus had a conventional ITRF-based scale that could not contribute to the definition of the ITRF scale. The situation has changed however with the release of the Galileo satellite (PCOs) by the European Global Navigation Satellite Systems Agency (GSA), which opens the way for a GNSS-based determination of the terrestrial scale, and a possible contribution of GNSS to the definition of the ITRF2020 scale. The IGS ACs decided to take this opportunity in repro3. The z-PCOs of all GPS and GLONASS satellites were therefore re-evaluated based on the Galileo satellite z-PCOs provided by GSA, and those re-evaluated z-PCOs were included in igsR3.atx so that the repro3 products will have an ITRF-independent, Galileo-based scale.

The preparation of the igsR3.atx set of satellite z-PCOs actually involved three steps:

- updates to the igs14.atx z-PCOs of particular GPS and GLONASS satellites,
- verification of the relative consistency of the z-PCO values provided by GSA for the different Galileo satellites,
- estimation of a common correction to all GPS satellite z-PCOs and of a common correction to all GLONASS satellite z-PCOs based on the Galileo satellite z-PCOs provided by GSA (i.e., "scale transfer" from Galileo to GPS and GLONASS).

The next paragraphs detail each of these steps.

From the repro2 and operational solutions of seven ACs (CODE, EMR, ESA, GFZ, JPL, MIT and ULR), daily estimates of the z-PCOs of all GPS and GLONASS satellites were first obtained by fixing the average of the satellite z-PCOs in each daily solution to that of their igs14.atx z-PCO values. The purpose of this first step was to evaluate the relative consistency of the igs14.atx z-PCO values of the different GPS and GLONASS satellites, and determine whether some of them would benefit from being updated in igsR3.atx. Figures showing monthly averages of the corrections thus estimated to the igs14.atx z-PCO value of each GPS and GLONASS satellite can be found at ftp://igs-rf.ign.fr/pub/repro3_tests/2017-2018/plots/dz-GR. The estimated z-PCO corrections show all sorts of variations (periodic signals, trends, jumps, etc.) but stay within ± 10 cm for most satellites, which can be considered as an acceptable range – according to Cardellach et al. (2007), a 10 cm error on the z-PCO of one particular GPS satellite results in sub-millimetric positioning errors. The z-PCO corrections estimated for two particular GLONASS satellites (R730 and R737) however show clear jumps with amplitudes larger than 10 cm, and it was therefore decided to introduce time-variable z-PCOs for those two satellites in igsR3.atx. It was also decided to introduce estimated z-PCOs in igsR3.atx for two recently launched GLONASS satellites (R856 and R857) that have preliminary z-PCO values in igs14.atx. Finally, it was agreed to apply in igsR3.atx an estimated correction to the igs14.atx z-PCO of satellite G074 provided by Lockheed Martin [IGSMAIL-7744].

Once the list of GPS and GLONASS satellite z-PCOs to be updated in igsR3.atx was finalized, daily corrections to their igs14.atx z-PCOs were estimated from the daily repro2 and operational solutions of different ACs, while fixing the z-PCOs of all other satellites to their igs14.atx values. Weighted average corrections were finally computed for each re-evaluated satellite z-PCO – over several successive periods for R730 and R737 – and applied into igsR3.atx.

To evaluate the relative consistency of the z-PCO values provided by GSA for the different Galileo satellites, a similar approach was followed as for the evaluation of the relative consistency of the igs14.atx z-PCO values of the different GPS and GLONASS satellites. From the 2017-2018 multi-GNSS test solutions of CODE and ESA, daily estimates of the z-PCOs of all Galileo satellites were obtained by fixing their average to that of the z-PCO values provided by GSA (while freely estimating all GPS and GLONASS satellite z-PCOs). Figures showing the daily corrections thus estimated to the z-PCO value provided by GSA for each Galileo satellite can be found at ftp://igs-rf.ign.fr/pub/repro3_tests/2017-2018/plots/dz-E. Figure 2 shows the mean and scatter of the time series of daily corrections obtained for each Galileo satellite. Apart from satellite E102, all average corrections are within ± 7 cm and most within ± 3 cm. With the exception of E102, the z-PCO values provided by GSA are therefore consistent, relatively to each other, with estimates of the actual in-orbit z-PCOs to within ± 7 cm. While the accuracy of the z-PCO values from GSA cannot be inferred from this result, it nevertheless indicates that their precision is sufficient for precise positioning (assuming that Cardellach et al. (2007)'s GPS-based results also hold for Galileo).

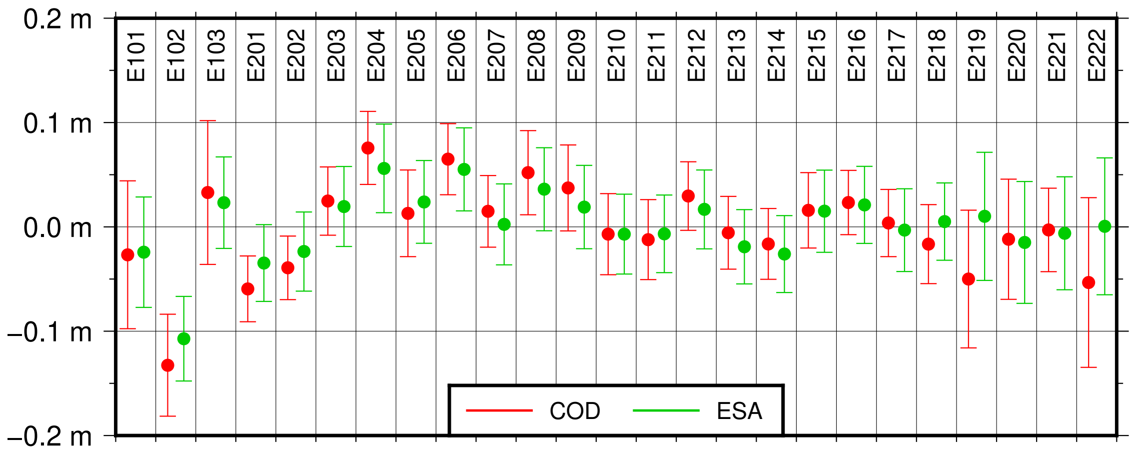

Figure 2: Mean and scatter of the time series of estimated daily corrections to the GSA z-PCO value of each Galileo satellite, relatively to the average of all z-PCO values provided by GSA.

