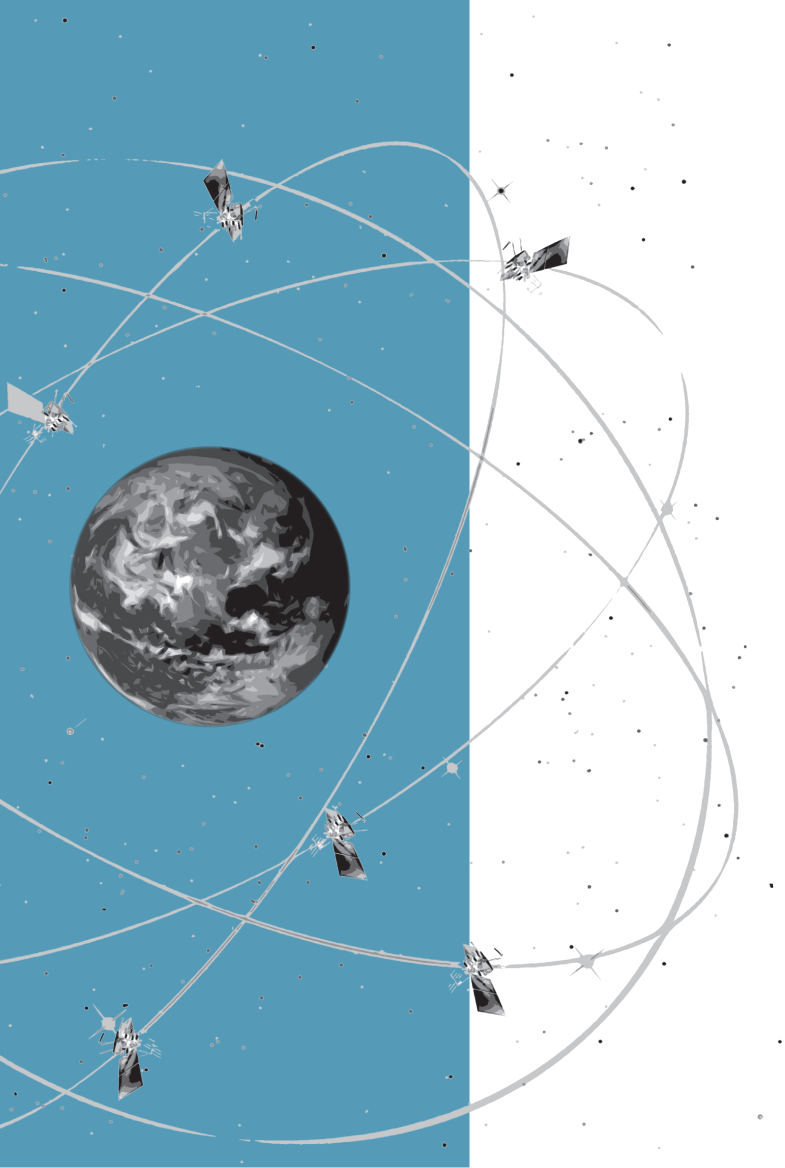
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2020



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**ASTRONOMICAL INSTITUTE
UNIVERSITY OF BERN**

International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

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Technical Report 2020

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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 2020* 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 2020.

This report is available in electronic version at
https://files.igs.org/pub/resource/technical_reports/2020_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

2020 State of the Service: the IGS Governing Board Chair Report

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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 2020, despite a global pandemic and interruptions on our life and work schedules, the IGS continued to sustain our community's needs by continuously providing. 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 are added into the core IGS network and as we re-evaluate the IGS role in achieving multi-GNSS excellence. As such, we continue to engage with the International Committee on Global Navigation Systems (ICG).

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 IGS Workshop was postponed due to the travel restrictions that resulted as a consequence of the novel COVID-19, however, we continued to interact with the community members discussing the extensive contribution and views of the organization as it pertains to the next decade. With this in mind, during 2020 we unveiled three new formats in line with community requirements (RTCM SSR, RINEX 3.05 and GZIP RINEX) and completed the third reprocessing campaign (repro3) in support of the ITRF2020. Additionally, the process for our 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 2020. The results of this plan will be published early 2021.

2 IGS Membership and Governance

2.1 Membership Growth and Internal Engagement

In 2020, IGS membership reached 335 Associate Members (AM), representing over 45 countries. The 36-member IGS 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 Figure 1.

2.2 Governing Board Appointments and 2019 AM Elections

The IGS is led by an International GB that is elected by Associate Members who represent the principal IGS participants. 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. During 2020, the GB experienced several personnel changes. The GB Chair position transitioned from Mr. Gary Johnston (Geoscience Australia) to Dr. Felix Perosanz (CNES, France) in May 2020, following Johnston's retirement. Additionally, Dr. Ignacio Romero transitioned from his former position as the Infrastructure Committee Chair to lead the RINEX WG. This position had remained vacant after the retirement of Mr. Ken McLeod from National Resources Canada (NRCan) in 2019. Another major introduction was the election and approval of Markus Bradke as the new Infrastructure Committee Chair in August 2020, and later in the year transitioned to the role of Infrastructure Committee Coordinator. Finally, several ex-officio appointments were confirmed and renewed.

Notable retirees from the GB in 2020 include Ms. Carey Noll (Data Center Coordinator) and Dr. Charles Meertens (Executive Board Member and IERS representative), long standing members of the Governing Chair. They are succeeded by Dr. Pat Michael (NASA Goddard/CDDIS, USA) and Appointed Member Dr. Elisabetta D'Anastasio (GNS, New Zealand)

Table 1 summarizes the Governing Board Membership at the end of 2020. Blue represents

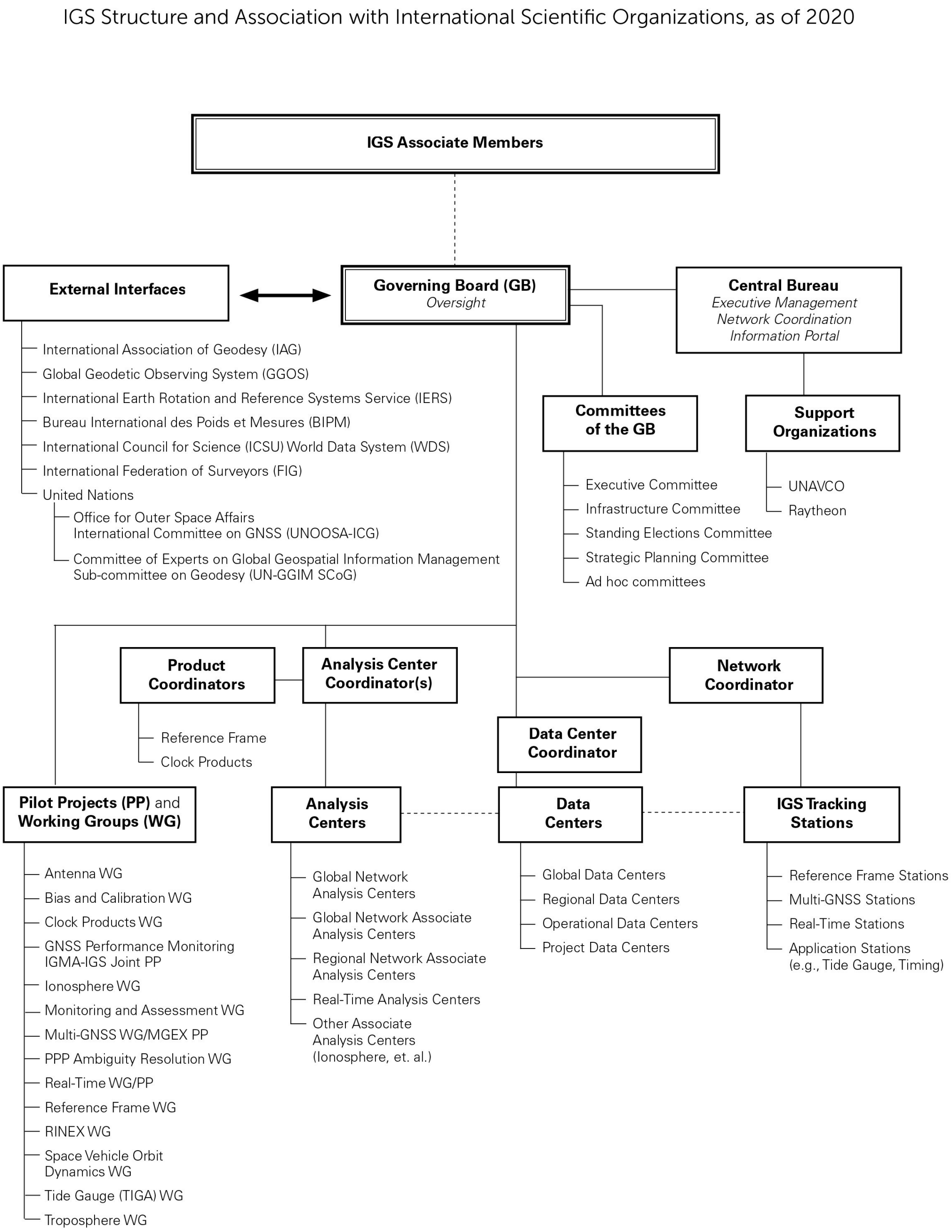

Figure 1: IGS Structure

members of the GB who have transitioned into a new position. Purple are new members to the GB.

3 Summary of Accomplishments and Decisions:

1. Successfully transition of a new Governing Board Chair, Dr. Felix Perosanz
2. Successfully led the transition of our new Infrastructure Coordinator, RINEX WG Chair, Data Center Coordinator (DCC) and two new appointees to the Governing Board.
3. Successfully conducted 3 around-the-world clock virtual Governing Board Meetings with the highest attendance in recent history.
4. Initiated the 2021 Strategic Planning process (to include conducting a wide-community survey)
5. Despite the COVID-19 pandemic, the IGS continue to provide timely and openly data and products
6. IGS stations continued operations with no interruptions
7. Completed repro3 activities
8. Approved the new Disclaimer, Terms of Use, and Attribution Policy policy development and implementation
9. Continues to support the appropriate IGS response to the EU General Data Protection Regulation (GDPR) and other privacy regulations.
10. Approved the development of the RTCM SSR
11. Continues to support the improvement of metadata services through monthly interaction with the World Data Service Metadata Working Group
12. Co-Organized the IGS session at the virtual American Geophysical Union Fall meeting
13. Approved the dissemination of newly developed IGS Products to include RINEX3.05, GZIP format for RINEX 2, etc.

Table 1: Members of the IGS Governing Board, 2020

Name	Institution	Country	Position
Felix Perosanz	CNES	France	Board Chair
Ryan Ruddick	Geoscience Australia (GA)	Australia	Network Representative
Qile Zhao	Wuhan University	China	Appointed (IGS)
	VACANT		Board Vice Chair
Zuheir Altamimi	IGN	France	IAG Representative
Paul Rebischung	IGN	France	IGS Reference Frame Coordinator
Benjamin Männel	GFZ	Germany	Analysis Center Representative
Werner Enderle	ESA/European Space Operations Centre	Germany	Appointed (IGS)
Laura Sánchez	DGFI-TUM	Germany	Network Representative
Wolfgang Söhne	BKG	Germany	Network Representative
Loukis Agrotis	ESA	Germany	Real-time Analysis Coordinator
Satoshi Kogure	NSPS	Japan	Appointed (IGS)
Basara Miyahara	GSI	Japan	IAG Representative
Rolf Dach	AIUB	Switzerland	Analysis Center Representative
Thomas Herring	MIT	USA	Analysis Center Coordinator
Charles Meertens	UNAVCO	USA	Appointed (IGS)
Allison Craddock	NASA JPL	USA	Central Bureau Director
David Stowers	NASA JPL	USA	Data Center Representative
Richard Gross	NASA JPL	USA	IERS Representative
Michael Coleman	NRL	USA	IGS Clock Products Coordinator
Patrick Michael	NASA GSFC	USA	Data Center Coordinator
Salim Masoumi	GA	Australia	Analysis Center Co-Coordinator
Suelynn Choy	RMTI	Australia	International Federation of Surveyors (FIG) Representative
Simon Banville	NRCan	Canada	PPP-AR Working Group Chair
Gérard Petit	BIPM	France	BIPM/CCTF Representative
Tim Springer	ESA	Germany	IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair
Ignacio Romero	ESA	Germany	RINEX-RTCM Working Group Chair
Oliver Montenbruck	DLR	Germany	Multi-GNSS Working Group Chair
Andre Hauschild	DLR	Germany	Real-time Working Group Chair
Tim Springer	ESA	Germany	Satellite Vehicle Orbit Dynamics Working Group Chair
Tilo Schöne	GFZ	Germany	TIGA Working Group Chair
Andrzej Krankowski	University of Warmia and Mazury in Olsztyn	Poland	Ionosphere Working Group Chair
Arturo Villiger	AIUB	Switzerland	Antenna Working Group Chair
Stefan Schaer	swisstopo	Switzerland	Calibration & Bias Working Group Chair
David Maggert	UNAVCO	USA	Network Coordinator
Mayra Oyola	NASA JPL	USA	Central Bureau Deputy Director & GB Executive Secretary
Sharyl Byram	USNO	USA	Troposphere Working Group, Chair
Markus Bradke	GFZ	Germany	Infrastructure Committee Chair (Interim, later confirmed)
Elisabetta D'Anastasio	GNS Science	New Zealand	Appointed (IGS)
José Antonio Tarrio-Mosquero	Universidad de Santiago de Chile	Chile	Appointed (IGS)

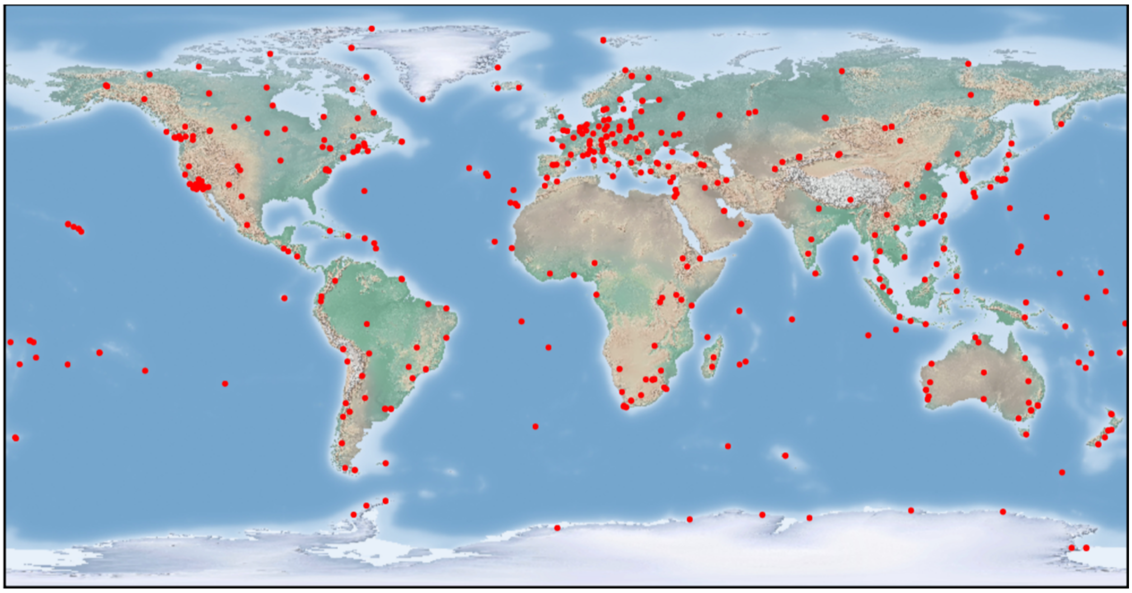

Figure 2: The 507 IGS stations as of January 31, 2020. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

4 IGS Operational Activities

4.1 Network Growth

With the assistance of the CB Network Coordinator and the Infrastructure Committee, the IGS network (Figure 2) added 5 new stations and identified 5 stations for decommissioned in 2020, bringing the total to 506 stations. The number of muti-GNSS stations increased from 308 to 326; while real-time stations increased from 259 to 270. Additionally, 95 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 573 site log updates (45 per month) and 41 antenna changes (11 of those at IGS14 core stations).

During 2020, 186 new user accounts were added to the CB real time caster, which as of January 2021, will be manned by the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado. The CB Network Coordinator also responded to over 140 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.

Table 3: ACC repro3 initial contributions

Center	GPS Contribution	GLONASS Contribution from:	Galileo Contribution from:
COD	1994-01-02 to 2019-12-31	2002-01-01	2013-01-01
ESA	1995-01-01 to 2020-12-31	2009-01-01	2015-01-01
GFZ	1994-01-02 to 2020-12-31	2012-01-01	2013-12-31
GRG	2000-05-03 to 2020-12-31	2008-11-04	2016-12-31
JPL	1994-01-02 to 2019-12-28	None	None
MIT	2007-01-07 to 2019-12-28	None	2017-01-01
NGS	1994-01-02 to 2020-12-31	None	None
TUG	1994-01-02 to 2020-12-31	2009-01-01	2013-01-01
ULR	2008-01-01 to 2020-12-31	None	None
WHU	2008-01-01 to 2019-12-31	2010-09-28	None

4.2 Product Generation and Performance

Joint management of the IGS ACC by Michael Moore of Geoscience Australia and Tom Herring of the Massachusetts Institute of Technology continued, with operations based at Geoscience Australia in Canberra, Australia. The ACC combination software is housed on cloud-based servers located in Australia and Europe, and coordination of the IGS product generation continues to be carried out by personnel distributed between GA and MIT. The IGS continues to maintain a very high level of product availability. At the end of 2020, Salim Masoumi of Geoscience Australia, succeeded Michael Moore as the IGS Co-ACC.

4.3 IGS Reprocessing Campaign 3 (repro3)

At the 2018 IGS workshop, it was decided to carry out a reprocessing that will lead to the third generation, in time for a contribution to the ITRF2020. The activities pertaining the third reprocessing (repro3) occurred during 2020.

A first set of daily and weekly combined terrestrial frame solutions from repro3 has been made available as preliminary IGS contribution to ITRF2020. The final IGS repro3 terrestrial frame solutions will be released by the extended IERS deadline (10 April 2021). It is expected that by then, all participating Analysis Centers (ACs) will have completed their reprocessing, and some minor issues identified in current AC contributions will be resolved. For now, the preliminary IGS repro3 terrestrial frame solutions are combinations of the following AC contributions:

Initial Available repro3 contributions:

Details about the available products, the modeling updates since the repro2 campaign and the combination strategy can be found in the ACC and Reference Frame WG Chapters of this document .

4.4 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.

The intense interest of users in IGS data and products is reflected in the 2020 user activity recorded by the Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center

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

4.5 Web Services, Social Media and others

A new and secured https://igscb.org has been developed with the intent to replace the functionality of the very convoluted and unsecured old webpage. A simplified domain was created under NASA's GovCloud to ensure the system is properly maintained, secured, and identified as a service within NASA/JPL. 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), does not only offer a modern interface, but 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 occurred during the last portion 2020. Ftp services have also been upgraded to https. IGS social media has also been integrated throughout the website, to facilitate sharable content and optimize engagement with IGS stakeholders. IGS audio-visual resources, made available through IGS YouTube account, were upgraded to include the last IGS Workshops and videos on how to manage the new IGS.org resources for WGs.

An effective, functional, secure, and attractive website is essential to the organization's success. Numerous GB members provided reviews, testing, and feedback throughout the redevelopment process of the IGS.org website. GB members continue to consult and advise the Central Bureau to ensure the website and other information systems resources are maintained and improved on a continuous basis.

GB and other community feedback was included in the IGS 2020 Update poster, developed by the Central Bureau to highlight the new IGS webpage and presented at the American Geophysical Union Fall Meeting. A comprehensive summary of the website refresh, describing all major improvements, was published on the IGS.org webpage and can be found at: https://www.igs.org/news/introducing-igsorg-20-whats-new/.

4.6 Scientific Applications of IGS Data and Analysis Products Session at AGU 2020

The IGS organized a session at this year's virtual American Geophysical Union (AGU) in San Francisco, CA, United States. The Session, was convened by Governing Board Executive Committee member Rolf Dach of the University of Bern, Switzerland and Allison Craddock, Director of the IGS Central Bureau and JPL. The description of the session is as follows: "The International GNSS Service (IGS) provides the scientific community with a broad range of high-precision products supporting a wide diversity of scientific applications. Currently three fully-deployed GNSS are analyzed by IGS Analysis Centers and included in the currently running reprocessing effort: GPS (USA), GLONASS (Russia), and Galileo (Europe). Developments including additional GNSS (Chinese BeiDou, Japanese QZSS, Indian NavIC, etc.) are ongoing within the IGS.

Several components of the IGS do already support a fully consistent processing of GPS, GLONASS, and Galileo in the operational chain as well as for the currently running reprocessing effort. The continuous improvement of IGS products in this fast-moving field with constantly evolving satellites, systems, signals, models, and data analysis methodology is a scientific challenge".

Table 5: 2020 GB Meeting

Date	Place	Comments
20 Feb, 2020 1230–1400 UTC	WG-Chairs Telecon	• Informal Updates from WG Chairs • Repro3 & ITRF 2020 • IC/DC Transition • SSR Activities within the IGS and path forward • Confirmation of appointments for 2020 and beyond • Working Group Pages Work • Meeting Frequency
20 May, 2020 1200–1430 UTC	GB-55 Meeting Telecon	• Workshop Status • AGU 2020 Planning • New Chair Election and Transition • RINEX WG Chair Resolution • RTM SSR Updates • IAG Updates • ACC and repro3 • Infrastructure Committee Update and Transition • IGS Technical Report Status • IGS.org updates and https transition • Upcoming Governing Board Updates *37 Participants, 34 GB Members, 20 Voting Members present*
25 Aug, 2020 1200–1430 UTC	GB-56 Meeting (Strategic Planning) Telecon	• IGS Slack Channel • COVID-19 Contingency Plan for Workshop and AGU • IC Chair Election • ITRF 2020 Status, Repro-3 Status and Progress • Strategic Planning • Update on IGS.org website • IERS representation *37 Participants, 34 GB Members, 20 Voting Members present*
16 Dec 2020 1900–2000 UTC	GB-57a Meeting Telecon	• IGS "State of Affairs" Summary: December 2019 – December 2020 • MGEX future • Workshop Status • RINEX 3.05 Format Standard • IAG President's Update • Working Group Charter Updates • ACC Update • Revised event schedule and format due to COVID-19 • Confirmation of GB Appointments for 2021 and beyond • IGS.org updates and https transition • Upcoming Governing Board Updates *37 Participants, 34 GB Members, 20 Voting Members present*

This session solicited presentations on scientific applications enabled by IGS products and new science enabled by improvements to quality and breadth of GNSS products.

4.7 Communications Development and Guidance

Numerous news pieces and social media posts covering IGS news, IGS activities, and other announcements were developed in collaboration with Governing Board members and contributing Working Groups. Many of these can be found on the IGS website under: https://www.igs.org/news/andhttps://twitter.com/IGSorg/.

5 IGS Governing Board Meetings in 2020

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. Table 5, summarizes the 2020 GB meetings.

6 IGS 2021 Strategic Planning

As detailed in the Central Bureau chapter of this report, the 2021 Strategic Planning process included an online Strategic Planning Survey (SPS) Strategic Plan for the organization. This was initiated at the virtual IGS 55th Governing Board Meeting, in May 2020. The entire road map for the next iteration of the Strategic Planning is depicted on Figure 1 of the CB chapter of this report, and can be followed online at https://igs.org/strategic-planning.

The questions included in the SPS were selected under careful scrutiny by the members of the IGS Executive Committee, taking into consideration initial feedback from the community obtained during the first Strategic Planning Associate Member Meeting, which took place in April 2019 during the European Geophysical Meeting in Vienna, Austria. The SPS was heavily advertised by the Central Bureau via social media platforms, web and IGS Mail, was available in two languages (English and Spanish) and consisted of three sections. The first section requested general information about the participant, GNSS applications and demographics. The second section asked the participant to rank the impact and relevance of the IGS role as facilitator, incubator, coordinator and advocate for the GNSS community. The last section allowed the participant to answer open questions in regards of the Strengths, Weaknesses, Opportunities and Threats (SWOT) the IGS is facing as we start the upcoming decade to include. This report is intended to summarize the results of each section of the survey for the members of the GB in preparation for the subsequent preparation and implementation of the IGS 2021 Strategic Plan

Upon analysis of both the 2020 Strategic Planning Survey the following three goals were identified for the 2021 Strategic Plan: 1) Multi-GNSS Technical Excellence, 2) Outreach and Engagement, 3) Sustainability and Resilience. This builds upon the four major community need categories that were outcomes of the 2019 Open Associate Member Strategic Planning Dialogue sessions: facilitation, coordination, incubation, and advocacy.

The discussion of each one of these goals and associated objectives will take place during the 57b Governing Board Meeting, which is solely dedicated to work and discuss the IGS Strategy for the next decade. For more details on the Strategic Planning survey response summaries, please refer to the Strategic Planning Final Response summary report compiled by the Central Bureau.

7 IGS Advocacy and External Engagement

7.1 United Nations GGIM Sub-Committee on Geodesy

IGS remains active in engaging with diverse organizations that have an interest in geodetic applications of GNSS. IGS Associate and Governing Board members continue to participate in contributing to five focus groups developed to draft the implementation plan for

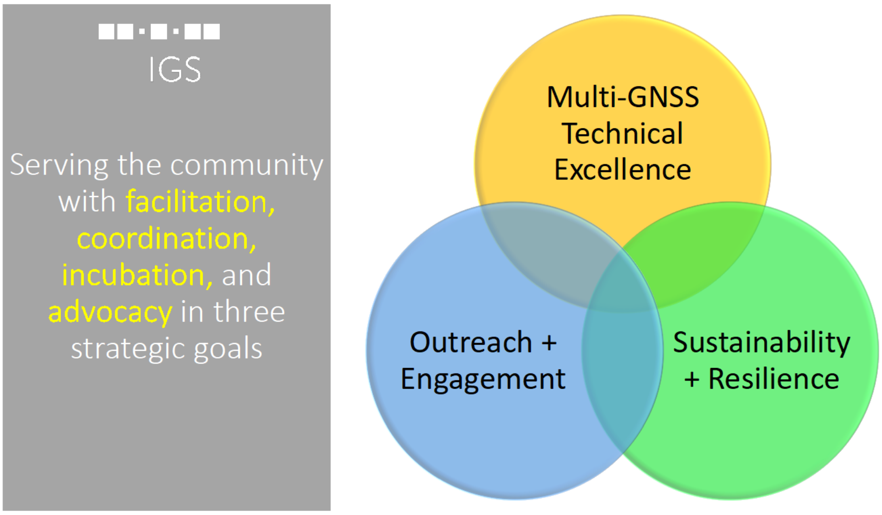

Figure 3: Suggested Organizational Goals for the 2021 Strategic Plan.

the United Nations Global Geodetic Information Management (GGIM) Global Geodetic Reference Frame Roadmap.

7.2 United Nations International Committee on GNSS

IGS serves as one of three official co-chairs of the ICG Working Group on Reference Frames, Timing, and Applications (WG-D). Due to the COVID-19 pandemic, it was decided to postpone all WG-D activity planned for 2020 to 2021.

Members of the IGS Governing Board also participate in the ICG International GNSS Monitoring and Assessment Pilot Project (IGMA).

7.3 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.

IGS Governing Board Members served on the Coordinating Board, Executive Committee, Consortium, and Science Panel of the IAG Global Geodetic Observing System (GGOS).

8 Outlook 2021 and beyond

It was expected than in 2020 the IGS workshop participants will travel to Boulder, Colorado for the 2020 IGS Workshop hosted by UNAVCO and 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 the first quarter of 2021, for which a virtual format was contemplated. However, after careful consideration, the Local Organizing Committee and the GB/CB decided to postpone it as a in-person workshop in 2022 in order to preserve the collaborative nature of the workshop. The location remains at Boulder, Co. USA.

8.1 Moving Forward

The IGS will continue to be challenged by the growing stakeholder expectations for improved product timeliness, fidelity and diversity. As these are achieved reconsideration of the IGS mission and goals will need to be undertaken to ensure we don't become tangential to the needs of our key stakeholders, the associate members. Continued efforts to enhance advocacy for the IGS are needed, with the GB and CB playing key roles in this, but not at the exclusion of all associate members. Accordingly, presentations at a variety of forums within our discipline and outside of it will need to be given, ensuring that the efforts of all contributors are acknowledged. In this way the IGS will continue to build its user base resulting in enhanced sustainability.

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 2020

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1 Introduction

The International Global Navigation Satellite System (GNSS) Service (IGS) first approved by its parent organization, the International Association of Geodesy (IAG), at a scientific meeting in Beijing, China, in August of 1993, with the goal to serve as advocate for and provide freely and openly available high-precision GNSS data and products 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). After twenty-seven years, the IGS continues to carry its original mission while 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.

The following report highlights progress made by the IGS Central Bureau (CB) in 2020. The mission of the IGS 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) and also represents the outward face of IGS to a diverse global user community, as well as the general public. The IGS CB is hosted at the California Institute of Technology/Jet Propulsion Laboratory, Pasadena, California, USA, and it is funded primarily by the US National Aeronautics and Space Administration (NASA). This office is led by Director, Allison Craddock and Deputy Director, Mayra Oyola (both at NASA-JPL, USA). The CB also works as the command-and-control center for tracking network operations, mostly overseen by the Network Coordinator, Mr. David Maggert (UNAVCO,

Table 1: IGS Central Bureau Staff (as of January, 2021)

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
Ashley Santiago	Raytheon Corporation	CBIS Intern
David Stowers	NASA Jet Propulsion Laboratory	CBIS Advisor

USA). Additionally, the CB manages the primary IGS information system (CBIS), the principal information portal where the IGS web, data and mail services are hosted. These tasks are led by Robert Khachikyan (Raytheon, USA) and Ashley Santiago (Raytheon, USA).

2 Summary of Accomplishments during the COVID-19 Pandemic

Our global IGS community continues to adapt to the impacts of COVID-19, particularly with the newly introduced changes in work environment and travel limitations. The IGS CB was faced with challenges on how to best address the various options for holding meetings virtually, particularly accommodating for various time zones and technology bandwidths. Similarly, a major concern was how to best continue to support all of our data and products dissemination through the Central Bureau Information System, as CB members have been working from their respective residences in order to comply with the stay in place measures implemented across the United States since March, 2020.

The challenges imposed by this period have provided a number of lessons that can be apply to IGS future events and projects. We have explored and mastered a number of technology applications and practices that have improve data management and membership engagement. Despite the constraints and restrictions imposed by the novel COVID-19, the CB has achieved the following:

1. Successfully led the transition of our new Governing Board Chair, Dr. Felix Perosanz
2. Successfully led the transition of our new Infrastructure Coordinator, RINEX WG Chair, Data Center Coordinator (DCC) and two new appointees to the Governing Board.
3. Achieved the timely launch of the new IGS webpage, as well as completed the transition from ftp to https data services
4. Successfully planned and conducted 3 around-the-world clock virtual Governing Board Meetings with the highest attendance in the history of the service

5. Started the 2021 Strategic Planning process (to include conducting a wide-community survey)
6. Successfully hired and trained staff member Ashley Santiago, who has been instrumental in the web page and new IGS brand development
7. Supported data and products timely delivery and maintained the IGS stations operations with no interruptions
8. Supported repro3 related activities
9. Led the new Disclaimer, Terms of Use, and Attribution Policy policy development and implementation
10. Continues to support the development of an IGS response to European Union General Data Protection Regulation
11. Supported the development of the RTCM SSR
12. Continues to support the improvement of metadata services through monthly interaction with the World Data Service Metadata Working Group
13. Continues working on the update of the Associate Members (AM) database
14. Co-Organized the IGS session at the virtual American Geophysical Union Fall meeting
15. Organized and executed monthly Executive Committee (EC) meetings
16. Opened new channels for virtual interaction, include topical Slack Channels and Google collaborative workspaces.
17. Led the recent update of Working Group Charters and Contributing Organizations
18. Supported the dissemination of newly developed IGS Products to include RINEX3.05, GZIP format for RINEX 2, etc.
19. Continues to represent the IGS and its community interests at various stakeholder levels, including the United Nations International Committee on GNSS (ICG), United Nations Committee of Experts on Global Geospatial Information Management (UN GGIM)– Subcommittee on Geodesy, World Data Service, International Association of Geodesy (IAG) Inter-Commission Committee on Climate, and the IAG Global Geodetic Observing System
20. Led pandemic response and contingency planning for the next major IGS Workshop, including developing alternative technical community interaction opportunities.

A major downfall of the pandemic in the IGS has been the postponement of the IGS Workshop, originally planned to occur in August 2020. The event was first delayed to an in-person event in 2021, with the Local Organizing Committee (LOC) and CB eventually contemplating the possibility of hosting the workshop virtually given the extension on travel restrictions and for the welfare of all participants. After a market assessment and considering feedback from the community and GB, it was decided that a virtual format would severely compromise the collaborative nature of the IGS workshop, and it was again postponed to 2022. The LOC and CB have identified a date and confirmed the availability of the facilities for a June 2022 Workshop. In the meantime, the IGS CB is working on a series of virtual technical mini-workshops dubbed as "Tour of IGS" which will focus on various topics of interest for our community.

Even during the pandemic, daily operations continue to be the heart of the IGS. Various components of the service ensure that tracking data and products are made publicly available on a daily basis. 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.