Based on these results, it was decided to keep the z-PCO values from GSA unchanged in igsR3.atx for all Galileo satellites except E102. Daily corrections to the GSA z-PCO value of satellite E102 were estimated from the 2017-2018 multi-GNSS test solutions of CODE, ESA, GFZ, GRGS and TUG, while fixing the z-PCOs of all other Galileo satellites to their GSA values (and freely estimating all GPS and GLONASS satellite z-PCOs). A weighted average correction to the GSA z-PCO value of satellite E102 was finally computed and applied into igsR3.atx.

At this point, the z-PCO values of all GPS and GLONASS satellites had been made internally consistent in igsR3.atx, and the internal consistency of the Galileo satellite z-PCO values provided by GSA had also been verified – except for E102 whose z-PCO value was consequently adjusted. The last remaining step in the preparation of igsR3.atx was to make both sets of satellite z-PCOs consistent with each other, i.e., to proceed to the "scale transfer" from Galileo to GPS and GLONASS. For that purpose, a common correction to all GPS satellite z-PCOs and another common correction to all GLONASS satellite z-PCOs were estimated from each 2017-2018 multi-GNSS daily test solution of CODE, ESA, GFZ, GRGS and TUG, while fixing the z-PCOs of all Galileo satellites to their igsR3.atx values. The daily corrections thus commonly estimated to all GPS (resp. GLONASS) satellite z-PCOs are shown in Figure 3 (resp. Figure 4). Their weighted average, –16.0 cm (resp. –15.7 cm), was applied to all GPS (resp. GLONASS) satellite z-PCOs in igsR3.atx.

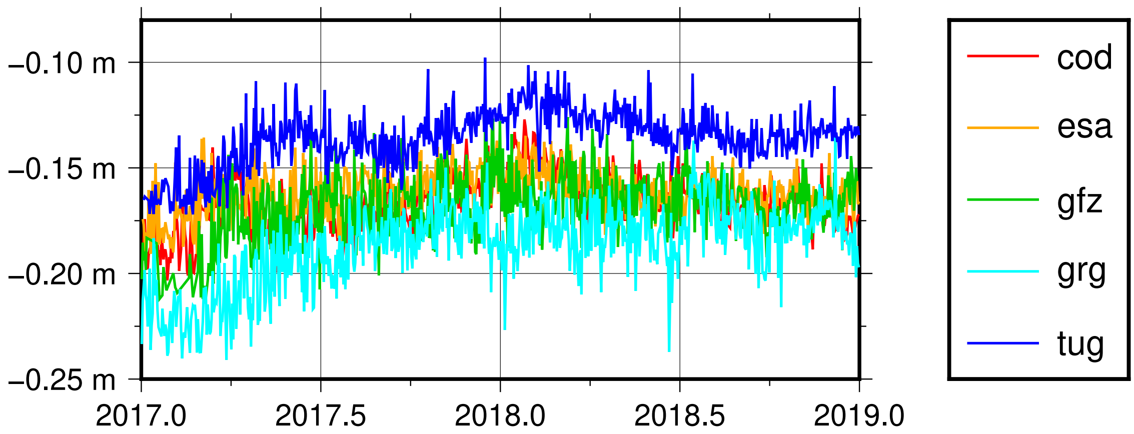

Figure 3: Daily corrections commonly estimated to all GPS satellite z-PCOs

According to Zhu et al. (2003)'s rule of thumb, this ≈–16 cm correction brought to the GPS and GLONASS satellite z-PCOs would have a ≈ +8 mm impact on the terrestrial scale. Since the igs14.atx GPS and GLONASS satellite z-PCOs were derived so as to give access to the ITRF2014 scale at epoch 2010.0, one can therefore expect that the Galileo-based scale of the IGS repro3 solutions will present an offset of ≈ +8 mm with respect to the ITRF2014 scale at epoch 2010.0. As for the scale rate of the IGS repro3 solutions, it will still be governed by the assumption that (most) satellite z-PCOs are constant with time, and should therefore be close to that of the repro2 solutions, i.e., ≈ +0.17 mm/yr with respect to ITRF2014 (Rebischung and Schmid 2016).

2.3 Elaboration of a repro3-specific reference frame (IGSR3)

Several changes from the current IGS operational standards to the repro3 standards make the current IGS reference frame (IGS14) inadequate for repro3:

- the change from the IERS2010 mean pole model to the new recommended secular pole model, which will introduce a time-variable deformation pattern between the IGS repro3 solutions and IGS14,
- the update of some ground antenna calibrations from igs14.atx to igsR3.atx, which will introduce antenna- and station-dependent position offsets between the IGS repro3 solutions and IGS14,
- the update of the satellite z-PCOs from igs14.atx to igsR3.atx, which will introduce a ≈+8 mm scale difference between the IGS repro3 solutions and ITRF2014/IGS14.

A repro3-specific reference frame (IGSR3), consistent with the new IERS secular pole model and igsR3.atx, was therefore constructed via the following procedure:

- Satellite PCOs were first fixed to their igsR3.atx values in the daily repro2/operational SINEX solutions from CODE, EMR, ESA, GFZ, JPL, MIT, NGS and ULR for GPS weeks 730 to 2069, in order to make their scale consistent with the satellite z-PCOs from igsR3.atx.
- Daily combinations of those AC SINEX solutions were performed.
- The stations selected to realize the IGSR3 reference frame were extracted from