3 Executive Management and Governing Board Participation

The CB coordinated the necessary logistics and administrative organization for three fully virtual Governing Board (GB) meetings held in May, August and December. The EC met additionally by teleconference on a monthly basis. Staff of the CB, as part of its work

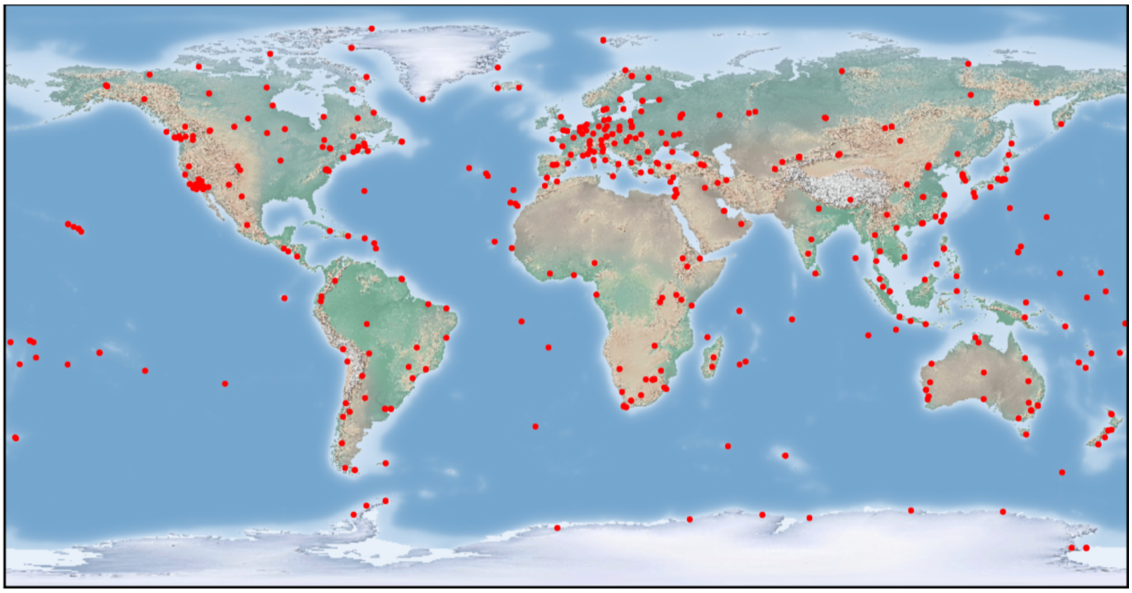

Figure 1: The 507 IGS stations as of January 31, 2020. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

program carrying out the business needs of the IGS, implemented actions defined by the GB throughout the year. A list of these activities is included in Table 2.

4 Network Coordination and User Community Support

With the assistance of the CB Network Coordinator and the Infrastructure Committee, the IGS network added 5 new stations and identified 5 stations for decommissioned in 2020, bringing the total to 506 stations. The number of muti-GNSS stations increased from 308 to 326; while real-time stations increased from 259 to 270. Additionally, 95 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 573 site log updates (45 per month) and 41 antenna changes (11 of those at IGS14 core stations).

During 2020, 186 new user accounts were added to the CB real time caster, which as of January 2021, will be manned by the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado. The CB Network Coordinator also responded to over 140 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 Governing Board chapter of this report.

5 New IGS Website and http services

The IGS has ensured open access, high-quality GNSS data products since 1994. These products enable access to the definitive global reference frame for scientific, educational, and commercial applications – a tremendous benefit to the public, and key support element for scientific advancements. Most of these resources are available or introduced to the community via our webpage, which had become outdated and difficult to navigate over time. Based on its own internal assessment and following community feedback, the CB decided it was time to redesign the site and improve its User Experience (UX) and User Interface (UI) focusing primarily on improving navigation, design and content. With this in mind, a new and secured https://igs.org was developed, with the intent to replace the functionality of the very complicated and unsecured previous site. A simplified domain was created under NASA's GovCloud to ensure the system is properly maintained, secured, and identified as a service within NASA/JPL.

The transition to the new website occurred in December 2020 along with the broadly advertised ftp to https transition. While the original transition date was scheduled for

Table 2: CB led and/or coordinated virtual meetings during 2020.

Date	Place	Comments
21 January, 2020 1800–1900 UTC	EC - Telecon	• Intro to M. Moore to the EC • Approval of DuCKs activities • Discussion of new ISO policy • RINEX Chair Elections • 55 GB Meeting Dates • Workshop Status Discussion • Status of IGS Tech Report, IGS Geodesy Handbook, IGS Chapter FIGFRFIP • ICG-14 updates • RT Caster Issues • Geodetic Infrastructure Questionnaire
19 February, 2020 1800–1900 UTC	EC-Telecon	• SSR Issues • 2020 Workshop Report • 55 GB Meeting Planning • Status of IGS Tech Report, IGS Geodesy Handbook, IGS Chapter FIGFRFIP • ICG-IGMA updates • GB Chair Call for Candidates • Website Transition Timeline and Updates
20 February, 2020 1230–1400 UTC	WG-Chairs Telecon	• Informal Updates from WG Chairs • Repro3 & ITRF 2020 • IC/DC Transition • SSR Activities within the IGS and path forward • Confirmation of appointments for 2020 and beyond • Working Group Pages Work • Meeting Frequency
20 March, 2020 1900–2000 UTC	EC-Telecon	• COVID-19 Contingency Plan • Japan Analysis Center Proposal • 55 GB Meeting Planning • Status of IGS Tech Report, IGS Geodesy Handbook, IGS Chapter FIGFRFIP • AGU IGS Session • GB Chair Call for Candidates • Website Transition Timeline and Updates
24 April, 2020 0400–0500 UTC	EC-Telecon	• 55 GB Meeting Dry Run • GB Chair Election • Website Transition • Boulder Workshop Status
20 May, 2020 1200–1430 UTC	GB-55 Meeting Telecon	• Workshop Status • AGU 2020 Planning • New Chair Election and Transition • RINEX WG Chair Resolution • RTM SSR Updates • IAG Updates • ACC and repro3 • Infrastructure Committee Update and Transition • IGS Technical Report Status • IGS.org updates and https transition • Upcoming Governing Board Updates *37 Participants, 34 GB Members, 20 Voting Members present*
17 June, 2020 0400–0500 UTC	EC-Telecon	• Felix vision as new GB Chair • 2021 Strategic Plan • Approval of GB Minutes • Boulder Workshop Status • Reporting • IGS.org updates
22 July, 2020 2000–2100 UTC	EC-Telecon	• GB 56 Preliminary Agenda • IGS Strategic Planning Survey • Repro3 status • Workshop Status • C. Meertens Retirement • IGS Chapter FIG RFIP • WDS Harvestable Metadata status
25 August, 2020 1200–1430 UTC	GB-56 Meeting (Strategic Planning) Telecon	• IGS Slack Channel • COVID-19 Contingency Plan for Workshop and AGU • IC Chair Election • ITRF 2020 Status, Repro-3 Status and Progress • Strategic Planning • Update on IGS.org website • IERS representation *37 Participants, 34 GB Members, 20 Voting Members present*
29 Sept, 2020 0400–0500 UTC	EC-Telecon	• GB 56 Minutes Approval • Repro3 status and reprOctoberfest • Workshop Status • AGU Session update • SSR and RINEX 3.05 updates • IGS Communication Plan • Website Updates
05 Nov, 2020 2100–2300 UTC	EC-Telecon (October / November)	• MGEX future • Transition of IGS ACC role to Salim Masoumi • Appointed Member candidates, IERS rep, Carey's retirement and search for new DCC • Boulder Workshop Status • IGS Fest • AGU Session Status • IGS Strategic Planning Survey Final Results • 57 a and 57b Governing Board Meeting Planning • IGS Comm Plan • Website Updates and Final Release
16 Dec 2020 1900–2000 UTC	GB-57a Meeting Telecon	• IGS "State of Affairs" Summary: December 2019 – December 2020 • MGEX future • Workshop Status • RINEX 3.05 Format Standard • IAG President's Update • Working Group Charter Updates • ACC Update • Revised event schedule and format due to COVID-19 • Confirmation of GB Appointments for 2021 and beyond • IGS.org updates and https transition • Upcoming Governing Board Updates *37 Participants, 34 GB Members, 20 Voting Members present*

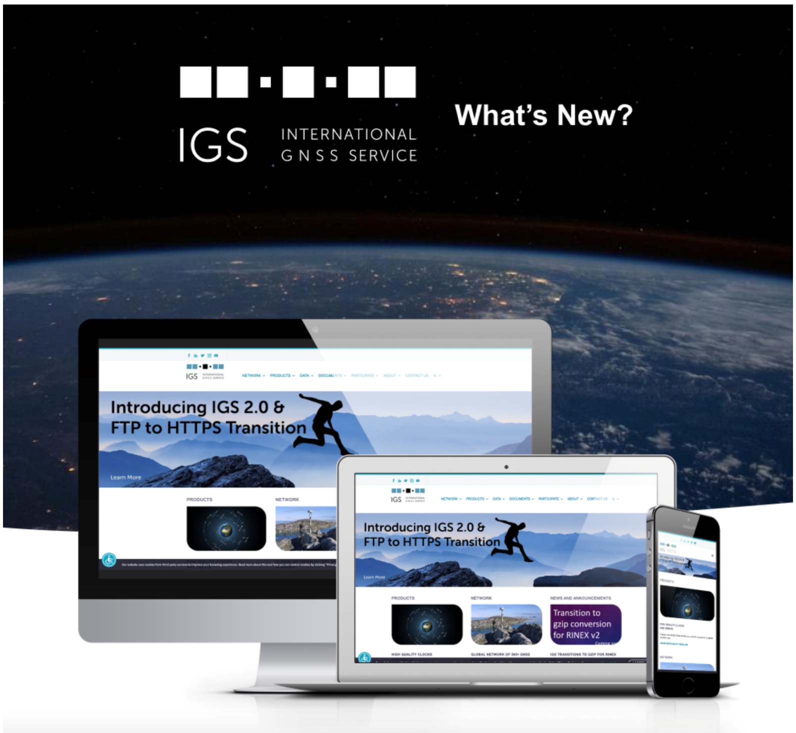

Figure 2: The new front page of IGS.org.

April 2020, the community requested for it to be extended to allow for additional time to deal with new COVID-related restrictions. In the meantime, the original site, which was located at http://igs.org continued to operate in parallel with the "beta site" https://igscb.org. As of 15 December 2020, the beta site (https://igscb.org) has transitioned into http://igs.org and the old website has been decommissioned.

The new refresh focused on creating a more functional and easier to navigate platform by implementation of larger and more graphically descriptive menus, 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), does not only offer a modern interface, but allows the website and its content to be optimized for different devices, browsers, data speed, search engines, and users. Some of the major areas that were improved include:

Front Page The new igs.org home page has been enhanced for diverse community engagement, with an eye-catching banner for the latest news and announcements, a slider highlighting IGS working groups, and a Twitter feed to encourage users to follow us on social media to stay up to date [https://www.igs.org/]

Navigation The old igs.org navigation menu had only had 5 top-level links with no dropdown menu. With the vast amount of information, the IGS currently has, it was difficult to navigate through the site without a significant time investment. Furthermore, users were relying on organic searches functions to be able to find their resources. The new "Mega Menu" navigation (as opposed to a traditional dropdown navigation), better supports the new and improved sitemap and ensures all links are clearly shown to users.

Contributing Organizations: Another important part of the IGS community are its contributing organizations. There is now a dedicated page that features contributing organizations where users can learn more about their role in the IGS as well as about that institution.

Events/News Viewing IGS Events has been enhanced with a more user-friendly design, including the ability to search, change view from list to month, easily view key info about each event, and export events onto your Google or iCal calendars. To keep our users up to date with the latest news and announcements, the team also updated the news page design with added visuals and easy navigation.

Station Maps [https://www.igs.org/network/#station-map-list]

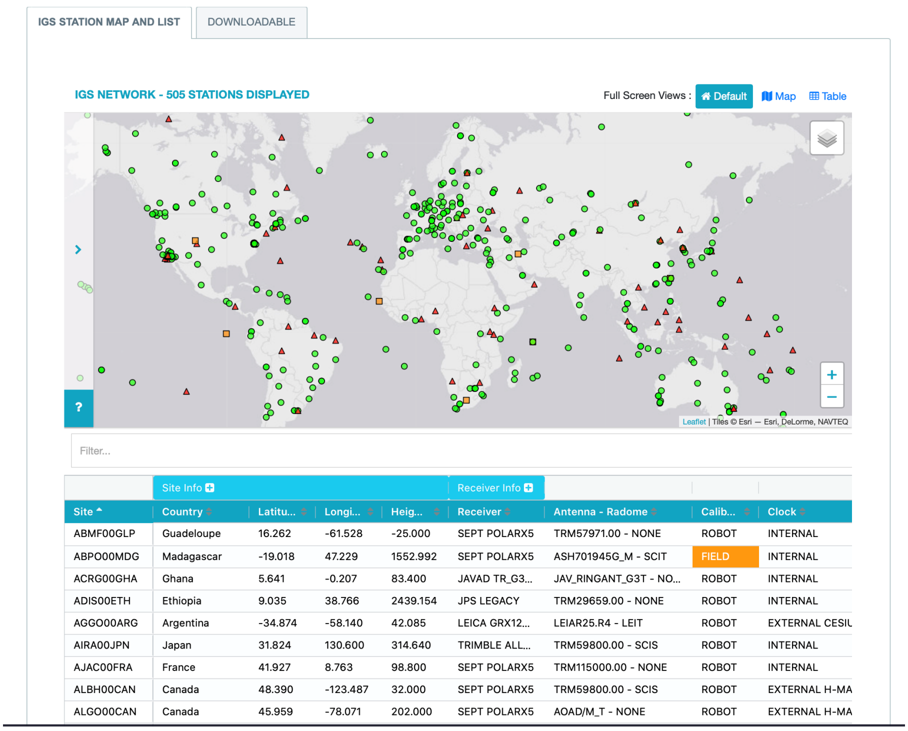

Figure 3: Station Maps.

Working Group and Pilot Project Pages Working Groups and Pilot Projects are an important part of the IGS community. In this new website, IGS Working Groups and Pilot Projects are heavily featured, appearing on both the home page and its own dedicated page. Now users can find all the information about a particular working group or pilot project in one place. Additionally, working group chairs now have the ability to securely manage their respective pages to keep them up to date with the latest information. For more information, please visit: https://www.igs.org/working-groups-pilot-projects.

6 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:

- Associate Members and IGS Election documentation
- Further integration of Multi-GNSS stations into the IGS Network
- Support of IGMA and other ICG initiatives
- Advocating for RINEX 3.05 and its support of all GNSS constellations
- Virtual coordination and execution of 2020 Governing Board meetings
- Leading the Standing Election Committee (SEC)
- Verification IGS Associate Member contact information and participation through both personal and the subsequent implementation of an automated processes to take place in 2021.
- IGS Workshop website
- IGS Strategic Planning surveys, announcements, and other communications
- Leading conversations on Strategic Planning for 2020 and forward

7 IGS Workshop Support

The IGS 2020 Workshop has been delayed to 26 June-01 July 2022, at the UCAR Center Green Conference Facility and NCAR MESA Lab, in Boulder Colorado (United States). GB meetings will be conducted prior and after the workshop. The CB has and will continue to play an active role in supporting both the local and the science organizing committees with the organization of the 2022 Workshop, as well as holding a call for proposals for 2024 workshops.

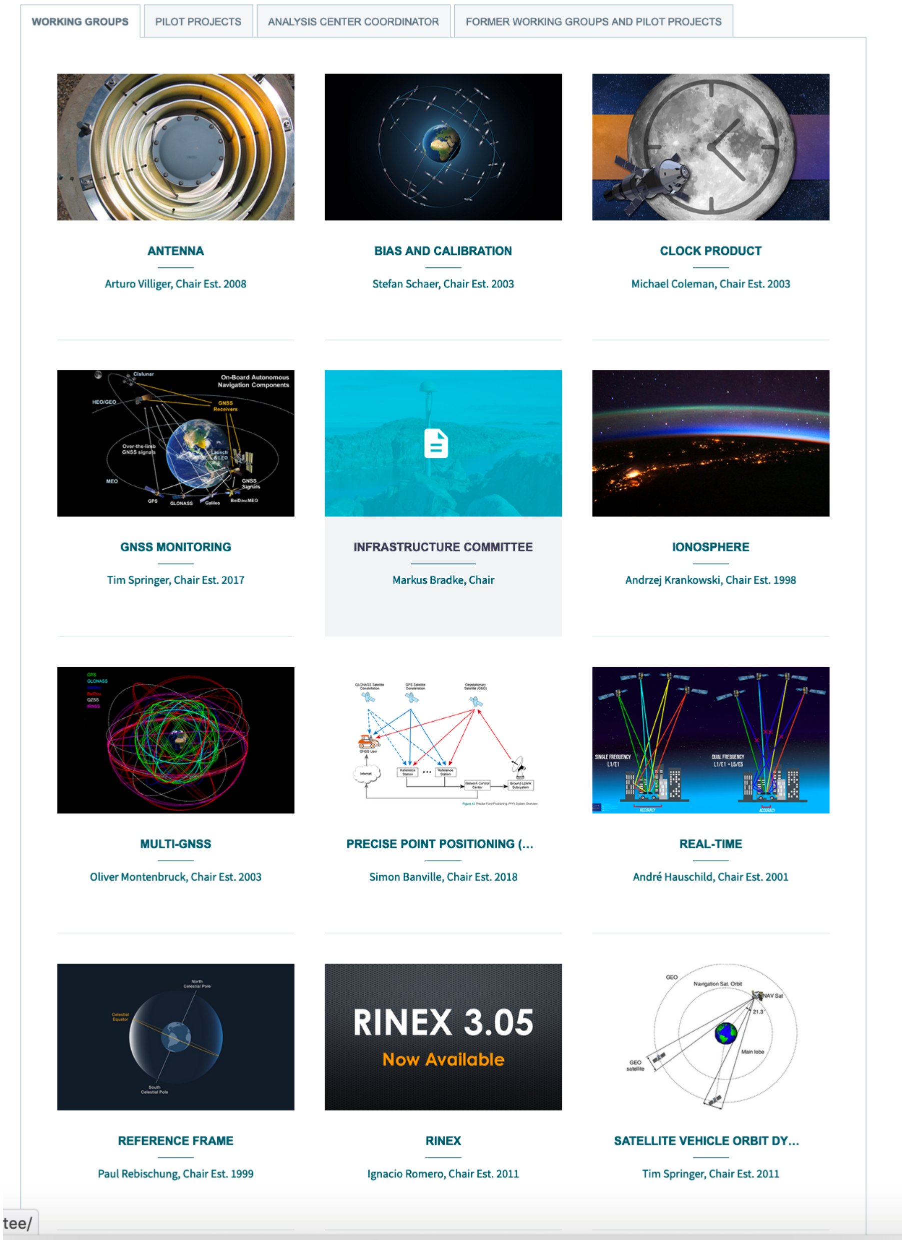

Figure 4: SWorking Groups and Pilot Projects.

For more information on the 2022 and 2024 Workshops, please refer to the GB Chapter of this Report.

8 Standing Election Committee

Elections for the Governing Board positions of GB Chair, RINEX Working Group Chair and Infrastructure Committee Chair (now Coordinator) took place in the first portion of 2020. CB staff worked with the GB Elections Committee to ensure nominations and voting processes were successfully carried out. The CB was the primary driver in conducting the "call for nominations", candidate vetting process, ensuring effective communications between AMs, candidates, EC and GB, development of the online voting interface, voting poll and counting, and relevant announcements before, during and after the election. The CB has also taken the lead in confirming and reviewing all appointments to the GB in consultation with the EC and GB Chair, and updating GB member rosters.

9 2021 Strategic Planning

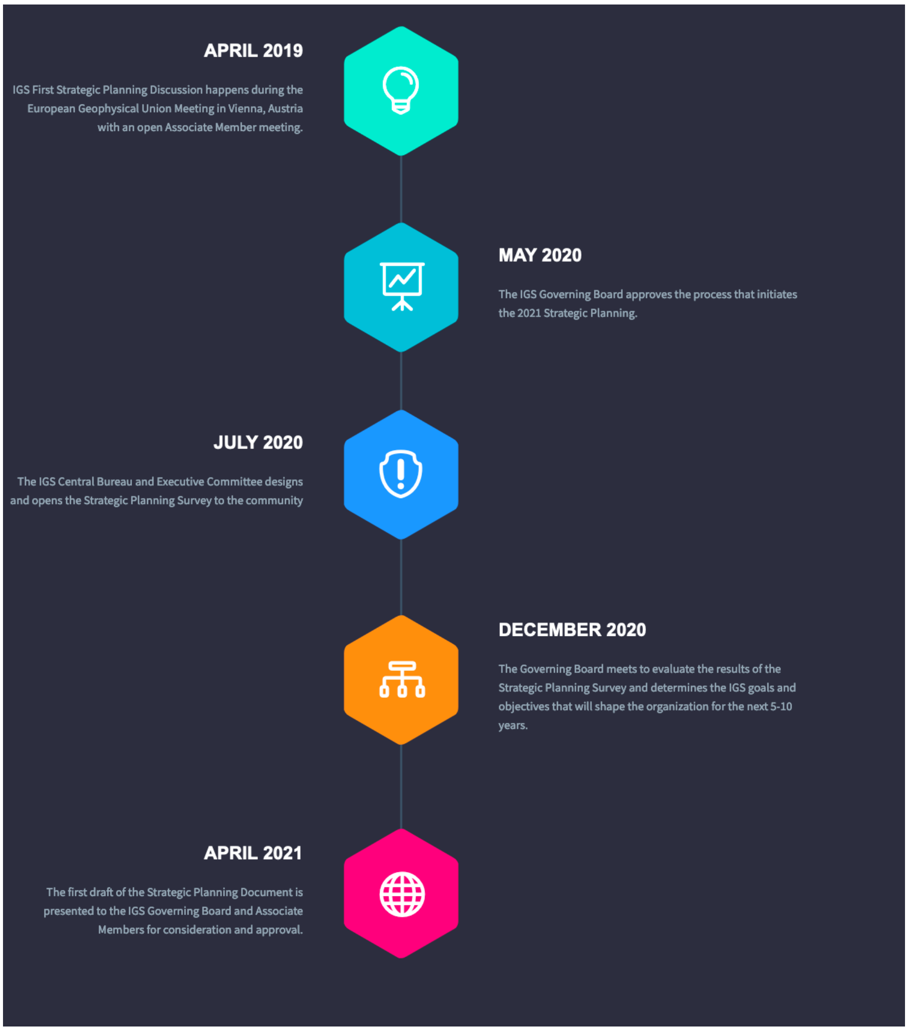

Figure 5: Strategic Planning Roadmap.

The IGS was originally designed as Geodynamic Service -a mechanism to support people and institutions who needed GNSS at their national level, but required the global network to support their local applications.

Over twenty-five years later, the IGS is looking to redefine its role in an everchanging GNSS community. The most recent Strategic Planning cycle commenced with two in-person IGS Community Strategic Planning Dialogue sessions, held in April 2019. From July through October 2020, the IGS Central Bureau conducted an online Strategic Planning Survey (SPS) via igs.org, as part of the activities related to the development of a new decadal Strategic Plan for the organization, which initiation process was approved during the virtual IGS 55th Governing Board Meeting, in May 2020. The current comprehensive road map for the next iteration of the Strategic Planning Process is depicted on Fig. 5 and can be followed online at https://igs.org/strategic-planning. The questions included in the SPS were selected under careful scrutiny by the members of the IGS Executive Committee, taking into consideration initial feedback from the community obtained during the first Strategic Planning Associate Member Meeting, which took place in April 2019 during the European Geophysical Meeting in Vienna, Austria.

The SPS was heavily advertised via social media platforms, web and IGS Mail, was available in two languages (English and Spanish) and consisted of three sections. The first section requested general information about the participant, GNSS applications and demographics. The second section asked the participant to rank the impact and relevance of the IGS role as facilitator, incubator, coordinator and advocate for the GNSS community. The last section allowed the participant to answer open questions in regards of the Strengths, Weaknesses, Opportunities and Threats (SWOT) the IGS is facing as we start the upcoming decade. The summary of this report as well as the GB discussions is included in the GB Chapter of this report. The review draft version of the Strategic Plan is currently under preparation by the Central Bureau, and will be released for GB consultation mid-2021.

10 Data Use, Contributions and Sharing (DUCkS) Guidelines and Policies: Disclaimer and Terms of Use Policy

Recently there have been a number of requests asking for clearer, more prescriptive, or otherwise better outlined policy regarding how members of the private sector may engage with, contribute to, and otherwise use/credit IGS data, products, and other resources. The CB recognized and presented the GB with a proposal to create such guidelines. The GB acknowledged that the current policy is in dire need of clarification and that there is a need to begin conversations to update such policies. A CB-led Task Force was established to lead this effort with new policies established and vetted by the Governing Board and publicly available through igs.org.

It was identified that DUCkS Guidelines should include organization of current data use, sharing, and contribution practices into a clear, impartial policy that forms parameters *for consistent and transparent guidance* to contributors and users. This should form a strong foundation that *organizes and facilitates connection to [existing] specific information* and guidance, including official IGS Policies, as well as established parameters and procedures for contributing to IGS components.

Following the GB support for a more comprehensive DUCkS suite of guidelines and policies, the Data and Product Disclaimer and Terms of Use was drafted by the CB and approved at the August 2020 GB meeting. Additional guidelines to address community needs and gaps in capacity building documentation are in development.

11 International Country Name Guidelines

Recently, the CB was notified of a need for a consistent and internationally-vetted and accepted list of country and territory names to be used for identifying IGS Network stations and in other applications. The CB researched and led discussions pertaining county name guidelines usage and which internationally-accepted list will be the most inclusive and useful for both IGS operations and the community requirements. After the 54th GB Meeting in December 2019, the CB has been tasks in drafting a new IGS policy statement for consistent and sensitive use of place names based on the International Organization for Standards (ISO) standard. This policy was reviewed during the May 2020 GB meeting and has been implemented.

12 Beyond 2021

Following the results from the Strategic Planning survey, the CB is focused in better serving the community as a platform for facilitation, coordination, incubation and advocacy. Looking forward, the CB will focus on supporting three major strategic goals identified in the 2021 Strategic Plan: achieve true multi-GNSS technical excellence, improve our outreach and engagement and improving our sustainability and resilience. The IGS CB 2021 information systems administrative goals are focused in providing support for dissemination of the results of the repro3 campaign and its contributions toward the ITRF2020. The CB is also looking forward to upgrade the Site Log Manager to a more modern and accessible language, as well as continue upgrades on the IGS.org website that include a better Associate Member database.

13 Internal Communications and Coordination

Additionally, the CB is working to implement a new communication plan that will bridge the gap between Working Groups and Associate Members and introduce a better and more diversified portfolio. This will be achieved by increasing the direct interaction with the community by virtual workshop, enhanced social network interactions, a regular circulation of a newsletter, enhancing our transdisciplinary collaborations (i.e with new or under-engaged scientific applications communities), and identifying opportunities for IGS engagement and support of the UN International Committee on GNSS, as well as the UN Sendai Framework for Disaster Risk Reduction and UN Sustainable Development Goals. Additionally, the CB will finalize the 2021 Strategic Plan and commence its implementation.

14 External Communications, Advocacy, and Public Information

Social media has been regularly maintained by CB staff and continued to grow in followers in 2020, 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 2021. IGS Social Media accounts and follower statistics are as follows:

- Slack (For GB use)
- Twitter (1586 followers): https://twitter.com/igsorg
- Facebook (1743 followers): https://www.facebook.com/internationalGNSSservice
- LinkedIn Page: https://www.linkedin.com/company/igsorg/
- YouTube (150 subscribers, 2000+ views): http://www.youtube.com/igsorg

15 External Participation

The Central Bureau 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 http://ggim.un.org/UN_GGIM_wg1.html.

On behalf of the Governing Board, the CB Director represents the IGS 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 (Z. Altamimi) and the International Federation of Surveyors (FIG, represented by S. Choy), in close collaboration with BIPM (G. Petit). The CB Deputy Director represents the IGS in the new IAG Inter-Commission Committee on Geodesy for Climate Research (ICCC), as both IGS and GGOS representative.

The CB Director continues to serve as a point of contact between IGS CB and the US

Federal Advisory Board for Space-based Position, Navigation and Timing (PNT). Other IGS representatives presenting at the PNT Advisory Board meetings include IGS Founding Governing Board Chairman Professor Gerhard Beutler (University of Bern, Switzerland). The CB Deputy Director represents the IGS in most of the ICG IGMA and Performance Standards Joint Monthly Meetings, along with T. Springer and S. Kogure.

16 Publications

- IGS 2019 Technical Report, IGS Chapter
- NASA SGP/ICPO annual progress update, NASA internal publication
- Craddock, A., Johnston, G., Perosanz, F., Dach, R., Meertens, C., Moore, M., Oyola, M. (2020) Twenty-Five Years of the International GNSS Service, [virtual conference] European Geosciences Union Virtual General Assembly, Austria
- Craddock, A., Oyola, M., Khachikyan, R., Santiago, A., Maggert, D., Stowers, D. (2020) Improvements and Enhancements to the International GNSS Service Central Bureau Information Systems [virtual conference] American Geophysical Union Fall Meeting, USA

17 Official IGS Citation

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

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

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

18 Acknowledgements

The Central Bureau gratefully acknowledges the contributions of our colleagues at the Astronomical Institute of the University of Bern, who edit, assemble, and publish the IGS Annual Technical Report as a service to the Central Bureau and IGS community. We would also like to express our thanks to everyone in the IGS Community for their patience and support during the COVID-19 pandemic.

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2020

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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 products. 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.

The main focus of the IGS Analysis Center Coordinator in 2020 was the third IGS reprocessing effort (repro3). We continued the processing and testing of the reprocessed products by ten analysis centers. We completed the development of a new version of the IGS orbit combination platform to allow multi-GNSS combined orbits. We have also been working with the Wuhan University and Natural Resources Canada to utilise their clock combination software for combining the multi-GNSS clock products from the analysis centers (e.g. Banville et al., 2020).

The different analysis centers contributing to the IGS operational products, as well as those contributing to the repro3, 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

In 2020, 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

Table 1: The abbreviations used by the IGS ACC in this report for different products of the individual analysis centers.

Analysis center	Ultra-rapid	Rapid	Final	repro3
Center for Orbit Determination in Europe (CODE)	COU	COD	COD	COD
Natural Resources Canada (NRC)	EMU	EMR	EMR	EMR
European Space Agency (ESA)	ESU	ESA	ESA	ESA
GeoForschungsZentrum Potsdam (GFZ)	GFU	GFZ	GFZ	GFZ
Centre National d'Etudes Spatiales (CNES/CLS)			GRG	GRG
Jet Propulsion Laboratory (JPL)	JPU	JPL	JPL	JPL
Massachusetts Institute of Technology (MIT)			MIT	MIT
NOAA/National Geodetic Survey (NGS)	NGU	NGS	NGS	NGS
Scripps Institution of Oceanography (SIO)	SIU	SIO	SIO	
Graz University of Technology (TUG)				TUG
University of La Rochelle, France (ULR)				ULR
The United States Naval Observatory (USNO)	USU	USN		
Wuhan University	WHU	WHU		WHU
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 (repro2)	IG2			
IGS third reprocessing (repro3) by the current combination software	IG3			

to errors in the automatic retrieval of the data from the global data centres, 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 2020, the IGS has been receiving 7 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 orbit can be split into two components, a fitted portion based upon observations, and a predicted component reliant upon forward modelling of the satellite dynamics. The fitted portion of the ultra-rapid orbits continue to agree to the rapid orbits at the level of 8 mm (see Figure 1) and has been consistently at 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

Table 2: ACs contributing to the Ultra-rapid products, *W* signifies a weighted contribution, *C* is comparison only. The SIO ERP solution is by default weighted, with the exception of the length of day estimate which is excluded from the combination.

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

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.

2.2 Rapid

There are nine individual analysis centers contributing to the rapid IGS products (see Table 3). The rapid orbit products from the different analysis centers weighted in the combination remained at a consistency level of up to 15 mm (Figure 4), and there has been no significant change in the difference between the combined IGS rapid orbits and the combined IGS final orbits, which was consistently below 5 mm level (see Figure 6). The consistency of the rapid satellite and station clock solutions from the weighted centres remain at around 75 ps of RMS, and their standard deviations are below 20 ps (Figure 5). In the late 2020, Wuhan clocks started to improve in terms of the RMS with respect to the other centers as a bug in their processing software was fixed regarding the correcting for differential code biases. Starting from GPS week 2142 (early 2021), the Wuhan clocks were hence included as weighted in the rapid combinations, with the improvement in both RMS and standard deviations of their clocks.

2.3 Final

There are nine individual ACs contributing to the IGS final products (see Table 4). Most AC final solutions are comparing at around 10 mm RMS level to each other (see Figure 6).

Starting from early 2020, the orbits from MIT significantly became closer to the orbits

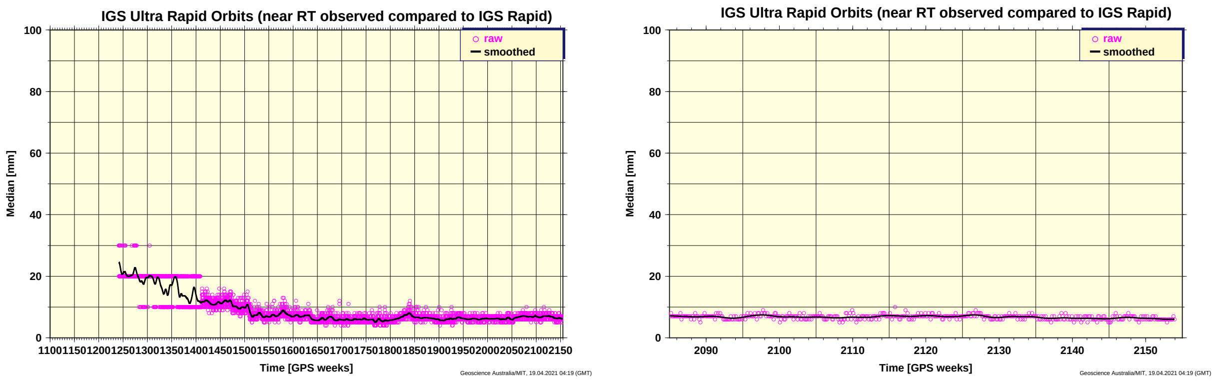

Figure 1: The median difference of the fitted component of the IGS ultra-rapid (IGU) combined orbits with respect to the IGS rapid (IGR) orbits. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

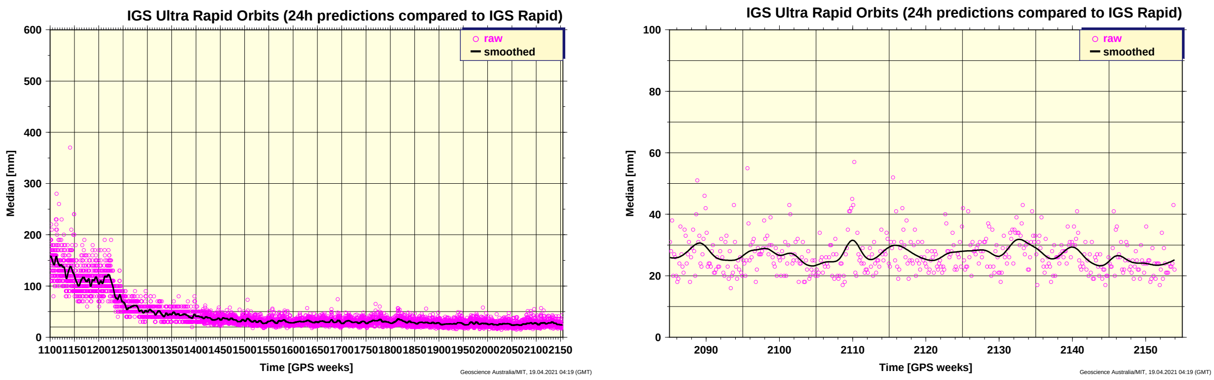

Figure 2: Median of IGU combined predicted orbits compared to IGR. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

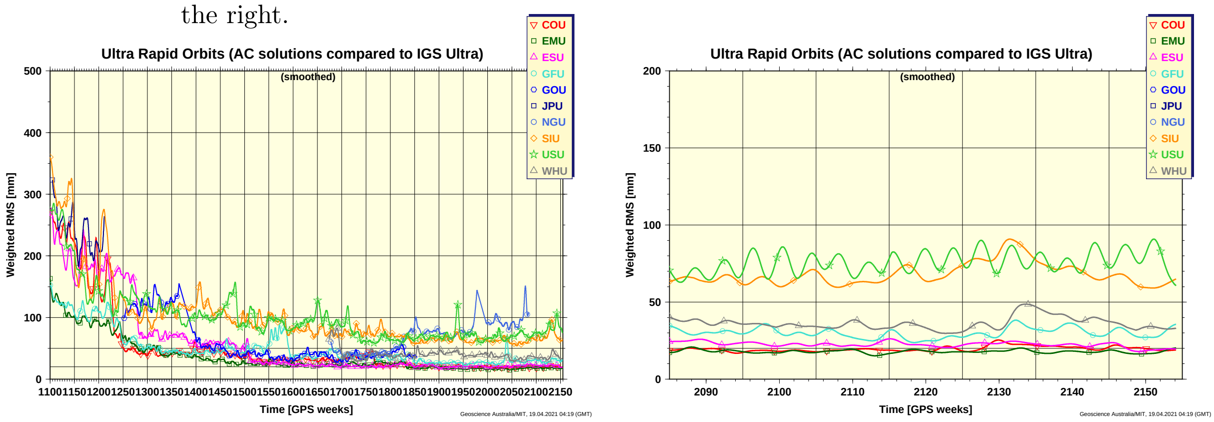

Figure 3: Weighted RMS of AC Ultra-rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

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. Wuhan clocks have been weighted in the rapid clock combinatoins since early 2021.