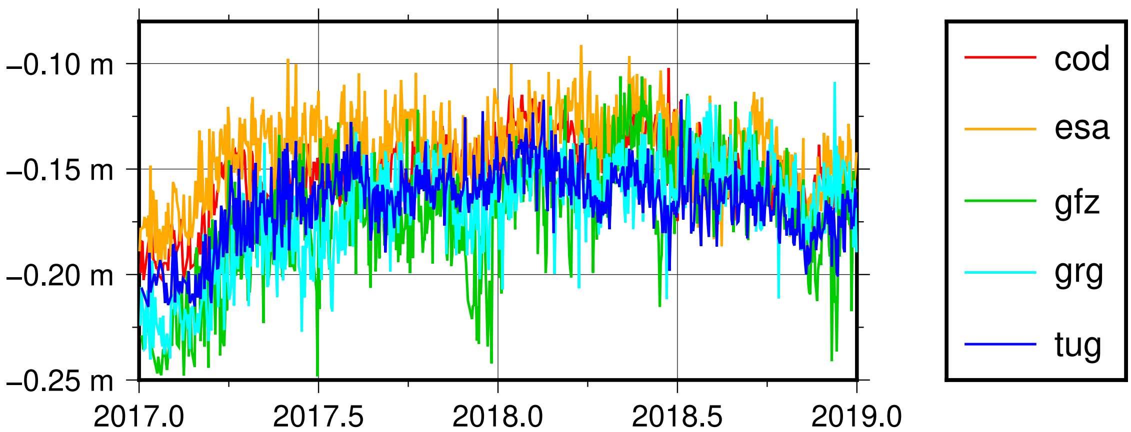

Figure 4: Daily corrections commonly estimated to all GLONASS satellite z-PCOs

the daily combined solutions. This includes all IGS14 stations and 9 additional stations (ASCG, BHR4, CUSV, DAKR, ISBA, KOUG, NOVM, SEYG, THU2) that are either substitutes for now decommissioned IGS14 stations, or located in areas sparsely covered by IGS14 stations.

- Station position corrections were applied to the daily combined solutions up to week 1933 to account for the "igs08.atx → igs14.atx" ground antenna calibration changes. Those corrections were taken either from ftp://igs-rf.ign.fr/pub/IGS14/igs08_to_igs14_offsets.txt when available, or computed from the latitude-dependent models provided at ftp://igs-rf.ign.fr/pub/IGS14/lat_models.txt.
- Pole tide corrections were applied to the daily combined solutions in order to make them consistent with the new IERS secular pole model.
- The daily combined solutions were stacked into a long-term solution (i.e., IGSR3) aligned in origin and orientation (but not in scale) to IGS14. The scale of this long-term solution was based on the intrinsic scale information of the input daily combined solutions, i.e., on the igsR3.atx satellite z-PCOs.
- Station position corrections were finally applied to IGSR3 in order to account for the "igs14.atx → igsR3.atx" ground antenna calibration changes. Those corrections were derived from dedicated differential PPP analyses and are available at ftp://igs-rf.ign.fr/pub/IGSR3/igs14_to_igsR3_2077.txt.

The final version of the repro3 reference frame SINEX file is available at:

- ftp://igs-rf.ign.fr/pub/IGSR3/IGSR3_2077.snx
- ftp://igs-rf.ign.fr/pub/IGSR3/IGSR3_2077.ssc (without covariance matrix)

The associated discontinuity list and post-seismic deformation models are respectively available at:

- ftp://igs-rf.ign.fr/pub/IGSR3/soln_IGSR3.snx
- ftp://igs-rf.ign.fr/pub/IGSR3/psd_IGSR3.snx

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IGS Realtime Service Technical Report 2019

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1 Introduction

The IGS Real-Time working group has started holding regular telephone conferences again in 2019. A summary of the two telephone conferences held on March 19 and November 11 is provided in the following sections.

2 Summary of RT-WG telephone conference on 2019/03/19

2.1 Transition to receiver-generated multi-GNSS RTCM-MSM streams

While the majority of the RTCM streams on IGS casters are generated by the receiver directly, some streams are generated by external software. This is the case, for example, for streams from GFZ and NRCan and most streams on the caster "mgex.igs-ip.net". Streams are typically switched to the caster "igs-ip.net", when a native (receiver-generated) stream becomes available.

Many stations still only disseminate a GPS+GLO legacy RTCM streams, even though the new RTCM multi-system-messages (MSM) could also be generated. In order to make more native multi-GNSS streams available and support processing of the new constellations, an email to station operators was sent out asking to upgrade legacy GPS+GLO streams to MSM if possible.

2.2 Alignment of receiver stream mountpoint names

A current inconsistency at some IGS casters is the some observation streams have the short mountpoint names and some are already provided as new long mountpoint names. It has been decided to make all streams available as long mountpoint names but still relay them to short mountpoint names. The short mountpoints will eventually be hidden in sourcetable. It is planned to have all mountpoints transitioned to long names by end of 2019.

2.3 Long mountpoint names for products caster

A new long mountpoint name conventions for the products streams has been proposed and discussed. A decision on the new format and the transition has not yet been reached.

2.4 SSR latest status in RTCM and future strategy for IGS

Geo++ summarized the latest activities concerning the RTCM SSR messages. Revised Multi-GNSS messages for phase biases without flags haven been proposed to RTCM. Vote on acceptance of format and interoperability testing expected in May 2019. Vote for standardization potentially by end of 2019. In addition SAPCORDA and geo++ are planning to publish their own formats, which are interesting candidates for the dissemination of IGS RT corrections.

2.5 Availability of validated ephemeris

It has been requested to report all observed issues with real-time broadcast ephemerides to Nacho and the station operators, so they can fix the issues. GMV has offered to provide their validated BCE stream to IGS.

2.6 Galileo Broadcast Navigation Data

It was noticed that the update period of the Galileo broadcast ephemerids seems variable. The reason is that while 10 minutes is the nominal update minutes, not all satellites are always updated at the nominal period. The SSR corrections should be computed with respect to the latest available ephemerides.

2.7 RTCM support of BeiDou-3

It was decided to bring BeiDou-3 support up at next RTCM meeting with the goal to implement the new signals into the RTM-MSM messages.

2.8 Guidelines for IGS broadcasters

It was noticed that there is a lack of IGS guidelines and definitions for caster operators. It was decided to identify and collect rules and guidelines (based on EPN Data Centers and Broadcasters) and possible additions to the site logs and publish them on IGS R-T website. Also, to improve traceability of stream sources, the regional broadcaster or source for each mountpoint shall be identified and listed in the sourcetable.

2.9 Consideration of RT aspects in site logs

It has been noted that no broadcaster section is present in the IGS site logs. The question was raised whether the IGS guidelines are up-to-date with respect to RT issues (e.g. "New Site Checklist", "Current IGS Site Guidelines"). It has been decided to address this issue in the actions related to the caster guidelines.

2.10 Long-term preservation of RT orbit and clock corrections in file formats

The question was raised whether a long-term archiving of RT orbit and clock corrections from individual ACs is necessary. It has been noted that so far at CDDIS only 'igc' (clk, sp3, CoM, GPS) and 'igt' (clk, APC, GPS) are archived, but neither 'i3a' and 'i3c' (IGS03 with GPS+GLONASS) nor individual AC solutions. BKG received some requests for such files in the past.

Loukis has generated and collected RINEX clock and SP3 files from individual AC solutions for the combination and comparison. He offers to transfer them to other DCs or ACs on demand, but they are not to be published on the official data servers of IGS.

2.11 Multi-GNSS ultra-rapid products

It has been noted that more hourly RINEXv3 observation files are needed to support the generation of multi-GNSS ultra-rapid products. It has been decided to make a list of stations not providing RINEXv3 hourly (but RINEXv3 daily) and contact those station operators to change file submission. It has further been decided to change stream-generated 15 minute RINEXv2 files to RINEXv3 for those stations providing multi-GNSS MSM-messages.

3 Summary of RT-WG telephone conference on 2019/11/20

3.1 Status of long observation mountpoint names

The CDDIS and the BKG casters have made good progress and is ready to hide short mountpoint names. The GA caster is not ready yet and envisages to complete switch end of February 2020. It has been decided to hide all short mountpoints for receiver streams by end of Feb 2020, decide about disabling short mountpoints at IGS Workshop in 2020.

3.2 Status of long product mountpoint names

An updated proposed format for the long product mountpoint names has been proposed, discussed and accepted. BKG will provide a mountpoint name transition table. It has been decided to introduce the new long mountpoint names until Feb 2020. At the next telecon it will be decided how to proceed with the short mountpoint names of the individual AC product streams. The short mountpoint names for legacy IGS combination streams.

3.3 Proprietary multi-GNSS SSR messages

It has been noted that a format description of the proposed multi-GNSS SSR messages for Galileo, BeiDou, QZSS (...) is not publicly available. Only SSR messages for GPS and GLONASS are currently part of the official RTCM messages. To move forward to multi-GNSS support the following options have been suggested:

1. Galileo (or other) messages could be included in IGS proprietary messages. IGS could define its own format and make that publicly available.
2. geo++ SSRZ-format multi-GNSS format to be published by the end of the year. Some manufactures already testing the new format.
3. SAPCORDA is also working on an independent format with multi-GNSS support. The release date not yet known.

It has been decided to re-evaluate at next RT-WG phone conference which (new) options for multi-GNSS messages are available.

3.4 Galileo navigation data type for SSR encoding

Galileo I/NAV is selected as reference for SSR corrections irrespective of the clock reference signals being used. This is documented in the SSR message description, but the information is not available to the public since the messages are not approved as official messages by RTCM.

3.5 Add encrypted uploads to BNC

It has been noted that the CDDIS caster can only accept encrypted stream uploads. This is currently not supported by BNC and as a result the IGS products cannot be streamed to the CDDIS caster. BKG reports that encrypted upload is under development for next BNC version coming in 2020. It has been decided to make the RT-WG needs for encryption and integrity a topic for next IGS workshop.

3.6 Status of Multi-GNSS real-time products and combinations

The following status of RT analysis and combination centers with respect to multi-GNSS processing has been reported:

RT Analysis Centers:

DLR-OP:	GPS, GLONASS, Galileo, BeiDou-2/ -3, QZSS
ESOC:	GPS-only, multi-GNSS as test products only internally
NRCan:	GPS-only, going towards multi-GNSS, GLONASS+Galileo planned first, then BeiDou
GMV:	GPS, GLONASS, Galileo, BeiDou
BKG:	GPS, GLONASS
GFZ:	GPS,GLONASS, Galileo, BeiDou-2 (addition of BeiDou-3 and QZSS planned Feb 2020) (received from GFZ by email)

RT Ionosphere Processing:

Wuhan:	IAG launched a WG 4.3.1 Real-time Ionosphere Monitoring and Modeling for the period 2019-2023, which will work closely with IGS Ionosphere and RT WGs in support of real-time VTEC and STEC modeling and dissimilation. An experimental IGS combined RT ionospheric data streams had been generated and transmitted based on the RT-GIMs from CAS, CNES and UPC-IonSAT, which hopefully, will be open to the public after more validations. (received from Wuhan via Email)

RT Combination Centers:

ESOC:	GPS-only
BKG:	GPS+GLONASS

Others Topics:

NRCan:	working on PPP-capable real-time stream combination
GFZ:	new orbit combination software being developed for multi-GNSS with focus on post-processed orbits (IGS final) using a new combination method

3.7 Status of guidelines for IGS broadcasters

BKG reports that a document with an overview of existing guidelines has been compiled. The working group needs a decision on how to go forward. It has been decided to disseminate the newest document to all WG members and make a vote on the way forward.

3.8 Alternative to NTRIP

GA reports that they are working on an independent caster development and investigating on alternative formats to NTRIP. The results will be shared in next RT-WG telecom.

3.9 Next RTWG phone conference

It has been decided that at least two phone conferences should happen next year in preparation for the IGS workshop in Boulder. The next one is anticipated at the end of Feb 2020.

Space Vehicle Orbit Dynamics Working Group Technical Report 2019

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1 Introduction

Several groups and individuals within the IGS community are working on topics related to spacecraft orbit dynamics and attitude modelling. Recent progress in these areas show there is scope to improve the accuracy of the orbits and observable modelling through these studies that will be of direct benefit to IGS products and users. Moreover, given the emergence of new constellations the IGS will need spacecraft specific force and attitude models in order to fully exploit the availability of the new signals. The formation of the group will help formalise and coordinate the efforts of the individual groups in this area.

2 Tasks of the Working Group

When it was established in 2011 the working group defined the following tasks:

- Solar radiation and thermal force effects: Develop physical models of solar radiation pressure and thermal re-radiation forces for all satellites tracked by the IGS; implement and test the models
- Earth radiation force effects: explore and assess sources of data for earth radiation flux modelling; develop accurate and/or compact models of earth radiation fluxes for both post- processing and predictive applications; develop enhanced methods for modelling the interaction of the radiation with the spacecraft structure/surfaces of all satellites tracked by the IGS; implement and test these models
- Antenna thrust: source information on the transmit power of all satellites tracked by the IGS; implement and test models of the resulting accelerations

- Given the enhanced physical modelling enabled by (1)-(3) the group will revisit the problem of proposing and assessing appropriate empirical/stochastic parameterisations required to account for the remaining force effects that we do not understand
- Satellite attitude behaviour: study and attempt to model the attitude behaviour of all satellites tracked by the IGS; implement and test models, disseminate guidance on implementation
- Develop a dialogue with spacecraft manufacturers and space agencies with a view to acquiring the optical and thermal properties as well as structural and attitude control algorithm data required for precision force modelling
- Provide a web repository of spacecraft data, force models, software, documentation and guidelines accessible to the entire community.
- Investigate the impact of the new modelling approaches on the terrestrial reference frame – seeking metrics that will validate the TRF changes in terms of accuracy and precision.