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	-
USN	C	C (LoD W)	C
WHU	W	W	C*

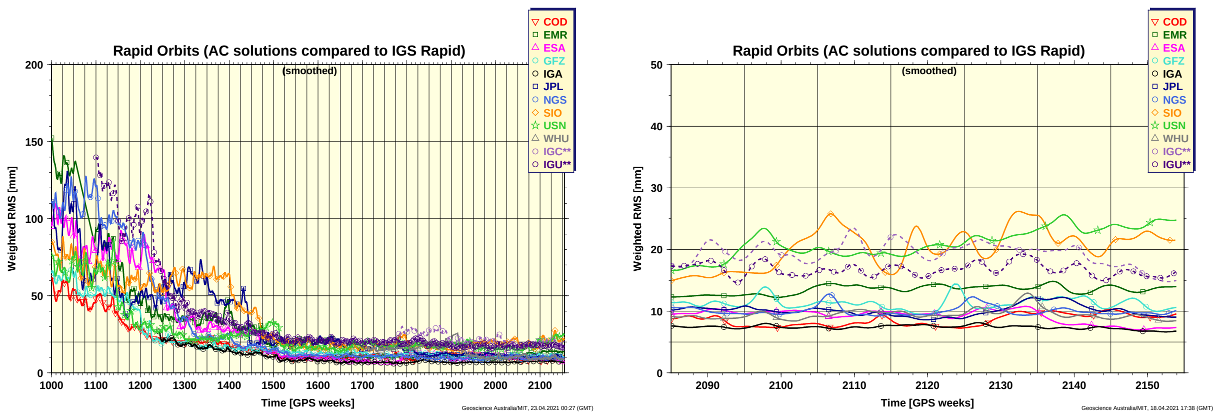

Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time stream. IGU** consists of four separate comparisons to IGR done each day over the first 6 hours of each IGS Ultra-rapid product.

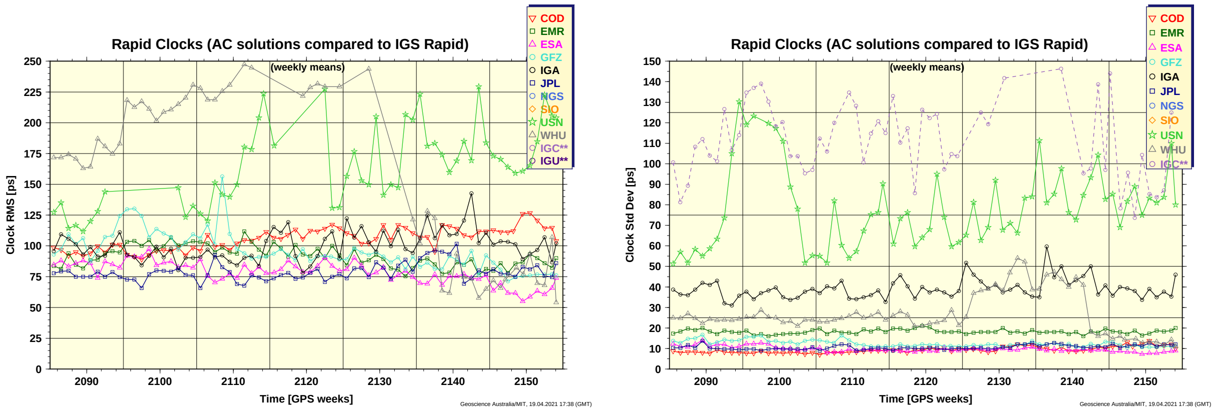

Figure 5: Weighted RMS (left) and standard deviation (right) of ACs Rapid clock submissions (smoothed). IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time stream. IGU** consists of four separate comparisons to IGR done each day over the first 6 hours of each IGS Ultra-rapid product.

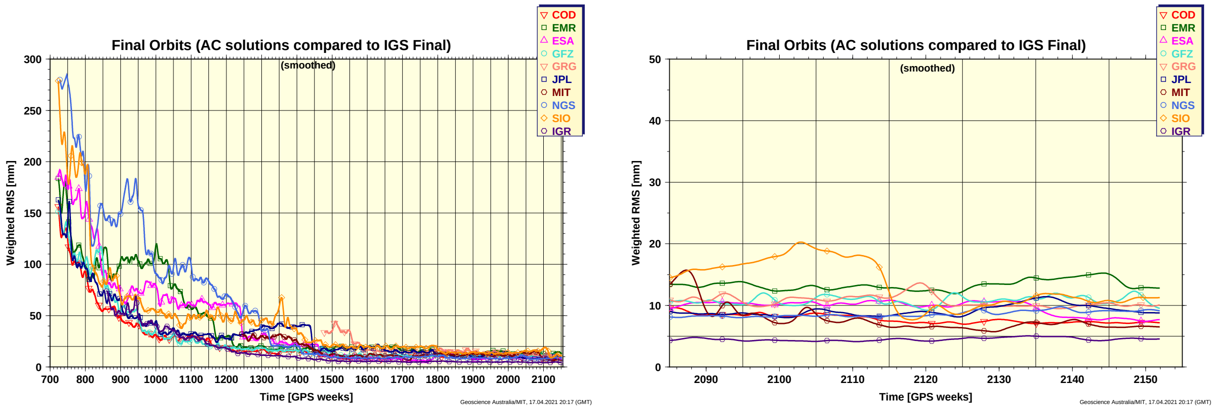

Figure 6: Weighted RMS of IGS Final orbits (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

Table 4: ACs contributing to the IGS Final products, W signifies a weighted contribution, C is comparison only. GFZ clocks were excluded from the final combinations from GPS week 2109 to GPS week 2131.

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	C	C

from the other centres. 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. This was followed by the improvement in the orbit solutions from SIO since mid-2020, as SIO uses the same processing software as MIT (GAMIT/GLOBK), and they started implementing the updates to their software and processing from GPS week 2115. The SIO Earth Orientation Parameters (EOP) estimates, in particular the pole coordinates, have been however drifted from the other centers since around the same time, due to the inconsistency between the orientation of the orbits submitted and the EOP values (Figure 7). SIO EOP values were therefore unweighted in the final combination procedure since GPS week 2118 to avoid biasing the combined EOPs.

The final clock solutions from the weighted ACs are usually around 100 ps level of RMS compared to the combined final clocks, and the standard deviations of the final clock solutions for the weighted centers are below 20 ps level for most of the weighted centers (Figure 8). The exception to this were the GFZ clocks which suffered from high standard deviations and RMS with respect to the combined clocks between the GPS weeks 2109 and 2131. This was due to a severe bug in GFZ processing software with the handling of the reference clock. Therefore, we excluded GFZ clocks from the final solutions during this period (reprocessing and re-submitting the final combinations for GPS weeks 2109 and 2110). This issue was resolved in the GFZ software starting from GPS week 2131, and hence their clock solutions were included back into the final combinations. Another change to notice is the MIT final clock solutions having improved significantly in terms of the standard deviations since around GPS week 2111 with the recent improvements in their processing software and models.

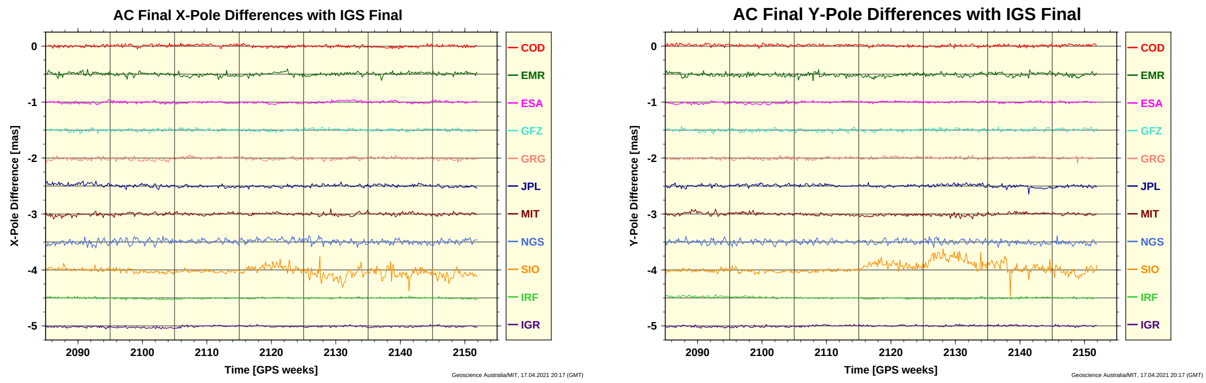

Figure 7: Differences of AC final pole coordinates from IGS Final solutions. X coordinates of the pole are plotted on the left, while Y coordinates are shown on the right.

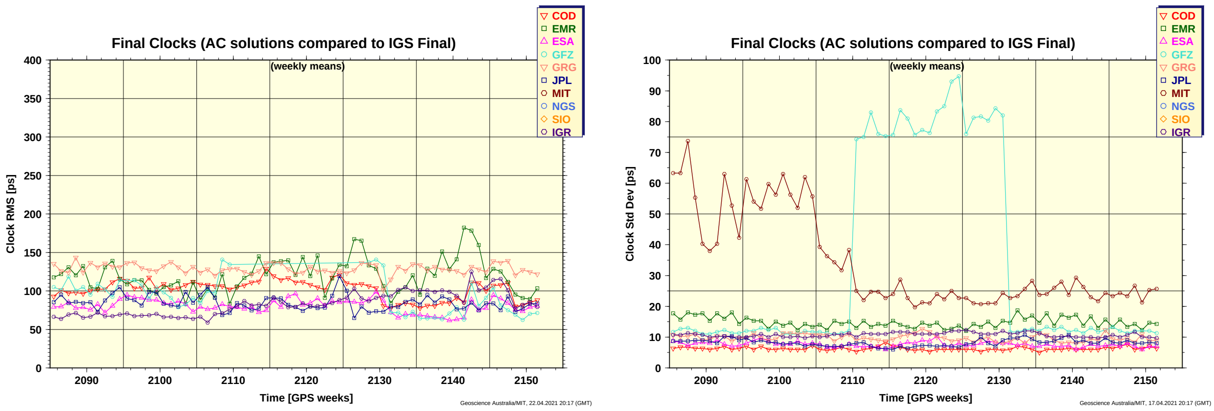

Figure 8: Weighted RMS (left) and standard deviation (right) of IGS Final clocks (smoothed)

Table 5: ACs contributing to the repro3 campaign. Some of the analysis centres are still in the process of submitting solutions for the remaining years.

AC	satellite systems	time period	SINEX	orbit	clock	attitude	bias	EOP	troposphere
COD	GPS GLONASS GALILEO	1994-2020 2002-2020 2013-2020	✓	✓	✓	✓	✓	✓	✓
ESA	GPS GLONASS GALILEO	1995-2020 2009-2020 2015-2020	✓	✓	✓			✓	✓
GFZ	GPS GLONASS GALILEO	1994-2020 2012-2020 2014-2020	✓	✓	✓	✓	✓	✓	✓
GRG	GPS GLONASS GALILEO	2000-2020 2008-2020 2017-2020	✓	✓	✓	✓		✓	✓
JPL	GPS	1994-2020	✓	✓	✓	✓		✓	✓
MIT	GPS GALILEO	2000-2020 2017-2020	✓	✓	✓			✓	
NGS/EMR	GPS	1994-2020	✓	✓	✓	✓	✓	✓	
TUG	GPS GLONASS GALILEO	1994-2020 2009-2020 2013-2020	✓	✓	✓	✓	✓	✓	✓
ULR	GPS	2003-2020	✓						
WHU	GPS GLONASS	2008-2020 2010-2020	✓	✓	✓	✓		✓	✓

3 The third IGS reprocessing campaign

The third IGS reprocessing campaign is aimed at reanalysing 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 is then combined and submitted as the IGS contribution to the next version of the International Terrestrial Reference Frame, ITRF2020. For the first time IGS is providing its own independent estimates of scale of the reference frame.

In total, eleven analysis centres submitted solutions to be included in the repro3. These analysis centres and their submitted solutions are listed in Table 5. We continued testing and using the newly developed version of the orbit combination software, in addition to the current combination software, for assessing the orbit solutions submitted for the repro3. The new version of the combination software is more flexible than the current version 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 is to maintain the robustness of the IGS products, as with the current combination software.

The tests on repro3 were performed in 'rapid' mode; i.e. no reference frame alignment was applied. With the availability of the repro3 terrestrial reference frame early 2021, we can also perform the reference frame alignment. As an example of the orbit combination test results, the median RMS of the individual satellites for each analysis center with respect to the IGS combination is shown in Figure 9 over 2014 for GPS, and 2018 for all three GNSS constellations. The results here are from a satellite-specific weighting approach using the new version of the orbit combination software.

For GPS, except for a couple of satellites, the combined orbits are below 10 mm of RMS level compared to the repro2 orbits (IG2). Also, the combined orbits from the multi-GNSS combination always compare to the GPS-only combined orbits by the current software (IG2) at below 5mm RMS; the median RMS is in fact at 1-2 mm level for most of the satellites. In addition to this, the AC solutions are clearly more consistent in 2018 than in 2014. For GLONASS, while some of the more recently launched satellites have RMS values of below 25 mm, the RMS values reach up to more than 50 mm for some satellites. For GALILEO, except for the more recently launched satellites in 2018, the AC orbit solutions agree at below 25 mm RMS. It is interesting to note that the RMS values from the GALILEO combinations have improved over the years, which is shown in Figure 10.

The final IGS repro3 orbit combinations is scheduled to be completed in 2021. This will include the alignment to the repro3 terrestrial reference frame, and will include comparisons of the combinations from the new version of the combination software to the current software, and careful investigation of the possible sources of discrepancy between the two solutions. The preliminary results from the clock combination software developed at Wuhan University are promising, and given these results, we will cooperate with Wuhan University to produce repro3 combined multi-GNSS clocks that are consistent with the combined multi-GNSS orbits. The collaborative work with Wuhan University also includes performing precise point positioning tests on the combined orbits and clocks in order to validate the combined solutions. When the repro3 is completed, the next plan is to start deploying both repro3 standards and the new combination software for the IGS operational combinations.