At the IGS workshop in Wuhan in 2018 the working groups existence was discussed in detail. It was decided that the working group was still very important for the IGS and that many different orbit modelling activities are taking place within the different groups participating in the IGS but also outside of the IGS. It was concluded that there was a clear lack of information flowing to the ACs who need these models to improve their orbit models and with that the IGS products. So it was considered best if the chairmanship of the working group would go to someone who is more closely involved and better connected to the different IGS ACs. Also all ACs were requested to have one of their group as a member of the working group in order to not miss any of the new development.

3 Recent Activities

Since the Wuhan workshop a couple of things have happened. Firstly, the mailing list was (re)activaited and new members were added and some old ones removed. An orbit integration test was performed and a detailed analysis of the different AC orbits was performed and discussed. A position paper was written for the 2019 IGS AC workshop in Potsdam, Germany.

Orbit Integration Test

A simple orbit integration test was developed which all IGS ACs can use to test their orbit integration. Different results were generated as "benchmark" to be able to test the implementation of different models like, e.g., effects of planets, solid earth tides, and ocean tides. Several ACs have participated in that and the agreement was very good. It is planned to continue this simple test and to enchance it to also be able to test solar radiation pressure implementations and Earth Albedo and IR implementations.

For more information on this see the Orbit Test Comparisons by Thomas Herring on the 2019 Workshop web-site:
http://acc.igs.org/workshop2019.html

Detailed Orbit Analysis

As discussed and initiated at the IGS workshop in Wuhan, China in November 2018 we have made an analysis of the IGS final orbit products to investigate what kind of systematic effects are visible between the different AC orbits. This investigation should lead to some recommendations to the ACs for the modeling of the orbits for the third reprocessing and of course also the IGS routine processing. Besides comparing the different IGS solutions the investigations also made use of solutions simulating certain modeling approaches using a homogeneous data set and the same software so that the differences between the solutions are purely caused by the difference introduced in the processing. These test solutions have assisted in understanding which models work for which satellites. Based on all this we have come up with a set of conclusions and a limited set of recommendation which are meant as base for discussion at the workshop.

If one looks at the presented orbit differences it becomes very obvious why all our IGS time series are full with signals with draconic periods as presented many times over the last decade! To reduce those signals we, the IGS ACs, must improve the orbit models! The somewhat disturbing fact here is that despite the very good performance of the JPL GSPM model even the JPL time series still show significant draconic periods. So it is obvious that also in repro3 we will not get rid of these artifacts in the IGS solutions. But hopefully we can get a better agreement between the different ACs then we currently have and with that hopefully also some real accuracy improvements. In any case these results clearly show that the largest error source in our IGS products today are in our GNSS orbits. And time spend on improving our understanding of the GNSS orbits is most likely time that is very well spend!

As we have distinctively different satellites it turns out that certain approaches work well on one type of satellite do not on an other. E.g. ECOM2 is clearly failing for the block IIF satellites but works well for the II/IIA and IIR satellites. So we, the IGS ACs, will not be able to avoid doing different things for the different satellite block types.

From the work we have done in the scope of this paper we have learned the following:

- The JPL GSPM model works very well
- The ECOM approach can no longer be considered adequate for modeling the block II/IIA and the block IIR satellites. It does, however, work well for the block IIF satellites

- The ECOM2 approach does not work very well for the block IIF satellites nor (most likely) for the GLONASS satellites
- The IGS/ESA box-wing model is not working properly for the IIF satellites, the newly "tuned" model seems to perform OK
- The SIO AC has to improve its handling of the IIR satellites, in particular the radial component
- The GRGS AC has to improve its handling of the II/IIA and the IIF satellites

Based on the results obtained in the scope of this paper we make the following recommendations:

1. The JPL GSPM model may be used for all GPS satellites
2. The ECOM2 approach may be used for the block II/IIA and block IIR satellites but not for IIF. Most likely not very well suited for GLONASS either
3. The IGS/ESA box-wing model may be used for all GPS satellites and for GLONASS (with tuned values for IIF)
4. Much more research effort has to be put into the satellite orbit model in order to reduce, if not eliminate, the spurious draconic terms in the different IGS products.

Although a lot of effort has been put into this work much more remains to be done as it is clear that the orbit errors the dominating error source in our GNSS products. Some further items to be investigate are:

- Is there is significant difference between the block II and IIA satellites. The values in the JPL GSPM model do seem to indicate this
- How good is our Earth Albedo modeling (EA). I assume that the mean effect (scale change) is reasonably accurate. However, we have no reliable material properties for the back side of the solar panels. This is may leads to significant modeling errors.
- How good is our Earth Infra-red modeling (IR). Here we have no reliable values for any of the surfaces. This may lead to significant modeling errors. In our IIF investigations where we tried to use the satellite clocks (the IIF satellites have good clocks) as a quality indicator for the radial orbit errors. In these test we found that turning of EA and IR did in fact improve the clocks, i.e. improved the radial orbit component. More work needs to be done in this direction.
- We have not done much with nor for GLONASS nor is there a JPL GSPM model for GLONASS. Some efforts in this domain are certainly warrented.

The presentation of this position paper may also be found on the IGS AC workshop of 2019 (Overview of White paper on Orbit Modelling by Tim Springer):
http://acc.igs.org/workshop2019.html

4 More Information

More information about this IGS Working Group can be found on the IGS web-site, in particular at the following links:

- IGS Working Groups page (click on the Space Vehicle Orbit Dynamics): http://www.igs.org/wg
- Charter and Membership page: https://kb.igs.org/hc/en-us/articles/203081487-Satellite-Vehicle-Orbit-Dynamics-Working-Group-Charter-and-Members

Tide Gauge Benchmark Monitoring Working Group Technical Report 2019

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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 2019

- TIGA-AC's are actively preparing for the participation in the IGS-repro3 or planning to align TIGA activities with IGS-repro3 time line.
- The integration of Tide Gauge information (nearest tide gauge) into the IGS Web Site (http://www.igs.org/network) was finished with the help of the SONEL TIGA Data Center, IGS, UNAVCO and the IGS-IC. Web users will see the particular next tide gauge with a link to http://www.sonel.org. The information is updated regularly in cooperation with IGS and SONEL.
- The Sixteenth session of the Group of Experts for the Global Sea Level Observing System (GLOSS) in Busan revealed a number of GNSS at tide gauge stations not part of TIGA and GNSS@TG. The TIGA Chair and TIGA network coordinator established contacts and integrated new station into the repository.
- 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 2019 in total 204 local ties information are available at http://www.sonel.org/-Stability-of-the-datums-.html?lang=en. The current number of GNSS@TG stations available on SONEL is 1151 (TIGA: 122 stations, with 18 decommissioned) stations (with 177 stations decommissioned). Still there are 149 stations where the GNSS data is not (yet) available for scientific research. At the GE16 GLOSS meeting and the IHO WG4 meeting, the importance of the leveling information was raised. Collaboration between SONEL and NOAA has been initiated for the definition of a unique file format for GNSS@TG leveling data exchange. In addition to the solution developed at the University of La Rochelle (ULR), SONEL provides now GPS solutions from Nevada Geodetic Laboratory (NGL) and Jet Propulsion Laboratory (JPL). SONEL plans to provide the TIGA combined solution and other individual solution in the near future.

3 Related important Outreach activities in 2019 (selected)

- Participation and reporting Tides, Water Level and Currents Working Group (TWCWG), 4th TWCWG Meeting, Busan, Republic of Korea - 8 to 12 April 2019
- Sixteenth session of the Group of Experts for the Global Sea Level Observing System. 11-13 April 2019, Busan, Republic of Korea
- Reporting IGS Membership Meeting, 8 December 2019 at AGU 2019 in San Francisco

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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 2019

Working group members are listed in Table 2.

Table 2: TIGA Working Group Members in 2019

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(s)	ex officio	USA
Michael Moore	IGS AC coordinator(s)	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 2019

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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 2019

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

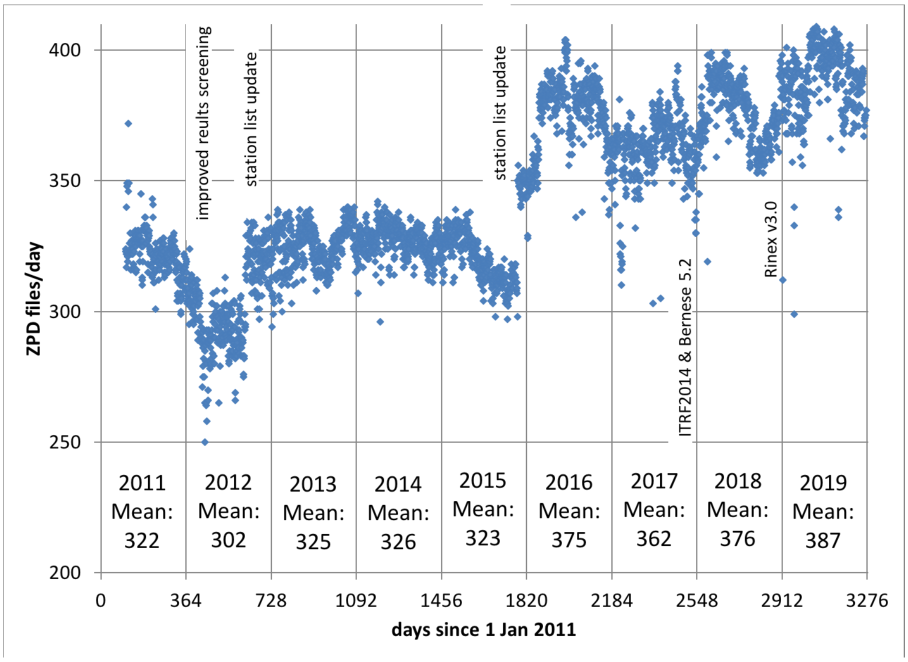

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011-2019. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011.)

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 2011-2019. The average number of quality-checked station result files submitted per day in 2019 was 387, slightly higher than the 2018 average value of 376 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`.

3 IGS Troposphere Working Group Activities 2019

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 once or twice per year: the fall in conjunction with the American Geophysical Union (AGU) Fall Meeting (USA), in the spring/summer, either in conjunction with the European Geosciences Union (EGU) General Assembly (Vienna, Austria), and/or at the IGS Workshop (location varies)

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 2019 Working Group Meetings

The working group met once in 2019 in conjunction with the 2019 AGU Fall Meeting in San Francisco, CA in December.

The December 2019 meeting lead by Dr. Sharyl Byram discussed:

- The quality and production of IGS Final Troposphere Estimates
- The status of current working-group projects
- The status of Repro2 troposphere estimates
- A discussion of future projects

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. 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

[1] Very Long Baseline Interferometry
[2] Doppler Orbitography and Radiopositioning Integrated by Satellite

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.

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 has defined 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, and the format has been accepted by the IGS Troposphere Working Group in late 2019 to present to the IGS Governing Board for formal approval. 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 Dr. 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]GCOS (Global Climate Observing System) Reference Upper Air Network: http://www.gruan.org
[4]European Cooperation in Science and Technology: http://www.cost.eu
[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:

- contact Dr. Sharyl Byram at sharyl.byram@navy.mil,
- 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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Part V

Additional Contributions

SLR data processing to GNSS satellites and GNSS precise orbit determination at Wroclaw University of Environmental and Life Sciences
IGS Technical Report 2019

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1 Introduction

In 2019, the Global Navigation Satellite System (GNSS) working group at Wroclaw University of Environmental and Life Sciences (UPWr) conducted two main branches of research involving the validation of multi-GNSS orbit products using Satellite Laser Ranging (SLR) data as well as the development of solar radiation pressure (SRP) modelling strategies for Galileo satellites. The description of the orbit validation system, which is maintained at UPWr in the framework of the Associated Analysis Center activities of the International Laser Ranging Service (ILRS, Pearlman et al. 2019a, b), is placed in section 2. Section 3 focuses on the analysis results of the experimental Galileo orbit products, which incorporate the macromodel of Galileo satellites called 'box-wing' for the purposes of SRP modelling. More information can be found in the given references as well as at: http://www.igig.up.wroc.pl/igg/.