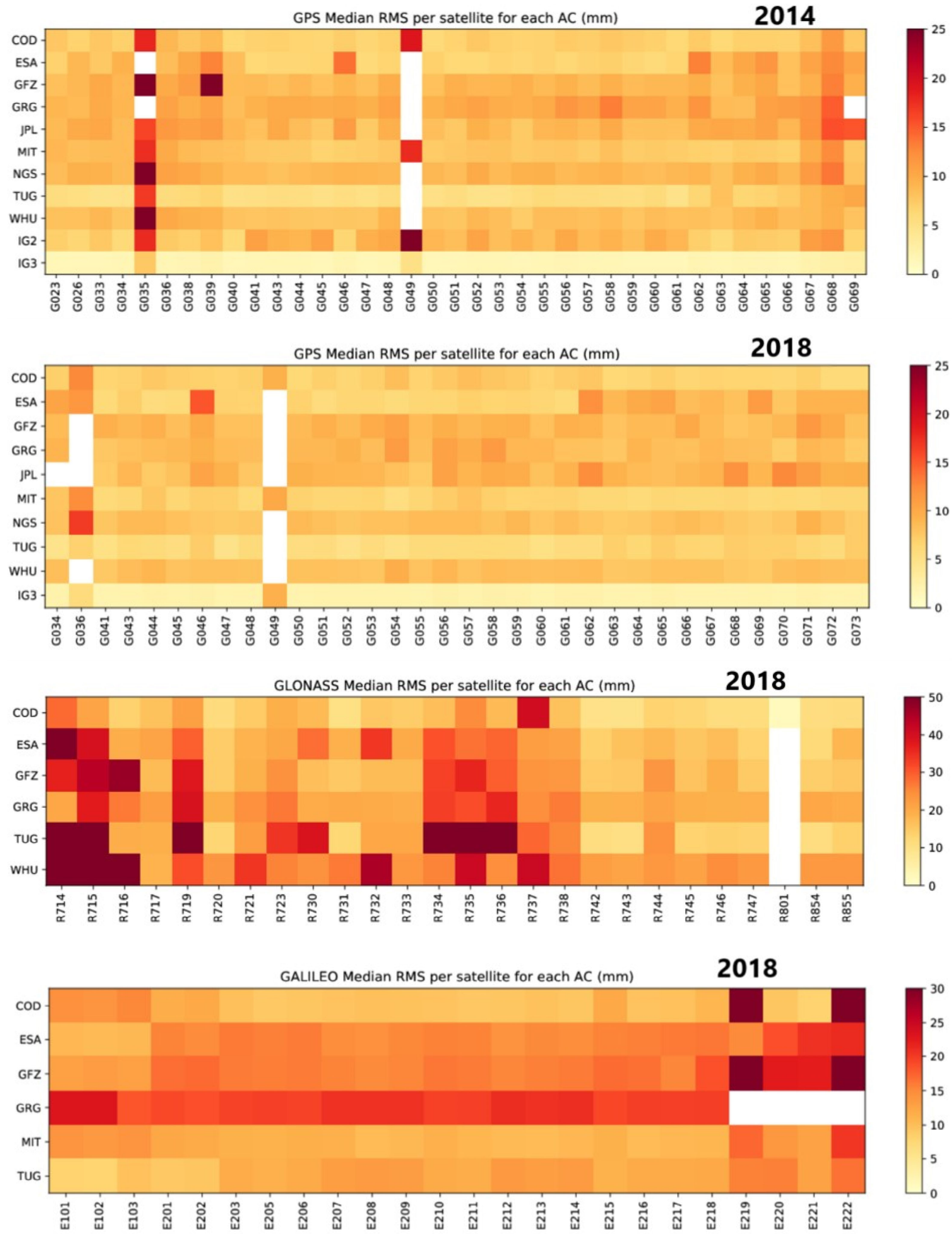

Figure 9: Median RMS of the individual satellites compared to the combined orbits for the test repro3 solutions of the ACs. From top to bottom: GPS 2014, GPS 2018, GLONASS 2018 and GALILEO 2018. IG2 is the IGS combined orbits from the second reprocessing campaign (repro2), and IG3 is the GPS-only combined orbits of the repro3 using the current combination software.

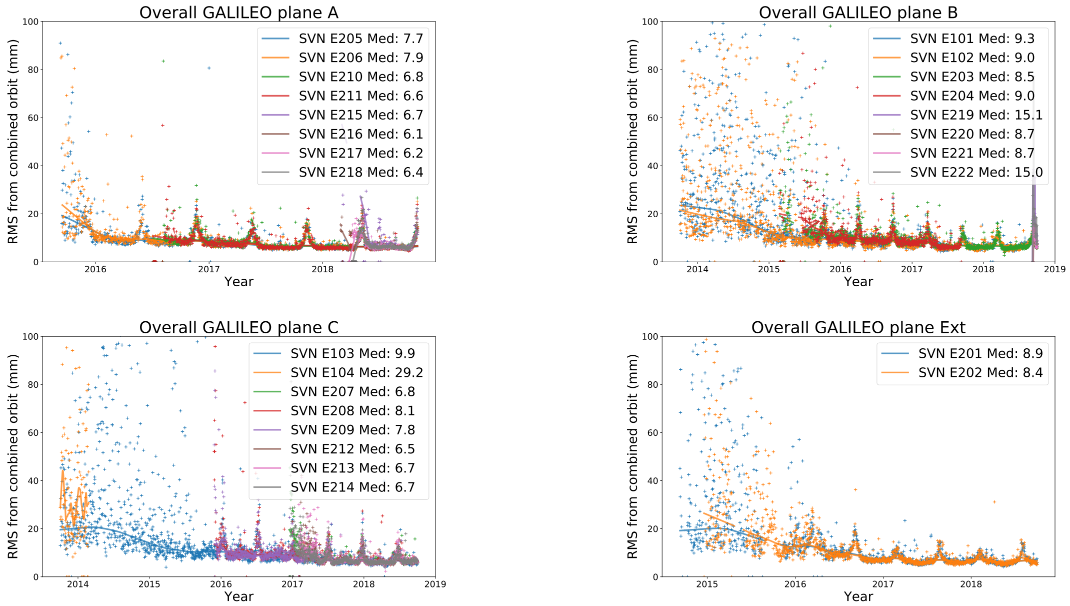

Figure 10: Overall RMS of the GALILEO orbits from the repro3 for different orbital planes.

References

S. Banville, 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(1):10,2020.

Center for Orbit Determination in Europe (CODE) Technical Report 2020

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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
- Institute for Astronomical and Physical Geodesy, Technical University of Munich (IAPG/TUM), 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/

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. (2020); 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).

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_v3.CLK.Z	same as above but in clock RINEX version 3.04
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_v3.CLK_05.Z	same as above but in clock RINEX version 3.04
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

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/

The triple-system solution (GPS, GLONASS, Galileo) from CODE's rapid processing is also kept accessable at:

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

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.Z`	CODE final rapid GNSS orbits: GPS+GLONASS+Galileo (before September, 23rd 2019 only GPS+GLONASS)
`yyyy_M/CODwwwwd.ERP_M.Z`	CODE final rapid ERPs belonging to the final rapid orbits
`yyyy_M/CODwwwwd.CLK_M.Z`	CODE GNSS clock product related to the final rapid orbit, clock RINEX format,
`yyyy_M/CODwwwwd.BIA_M.Z`	CODE daily code and phase bias solution corresponding to the above mentioned clock products (provided in the context of submission of the CODE final solution with a delay of about two weeks) See `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT` for the usage of the phase biases.

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

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_v3.clk.Z`	same as above but in clock RINEX version 3.04
`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_v3.clk_05s.Z`	same as above but in clock RINEX version 3.04
`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

Note, that the `COF`–series was stopped with GPS week 2112.

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

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

Files generated from three–day long–arc MGEX solutions:

`COD0MGXFIN_yyyyddd0000_01D_05M_ORB.SP3.gz`
: CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format

`COD0MGXFIN_yyyyddd0000_01D_12H_ERP.ERP.gz`
: CODE MGEX final ERPs belonging to the MGEX final orbits

`COD0MGXFIN_yyyyddd0000_01D_30S_CLK.CLK.gz`
: CODE MGEX final clock product consistent to the MGEX final orbits, clock RINEX 3.04 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

`COD0MGXFIN_yyyyddd0000_01D_01D_OSB.BIA.gz`
: GNSS code and phase (GPS and Galileo only) biases related to the MGEX final clock correction product, bias SINEX format v1.00

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

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

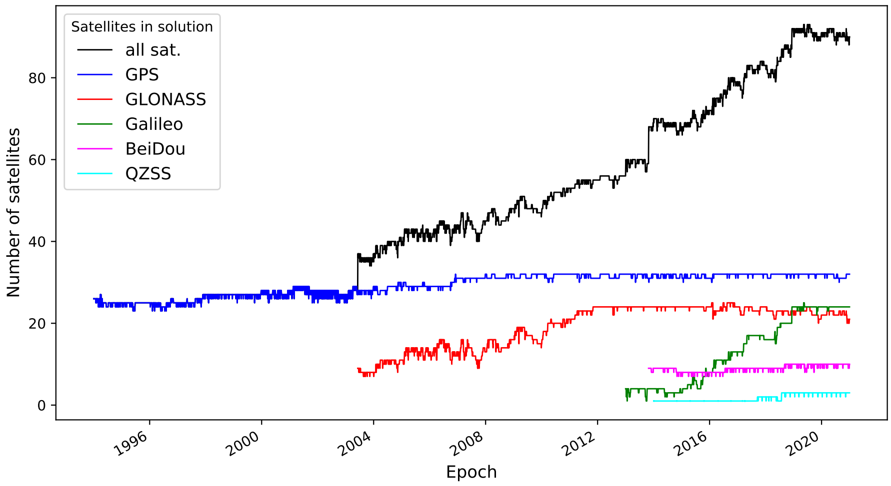


Figure 1: Development of the number of satellites in the CODE orbit products.

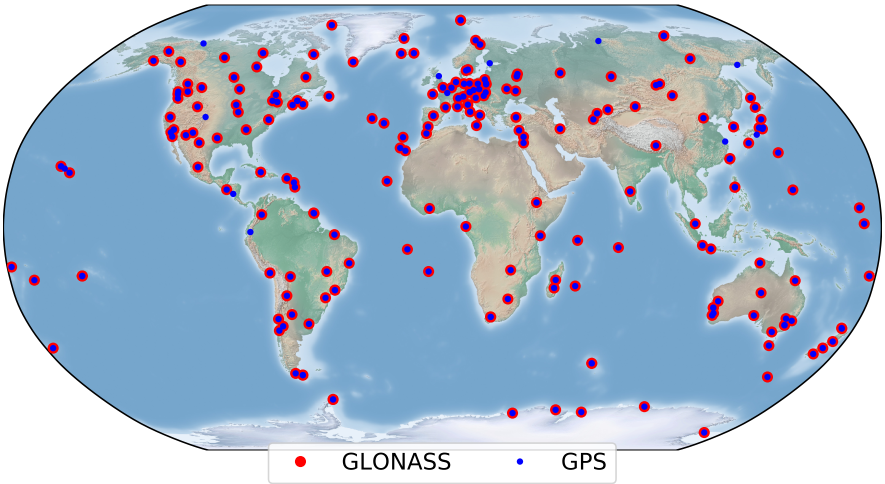
between 90 and 92 satellites.

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 data are available to a sufficient amount for a reasonable orbit determination for a long time; the extension for including the BDS-3 satellites is currently under the way.

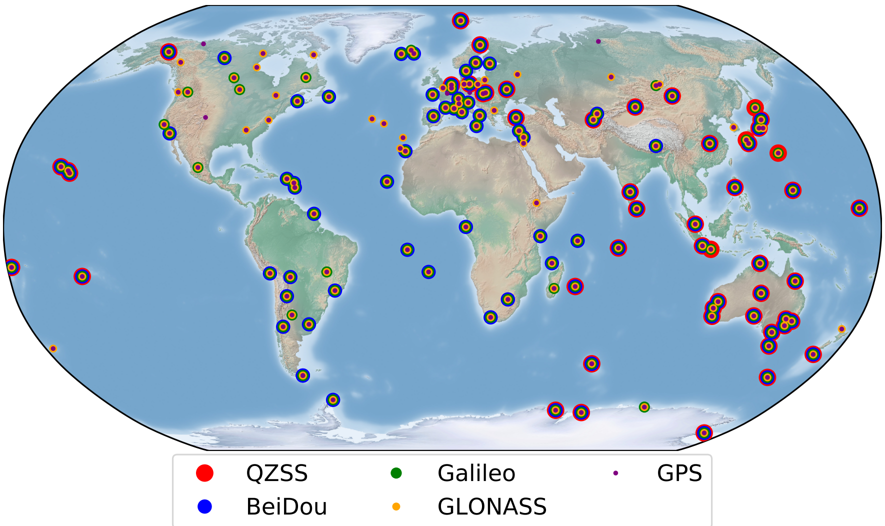
Referencing of the products

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

- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Kalarus, Maciej Sebastian; Prange, Lars; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2020). *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.75676.4 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Kalarus, Maciej Sebastian; Prange, Lars; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2020). *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.75854.4 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Kalarus, Maciej Sebastian; Prange, Lars; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2020). *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.75876.4 .
- Prange, Lars; Arnold, Daniel; Dach, Rolf; Kalarus, Maciej Sebastian; Schaer, Stefan; Stebler, Pascal; Villiger, Arturo; Jäggi, Adrian (2020). *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.75882.3 .
- Steigenberger, Peter; Lutz, Simon; Dach, Rolf; Schaer, Stefan; Jäggi, Adrian (2014). CODE repro2 product series for the IGS. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2013; DOI: 10.7892/boris.75680 .
- Sušnik, Andreja; Dach, Rolf; Villiger, Arturo; Maier, Andrea; Arnold, Daniel; Schaer, Stefan; Jäggi, Adrian (2016). CODE reprocessing product series. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2015; DOI: 10.7892/boris.80011 .



(a) final solution (about 250 stations)



(b) MGEX solution (140 stations)

Figure 2: Network used for the processing at CODE by the end of 2020.

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. (2020).

In Section 3.1 we give an overview of important development steps in the year 2020. In the context of the recent reprocessing effort CODE also returned to the long-arc solutions.

The related implementation is described in Section 3.2 and applied to the operational final processing since GPS week 2113 as well. 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 2020

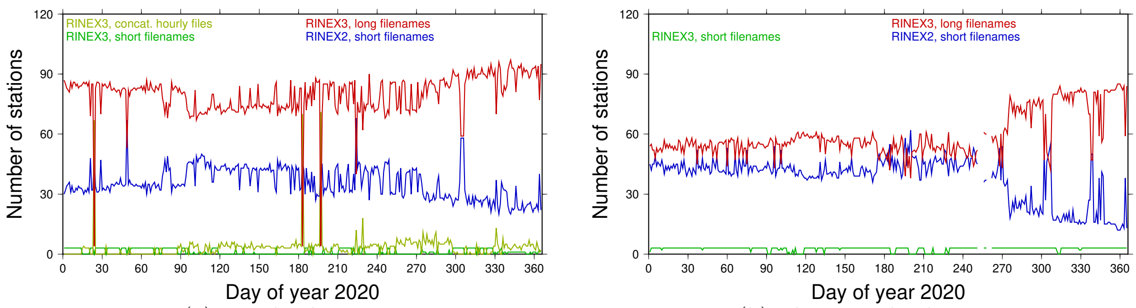
Table 3 gives an overview of the major changes implemented during the year 2020. Details on the analysis strategy can be found in the IGS analysis questionnaire at the IGS Central Bureau (`https://files.igs.org/pub/center/analysis/code.acn`).

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 is provided in Figure 3 .

During the year 2020 the number of RINEX 3 files in the final and rapid solution did again slightly increase towards 75%. In the ultra-rapid processing only hourly RINEX files are considered. Whereas at the beginning of the year only a bit more than half of the processed stations did provide their observations in hourly RINEX 3 files this ratio significantly changed in October 2020 towards the numbers known from the daily RINEX files (about 75% of the observation files are available in RINEX 3 format).



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

Figure 3: Usage of RINEX observations files for CODE processing.

Table 3: Selected events and modifications of the CODE processing during 2020.

Date	DoY/Year	Description
02-Feb-2020	033/2020	Correct settings regarding whether energy is absorbed or reflected for the solar panels in the box-wing model used for Galileo in the rapid und ultra-rapid solution as a priori solar radiation pressure model.
02-Feb-2020	033/2020	Switch from FES2004 to FES2014b for station deformation corrections and gravitational effect on the satellite orbits, Higher order ionosohere corrections: switch from IGRF12 to IGRF13, effecting rapid since GPS week 2091; final and MGEX week 2090.
26-Jan-2020	026/2020	Use a priori box-wing model for Galileo also in the MGEX processing.
17-Feb-2020	048/2020	Enable Galileo for the internal PPP solution providing the basis for the final clock solution.
16-Mar-2020		The CODE team – as all research personelle of the University of Bern – are forced to work at home without contacts in person with each other.
26-Mar-2020	086/2020	New SINEX product file obtained in the rapid and ultra-rapid processing chains (`CODwwwwd_TRO.SNX_R` and `COD_TRO.SNX_U`, respectively) containing in addition to the usual parameters also the troposphere zenith path delay and gradient parameters for selected sites.
22-Apr-2020	113/2020	Limit the number of ambiguities to 500 per day and station; otherwise the observation file is removed from the processing.
17-May-2020	138/2020	Switch reference frame to IGb14 for all product lines.
05-Jul-2020	187/2020	Stop the 1-day solution (with the ID COF) and reactivate the 3-day solution as the primary and only operational final contribution to the IGS final series. Reschedule the stochastic pulses to orbit midnight instead of noon/midnight GPS time. Reactivate the weekly IGSREPORT e-mail when submitting the solution.
05-Jul-2020	187/2020	Activate extended product information for final and MGEX series including the DOI reference as done in the repro3 product files. Orbit products are now delivered in SP3d format; clock RINEX format version 3.04 is submitted in parallel to the traditional version 2.00 format in the final and exclusively in the MGEX series.
Sep-2020 to Jan-2021		Regular problems with the stability of the storage server start in September with the inclusion of new computing nodes into the cluster system due to a bug in the related software. It will last until January 2021 until it is identified and fixed by an update.
02-Sep-2020	246/2020	New scheme for constraining the reference ambiguity when processing GLONASS observations was enabled.
04-Nov-2020	309/2020	General constraint on estimated observation type-specific biases of 10 ns in the inter-system bias solution and replace it by an alignment to the moving 30-day average in the rapid and final solution.
24-Nov-2020	329/2020	Switch processing to a new login server.
07-Dec-2020	342/2020	Stop using VMF in the rapid and ultra-rapid processing because of announced rescheduling of the provition for the VMF-corrections.