2 Online orbit validation service

At a time of growing demand for the multi-GNSS constellation, civil and scientific users need intuitive and real-time information about the quality of available multi-GNSS products. The SLR technique can be used as a data source of independent validation for the microwave-based orbit products. UPWr maintains the independent online tool called GOVUS, which allows the assessment of the quality of the multi-GNSS orbits. The

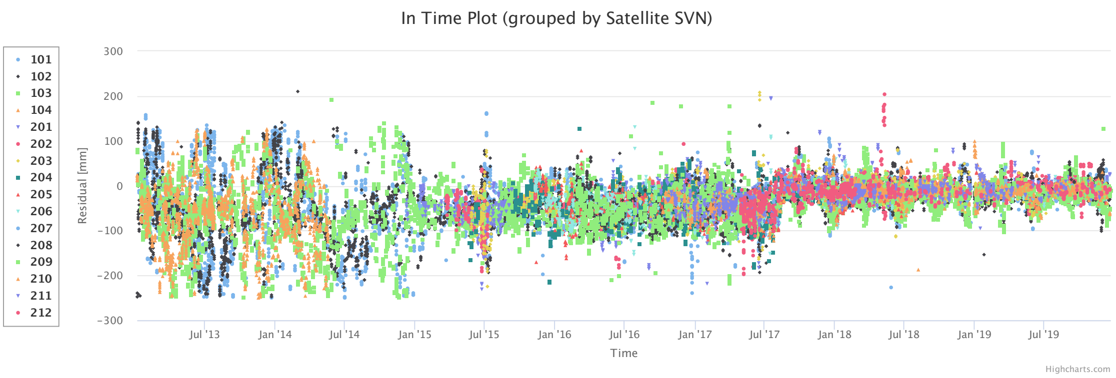

Figure 1: Example of the plot from the GOVUS service; Time series of SLR residuals for Galileo satellites in the period 2012-2019.

GOVUS service expands the capacity of the International GNSS Service (IGS) to support the precise orbit determination activities. GOVUS is available at http://www.govus.pl.

The GOVUS service (Zajdel et al. 2017a) is addressed to users of multi-GNSS orbit products and SLR stations belonging to the ILRS, which track GNSS satellites (Sośnica et al. 2018b). The main tasks of the developed service are to (1) store archival and current information about the ILRS laser stations and multi-GNSS satellites; (2) store the multi-GNSS microwave orbit validation results using SLR and prepare descriptive reports for users; (3) allow for fast and advanced online analyses on the stored dataset; (4) provide an autonomous computing center. Among all the current providers of multi-GNSS orbits, only the products delivered by the Center for Orbit Determination in Europe (CODE, Prange et al. 2017) are currently being validated as a representative example of 5-system orbit products delivered in the framework of MGEX. CODE multi-GNSS orbit includes particular types of satellites: GPS, GLONASS of type M, M+ and K, Galileo of type IOV and FOC, BeiDou-2 of type MEO and IGSO and QZSS IGSO. On the other hand, the GOVUS service is ready to use with other IGS Analysis Centers depending on the GNSS community demands.

The GOVUS service supports a large variety of potential applications with a strong focus on science and education. Continuous monitoring and independent validation are advised by both the MGEX and IGS to help in the description of satellites' behavior in space (Sośnica et al. 2018a). The service is divided between separate tools, which allow the user to adjust the scope of the analyses to the specific satellites or the selected time range. The validation results may be analysed in the form of the descriptive statistics, the SLR residual time series (see Fig. 1), histograms or plots, which show the dependencies between the SLR residuals and different angles in the Sun-Earth-Satellite frame (see Fig. 2, Zajdel et al. (2017b)). The dataset, which is generated by the user in GOVUS, is freely accessible and ready to download in *.csv format. Moreover, all the plots can be

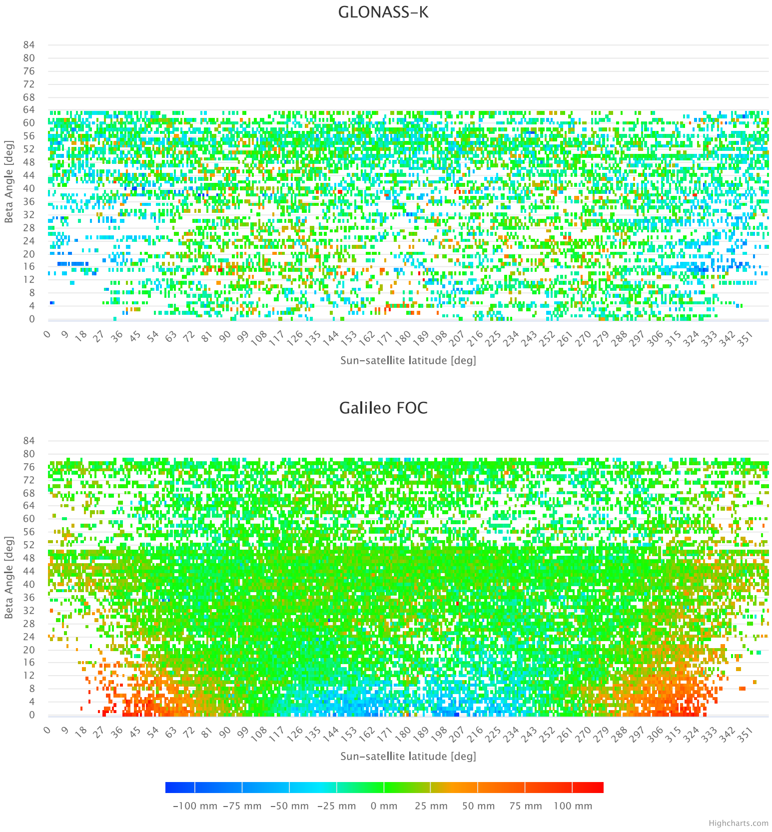

Figure 2: SLR residuals as a function of elevation of the Sun above the orbital plane (β) and argument of latitude of the satellite with respect to the argument of the latitude of the Sun (Δu) (period 09/2018-12/2019).

downloaded in raster (*.png and *.jpeg) or vector (*.svg and *.pdf) file formats, thus the users may adjust selected plots to their individual needs.