It should be noted that most of the hourly RINEX 3 files are usually downloaded from BKG data center (about 75%); the second most from IGN (about 10%). If there are connectivity issues in the near real time download procedure to the primary server, it cannot be fully compensated by other servers resulting in these drops of available RINEX 3 data in the ultra-rapid solution (visible in Figure 3(b)).

3.2 Procedure to generate the three-day solution at CODE

Because of any orbital arc has its biggest uncertainty at its end, it is beneficial to extend the orbital arc in order to shift these ending effects out from the period of interest. This can be done by extending the arc from 24 to, e.g, 30 hour length (beginning the arc at 21:00 of the previous day and extending it to 03:00 at the day after). Statistically, some of the observations are used twice others only once. A more appropriate approach would be to compute an orbit from noon of the previous day to noon of the day after in order to use each measurement exactly twice.

A similar effect can be achieved by computing three-day long-arc solutions as illustrated in Figure 4 . Here each observation is used in fact three times. The benefit of these longer arcs is that each measurement needs to be processed exactly once if the normal equation of the daily processing is stored. Based on the approach from Brockmann (1997),

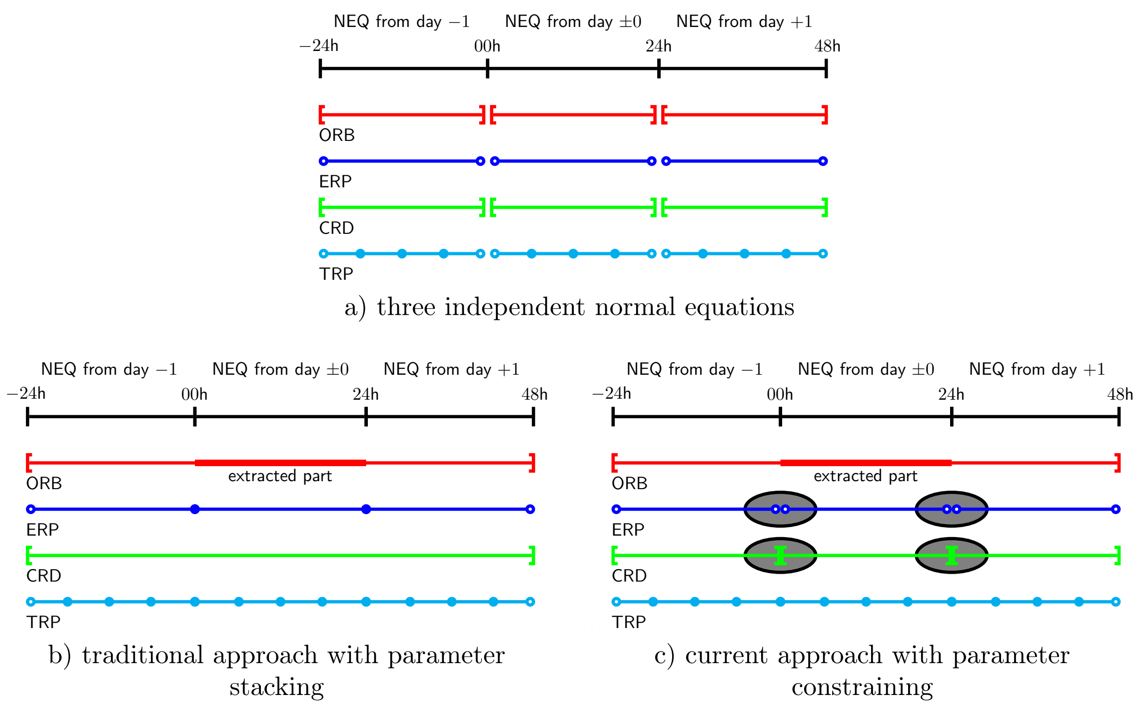


Figure 4: Principle of generating CODE's three-day final solutions.

three normal equations from the daily processing can be combined to a three-day long-arc solution. Regarding computation time this approach is very efficient but there are some points to be considered in the parameter handling.

The dynamical orbit parameters (as defined by Arnold et al., 2015) and the initial conditions from the three independent normal equations should be combined into one set valid through 72 hours. In order to obtain a continuous orbit in the inertial frame, the Earth rotation parameters should not have any discontinuity within the orbital arc. This can be solved with a piece-wise linear representation with two parameters per component and day. The parameters at 00:00 and 24:00 can be stacked together with this approach (as shown for the traditional approach in Figure 4 b).

On the other hand, this reduces the effective resolution of the Earth rotation parameters with respect to daily solutions with offset and drift per 24 hours whereas this long-arc approach with stacked Earth rotation parameters counts 4 parameters per 72 hours. This introduces inconsistencies when combining such solutions on SINEX level.

For that reason the parameters are not stacked but only constrained to construct a continuous series of Earth rotation parameters. The effect on the solution is the same as in case of stacking them but the resulting SINEX files contain still the independent parameters from the two consecutive days (see Figure 4 c). This allows even to convert them to offset and drift for each of the days in the SINEX file. Since the constraints are not frozen in the normal equation the SINEX file can be inverted with independent sets of Earth rotation parameters per day what is compatible to the parametrization of other IGS analysis centers. By reapplying the constraints as in the CODE final process generation, also the original solution can be reconstructed.

The motivation of using longer arcs is given not only by the performance of the orbit but also an improvement of the Earth rotation parameter estimates as reported by Lutz et al. (2015) . In order to compute longer arcs the requirements regarding the orbit model become bigger since the satellite trajectory needs to be represented over a longer period. Sidorov et al. (2020) has given an example where thermal radiation effects at the satellite are only visible in longer orbital arcs. In order to verify whether the orbit mode used by CODE is good enough to represent the GNSS orbits over 72 hours, the orbit misclosures for the GPS constellation in the year 2018 is shown in Figure 5 . On the left hand side the discontinuities in the orbits between one-day arcs are shown. The ends of the longer three-day arcs can be validated in a similar way when comparing the last position of the orbit for days n to $n+2$ with the beginning of the arc covering the days $n+3$ to $n+5$. This comparison in shown on the right hand side of Figure 5 . It is even better than the misclosures from the one-day arcs which confirms the performance of the orbit model also for longer arcs.

At the same time the rescheduling of the stochastic pulses (empirical velocity changes, see Beutler et al., 1994) was also introduced for the operational final processing line: the stochastic pulses are estimated at orbit midnight for each revolution instead of just every

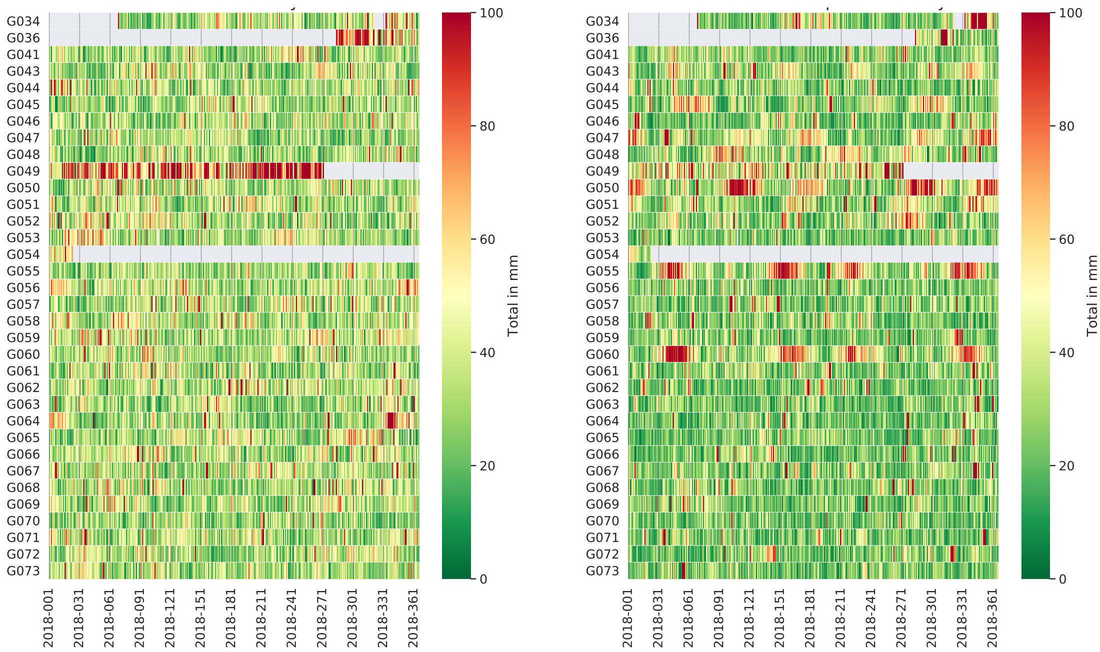
12 hours at noon and midnight. Dach et al. (2019) have shown an improvement of about 10% in the orbit misclosures at midnight for the GPS satellites due to this rescheduling.

4 Contribution to the IGS-Reprocessing

As a global analyis center CODE contributes to the IGS reprocessing effort for the ITRF 2020. Model changes with respect to the operational final processing at the beginning of 2020 have been reported in Dach et al. (2020) . Some of the model updates are already activated during 2020 in CODE's operational processing (see Table 3):

- ocean tidal loading corrections for station deformation and gravitational effect on satellite orbits based on FES2014b (Carrere et al., 2016) since Feb. 2020
- three-day solution with rescheduled stochastic pulses since July 2020

The reprocessing was carried out in 2020 at IAPG/TUM for the geometry part and at AIUB for adding the clock corrections and biases. The product files are submitted in time to the IGS for combination and made available at the server at AIUB as listed in Table 4 .



(a) one-day orbital arcs

(b) end of the three-day arcs

Figure 5: Orbit misclosures for GPS satellites from 1-day solutions and the end of three-day long-arc solutions

Table 4: CODE products available through anonymous ftp.

CODE *repro3* products available at ftp://ftp.aiub.unibe.ch/REPRO_2020/CODE/yyyy/
`COD0R03FIN_yyyyddd0000_01D_05M_ORB.SP3` GNSS ephemeris/clock data in 7 daily files at 5-min intervals in SP3d format, including accuracy codes computed from a long-arc analysis
`COD0R03FIN_yyyyddd0000_01D_01D_ORB.ERP` GNSS ERP (pole, UT1-UTC) solution in IGS ERP format
`COD0R03FIN_yyyyddd0000_01D_01D_SOL.SNX` GNSS daily coordinates/ERP/GC from the long-arc solution in SINEX 2.01 format
`COD0R03FIN_yyyyddd0000_01D_30S_CLK.CLK` GNSS satellite and receiver clock corrections at 30-sec intervals referring to the COD-orbits from the long-arc analysis in clock RINEX 3.04 format
`COD0R03FIN_yyyyddd0000_01D_05S_CLK.CLK` GNSS satellite and receiver clock corrections at 5-sec intervals referring to the COD-orbits from the long-arc analysis in clock RINEX 3.04 format
`COD0R03FIN_yyyyddd0000_01D_01D_OSB.BIA` CODE daily code and phase bias solution corresponding to the above mentioned clock products in BIAS-SINEX 1.00 format
`COD0R03FIN_yyyyddd0000_01D_01H_TRP.TRP` GNSS 1-hour troposphere delay estimates obtained from the long-arc solution in troposphere SINEX 2.0 format
`COD0R03FIN_yyyyddd0000_07D_01D_ORB.ERP` GNSS ERP (pole, UT1-UTC) solution, collection of the 7 daily COD-ERP solutions of the week in IGS ERP format; labeled with the starting day of the week
`COD0R03FIN_yyyyddd0000_07D_07D_SUM.SUM` Analysis summary for 1 week on the long-arc solutions of the week; labeled with the starting day of the week

The usage of the dataset should be referenced as

> Selmke, Inga; Dach, Rolf; Villiger, Arturo; Arnold, Daniel, Prange, Lars; Schaer, Stefan; Sidorov, Dmitry; Stebler, Pascal; Jäggi, Adrian; Hugentobler, Urs (2020). CODE repro3 product series for the IGS. Published by Astronomical Institute, University of Bern. URL: `http://www.aiub.unibe.ch/download/REPRO_2020`; DOI: 10.7892/boris.135946 .

In summary we computed

	Orbits, ERPs, station coordinates	Clock corrections (30 s), code and phase biases	Ultra-high rate clock corrections (5 s)
GPS	since 1994	since 2000	since 2003
GLONASS	since 2002	since 2008	since 2012
Galileo	since 2013	since 2014	— [a]

[a] Product not needed because the 30 s satellite clock corrections can be linearly interpolated.

Figure 6 provides a statistics on the number of estimated parameters. About two third of

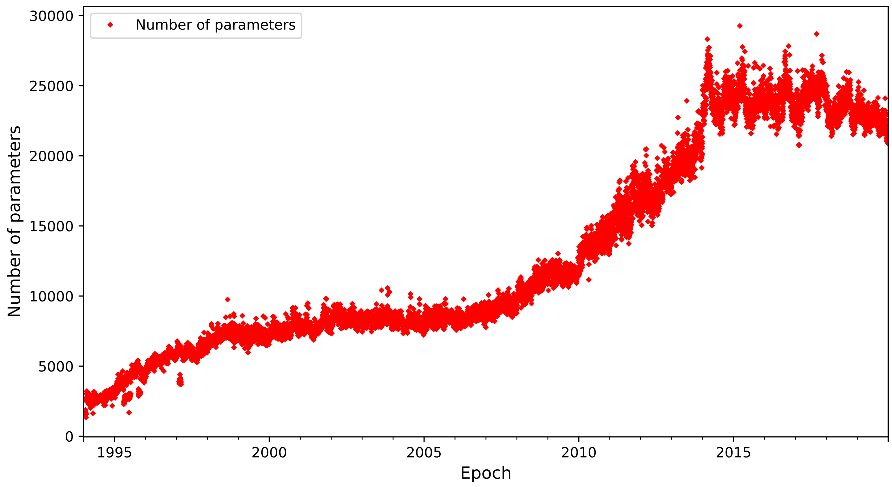


Figure 6: Number of estimated parameters in the repro3 series from CODE (from a one-day solution series).

the estimated parameters are phase ambiguity that have not been resolved to their correct integer numbers – even if the resolution rate is about 90%. Apart from the 6 Earth rotation parameters (one of them is constrained to the UT-value), 3 station coordinates and 17 troposphere parameters per station as well as 6 initial conditions, 7 dynamical orbit parameters in the ECOM2 system and 2 sets a three of stochastic orbit parameters per satellite are estimated per day. Other parameters like satellite antenna phase center offset and variation parameters as well as other monitoring parameters are only set up in the normal equations but removed directly before the inversion in order to fix the a priori values for the solution submitted to the IGS .

During the nineties the increasing number of parameters in Figure 6 indicate the increasing number of tracking stations included in the IGS network. The short sequences where the number of parameters is reduced is related to a higher success-rate in the ambiguity resolution because of the inactive anti-spoofing function. The inclusion of the GLONASS constellation into the solution in 2002 is not really visible in time series of estimated parameters because of the low number of active satellites (only about 10 tracked by 30 stations at the beginning). Since the number of not-resolved phase ambiguities is the dominating effect in the plot, the increasing number of GLONASS tracking stations starting in about 2007 is clearly visible as an increasing number of parameters, because for GLONASS only 50 to 60% of the ambiguities are resolved (no ambiguity resolution between satellites with different frequencies is done for longer baselines). This explains also the variations towards the end of the series. Since the ambiguity resolution rate for Galileo quickly develops towards the values for GPS with the densification of the network with Galileo-tracking stations and the increasing number of satellites, there is a contribution of decreasing number of parameters from unresolved ambiguity parameters towards the end of the time series.

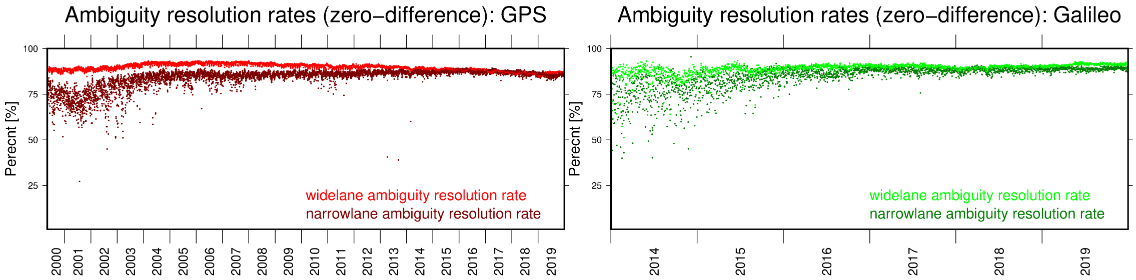


Figure 7: Percentage of resolved zero-difference WL and NL (with resolved WL) ambiguities for the clock analysis.