Daily reports of SLR validation are available at `https://www.govus.pl/slr/daily/`.

3 Precise orbits of the Galileo satellites

Based on the metadata for the Galileo satellites[1] released by the European Global Navigation Satellite System Agency (GSA), we have composed the box-wing model. The box-wing model is suitable for both types of the Galileo satellites, i.e., the In-Orbit Validation (IOV) and Fully Operational Capability (FOC). The box-wing model is capable of absorption of the accelerations resulting from solar radiation pressure (SRP), albedo and

[1]https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata

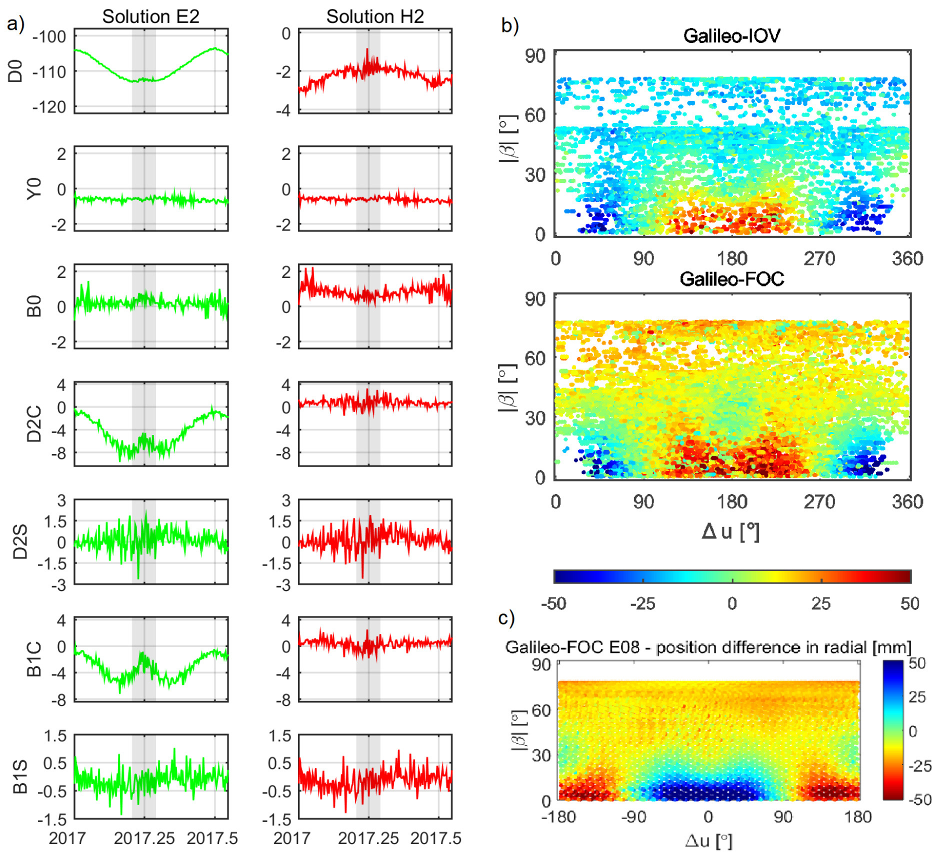

Figure 3: a) Empirical parameters estimated in empirical *(left)* and hybrid *(right)* strategies for the Galileo-FOC E09 expressed in nm/s^2. b) Differences between SLR residuals to Galileo-IOV *(top)* and FOC *(bottom)* provided from solutions with and without a box-wing model. c) Differences in the radial component of satellite's position from solutions with and without the box-wing model for the Galileo-FOC E08. All values are expressed in mm based on Bury et al. (2020).

infrared radiation (IR). The box-wing is consistent with that of Rodriguez-Solano et al. (2012) with the consideration of shadows resulting from both the Earth and Moon as a fraction of the eclipsed part of the Sun disk comprising antumbra and penumbra periods. The details of the box-wing model are presented in Bury et al. (2019, 2020).

The Galileo-FOC satellites are equipped with thermal radiators on -Z, +Y, -Y, and -X. During the yaw-steering, none of the Y-panels is illuminated by the Sun, nor is the -X panel which covers the clock. However, the re-radiation which comes from the radiators may cause some effects on the Galileo precise orbits. We consider only the immediate thermal re-radiation and neglect the remaining heating or cooling effects, however, the non-instantaneous thermal effect may be absorbed by the empirical models such as the Empirical CODE Orbit Model (ECOM2, Arnold et al. 2015).

Based on the analysis of the empirical parameters we found that the box-wing model can absorb up to 97% of the accelerations resulting from the direct SRP, whereas the rest can be compensated by the estimated parameters, especially, the D_0 (see Fig.3). Moreover, based on the estimated empirical parameters, we assessed the accelerations absorbed by the terms Y_0 and B_0 which are nearly the same from both solutions; hence do not have a physical interpretation explainable by direct SRP. The Y-, and B-biases may, however, be caused by the asymmetrical radiators on +/-Y panels of the Galileo-FOC.

The impact of the box-wing model was evaluated based on the analysis of the SLR residuals, i.e., the differences between SLR residuals from purely-empirical and hybrid (box-wing+empirical) solutions. The box-wing model compensates for the neglecting of the higher-order terms of the ECOM2 model which causes the effect at the level of 50 mm. A similar effect has been achieved by the analysis of the satellite position differences from the empirical and hybrid solutions.

We also assessed the most suitable strategy for the precise Galileo orbit determination. According to Bury et al. (2019), the best strategy considers both the analytical box-wing model and a reduced set of estimated empirical parameters, e.g., using ECOM1 parameters. Such a strategy provides the Galileo-FOC orbits of the accuracy at the level of 25 mm in terms of the RMS of SLR residuals (Bury et al. 2019).

The precise GNSS orbits allow to determine and analyse the global geodetic parameters from GPS-only, GLONASS-only, and Galileo-only solutions. Such studies on global network containing and deriving system-specific geocenter motion has been discussed by Zajdel et al. (2019).

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