The reprocessing is accomplished in two analysis steps. First, the geometry part is estimated based on the double-difference approach. Subsequently, satellite clock corrections are generated based on a zero-difference analysis including ambiguity resolution using the so called OSB Common Clock approach (Schaer et al., 2020) for GPS and Galileo. Due to the frequency divison multiple access (FDMA) technique used by GLONASS, the corresponding ambiguities are not resolved leading to "float" type clocks. The success rate for widelane (WL) ambiguities is about 90% using a cut-off elevation angle of 3 degrees. Out of these resolved WL ambiguities, 85% of the associated narrowlane (NL) ambiguities could be resolved (see Fig. 7). Our PPP-AR enabling clock products includes satellite clock corrections at intervals of 300 s, densified in a phase-based interpolation to 30 s resp. 5 s intervals. The accompanying code and phase biases relying on the BIAS-SINEX format using the OSB representation.

A detailed description of the characteristics of the reprocessing solution and the influence of the model changes on the solution is provided in Dach et al. (2021) .

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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 2020

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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 2020 (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 2020, 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. NRCan adopted the IGb14 reference frame for the Final, Rapid, and Ultra-Rapid products starting with GPS week 2106 (May 17, 2020).

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) • From 2020-10-20, 30-sec GLONASS clocks produced hourly in addition to orbits and ERP with a delay of less than one hour.
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 continued to be produced at 1 hour intervals
(emrg[ddd]0.[yy]i), and include GPS and GLONASS differential code biases (DCBs). They are 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 their performance was being monitored. Station and satellite specific GLONASS DCB estimation using about 250 IGS stations collecting GLONASS measurements continued to be monitored. Ionospheric irregularities as sensed by 1Hz GPS and GLONASS phase rate measurements continued to be monitored in near-real-time and have been used for research and developments studies on mapping ionospheric irregularities over Canada (Ghoddousi-Fard et al., 2020) and studies of geomagnetic storms (Prikryl et al., 2020).

4 Real-time correction service

NRCan continues to encode its near-real-time TEC maps (Ghoddousi-Fard , 2014; Garcia-Rigo et al., 2019) for real-time distribution in the RTCM format. NRCan distributes the proposed RTCM SSR message type 1264 at a 30 sec rate from a development platform. NRCan is considering broadcasting the messages from our next-generation production platforms in a separate stream from the regular clock/orbit/bias corrections (Table 1). The ionosphere product is uploaded every 15 minutes (at 5, 20, 35 and 50 minutes after the hour).

NRCan is investigating cloud-computing to host its real-time platform. The goal remains to maximise flexibility when generating multiple constellation corrections in real-time.

5 CSRS-PPP service

The CSRS-PPP engine was updated to SPARK v3 on 20 October 2020 (Banville et al., 2021). This update introduces precise point positioning with ambiguity resolution (PPP-AR). Ambiguity resolution offers significant benefits to users by transforming ambiguous carrier-phase observations into precise ranges. As a result, centimeter-level accuracies can often be obtained more rapidly. Furthermore, due to satellite geometry, resolving carrier-phase ambiguities results in improved estimates for the longitude (east) component.

To enable GPS ambiguity resolution at the user end, three product lines are used as described in Table 2. The ultra-rapid products include GPS orbits as well as GLONASS orbits and clocks and Earth orientation parameters from the EMU products. The EMU GPS clocks are replaced by "integer clocks" computed using an in-house software based on the

Table 2: Satellite orbit, clock, bias and Earth orientation parameter products used in CSRS-PPP version 3.

Product Line	Internal Code	Availability	Latency
Ultra-rapid	DCU	Hourly	60 minutes after the hour
Rapid	DCR	Daily	12-18 hours after the end of the day
Final	DCF	Weekly	12-15 days after the end of the week

decoupled-clock model (Collins et al., 2010). These decoupled clocks contain ionosphere-free phase clocks, ionosphere-free code clocks and epoch-specific satellite widelane biases. These estimates are then transformed into observable-specific biases (OSBs) following (Banville et al., 2020). Both GPS and GLONASS satellite clock corrections are provided at a 30-second interval. The rapid products follow the same principles but are based on the EMR (rapid) products rather than the EMU products.

Final products use combined GPS orbits and Earth orientation parameters provided by the IGS. GPS satellite clock corrections and phase biases are obtained from an in-house combination using IGS analysis centers solutions (Banville et al., 2020). These clock corrections differentiate themselves from the IGS combined clocks since they preserve the integer nature of carrier-phase ambiguities at the user end. The final products also include NRCan's final GLONASS satellite orbit and clock corrections. These products are available for data starting 1 January 2018 and, prior to this date, the CSRS-PPP service continues using standard IGS products (with NRCan's GLONASS contribution) and does not offer ambiguity resolution.

CSRS-PPP version 3 also offers improved support for multiple GPS and GLONASS signal modulations defined in the RINEX 3 standard (Gurtner and Estey, 2020). This is achieved by performing a daily differential code bias combination from contributions by NRCan (Ghoddousi-Fard , 2014), the Center for Orbit Determination in Europe (CODE) (Villiger et al., 2019), the Chinese Academy of Science (CAS) (Wang et al., 2016), and the German Space Operations Center (DLR) (Montenbruck et al., 2014).

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 NR-

Table 3: NRCan-IGS Station Upgrades in 2020.

Station	Date	Remarks
algo	2020-08-18	Station receiver upgraded to SEPT POLARX5
flin	2020-02-18	Station receiver upgraded to SEPT POLARX5
kuj2	2020-02-07	Station added to IGS network ([IGSSTATION-7870])

Can's IGS stations were completed in 2020 and these are listed in Table 3. Figure 1 shows a map of the NRCan GNSS network as of January 2021. 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/station_logs/

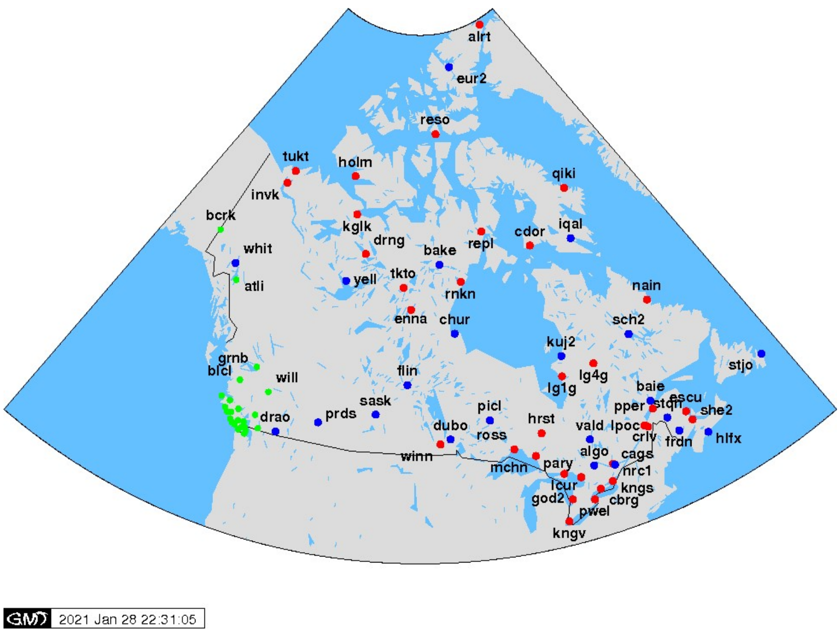

Figure 1: NRCan Public GNSS Stations (CGS-CACS in blue, CGS-RACS in red and CHIS-WCDA in green).

Table 4: Products contributed by NRCan in the IGS repro3 campaign.

Product Type	Period	GNSS	Output interval (sec)
Clocks	1996-2020	GPS	30
Biases (code and phase)	2000-2020	GPS	86400 (or less)
Attitude	1996-2020	GPS	30

7 Third IGS Reprocessing Campaign (Repro3)

NRCan participated in the IGS repro3 campaign. Using satellite orbits, Earth rotation parameters and station coordinates estimated by the National Geodetic Survey (NGS), NRCan provided the products listed in Table 4.

8 Acknowledgement

NRCan Contribution number / Numéro de contribution de RNCan: 20200678

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GFZ Analysis Center Technical Report 2020

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1 Summary

During 2020, 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 2020 including GPS, GLONASS, BeiDou, Galileo, and QZSS. In the past year we processed the GFZ contribution to the IGS repro3 campaign including GPS, GLONASS, and Galileo.

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. In November 2020, we added several IGS stations so far not contained in any AC submission to our final processing chain (in accordance to IGS e-mail [IGS-ACS-1421] from Paul Rebischung). Recent changes in the processing

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.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
gfzWWWWD.sum	Summary file
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
gfzWWWWD_HH.sum	Summary file
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

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. Starting from day 2109.5 the Final clock solution provided by GFZ became very noisy. This issue related to the reference clock selection was finally solved for week 2131. In additon, we corrected two software bugs related to antenna PCO (affecting the application of frequency specific values especially for GPS block III satellites) and PVs (affecting the interpolation in azimuth direction). Since 2020 the Ultra-rapid, Rapid, and Final products are available via GFZ Information System and Data Center (ISDC, https://isdc.gfz-potsdam.de/gnss-products/) and referenced under DOIs:

- Männel, B., Brandt, A., Nischan, T., Brack, A., Sakic, P., Bradke, M. (2020): GFZ final product series for the International GNSS Service (IGS). GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2020.002
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Table 2: Recent processing changes

Date	IGS	IGR/IGU	Change
2020-05-17	w2105	w2106.0	switch to IGb14
2020-10-07	w2126	w2126.3	software update (increased field boundaries according to repro3)
2020-10-26	w2128	w2129.2	software bugs regarding PCO and PV corrected
2020-11-17	w2131		reference clock issue solved
2020-11-20	w2132		refined station selection for final processing

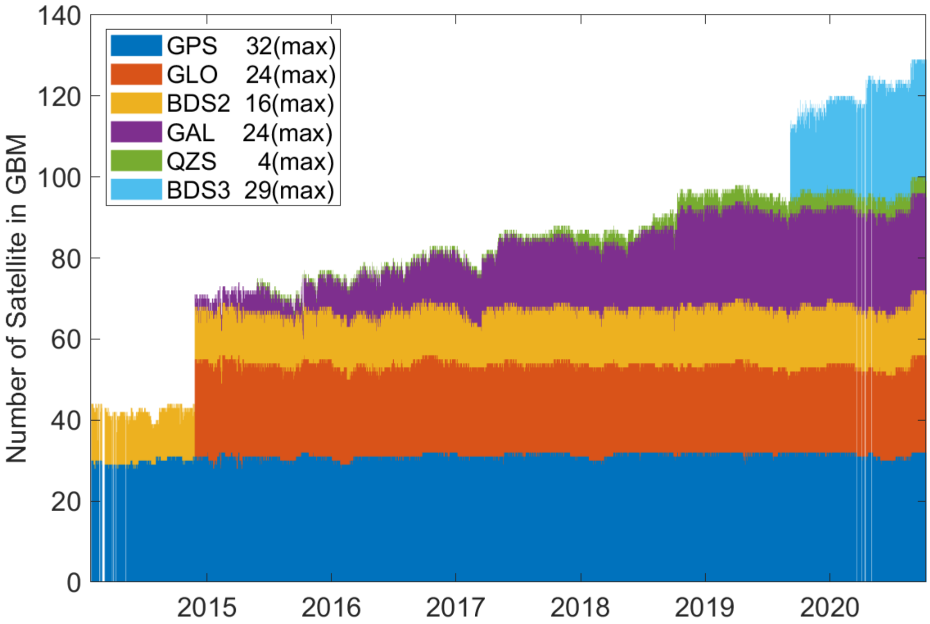

Figure 1: Total number of satellite per GNSS included in the daily multi-GNSS data processing (GBM).

4 Multi-GNSS data processing

The rapid multi-GNSS product GBM was continued in 2020. The ultra-rapid multi-GNSS processing GBU was stopped at the beginning of 2020. The GBM product file name is now following the IGS long-name definition. The IGS standard antenna PCO/PCV corrections are used to generate the long-name GBM products. In the long-name GBM product the BDS3 satellites are included. Figure 1 shows the number of satellites per GNSS included in the GFZ MGEX solution. The total number of GNSS satellites in GBM is 129. The GBM product are available at ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

5 Multi-GNSS Combination

During 2020, we pursued our efforts into the elaboration of an orbit and clock combination strategy compatible with a multi-GNSS environment. To do so, we used the IGS Multi-GNSS products provided within the framework of MGEX. Our investigations focussed on developing a new combination strategy that is entirely consistent for all constellations (Mansur et al., 2020, 2021). This new approach includes an improved satellite outlier detection based on the three orbit components (i.e., radial, transverse, and normal) and a satellite weighting based on a Variance Component Estimation. We introduced two weighting strategies, where either AC-specific weights or AC+constellation specific weights are used. They yield similar results with an agreement with the ACs' orbits at ∼1 cm level for GPS and up to a few centimeters for the other constellations. The agreement is generally slightly better with the AC and constellation weighting. Our method is validated with a sub-centimeter level consistency with the official legacy GPS-only IGS combination.

We communicated during the European Navigation Conference (initially May 2020 in Dresden, Germany and then shifted to November online) about enhancing the legacy IGS combination software. to make it compatible with the new GNSS constellations. The RMS of combined orbit w.r.t. input ACs ones are 30±15 mm for recent weeks of a test period from GPS week 1800 to 2000. This combination is also consistent at the centimeter level with the legacy IGS final combination (Sakic et al., 2020).

Our current work focusses on the clock offset combination. We want to apply a Variance Component Estimated weighting scheme similar to the orbits. We also focus our efforts on a better time reference alignment strategy to handle properly the ISB estimated by each AC and potential single-system stations.

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 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), and summarized the first results in Männel et al. (2019). The final submission (solution indicated as GFZ2) is now available via the ISDC (https://isdc.gfz-potsdam.de/gnss-products/) and can be cited as Männel, B; Brandt, A; Bradke, M; Sakic, P; Brack, A; Nischan, T (2021): GFZ repro3 product series for the International GNSS Service (IGS). GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2021.001. Figure 3 shows the number of daily solutions per station.

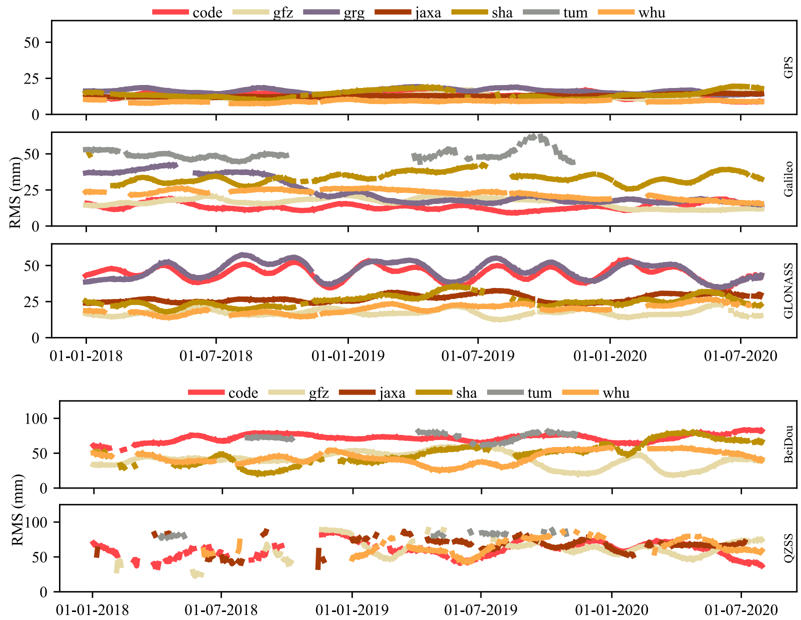

Figure 2: Constellation-specific RMS differences between the individual AC orbits and the combined solution using AC+constellation weighting.

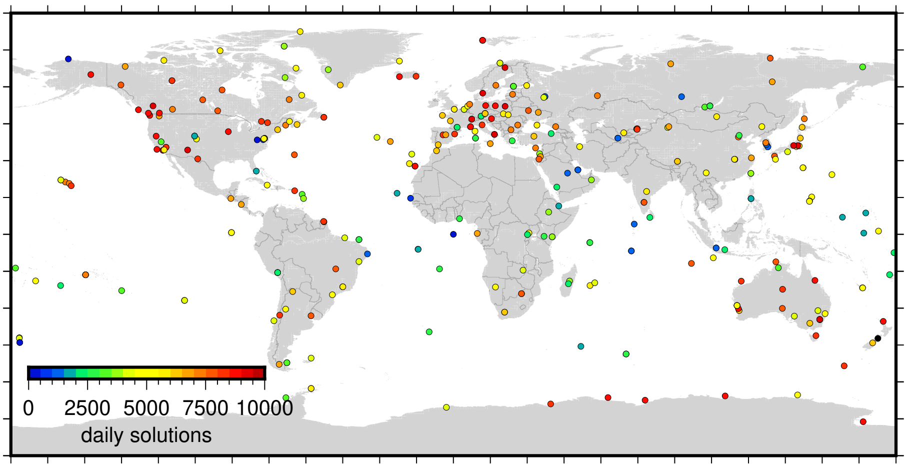

Figure 3: Number of daily solutions per station contained in the GFZ repro3 solution.

7 Operational GFZ Stations

The global GNSS station network operated by GFZ comprised 24 GNSS stations contributing to the IGS tracking network in 2020. The following stations were upgraded in the past year: TASH (Tashkent, Uzbekistan), KIT3 (Kitab, Uzbekistan), UNSA (Salta, Argentina), and RIO2 (Rio Grande, Argentina) are now equipped with SEPT ASTERX4

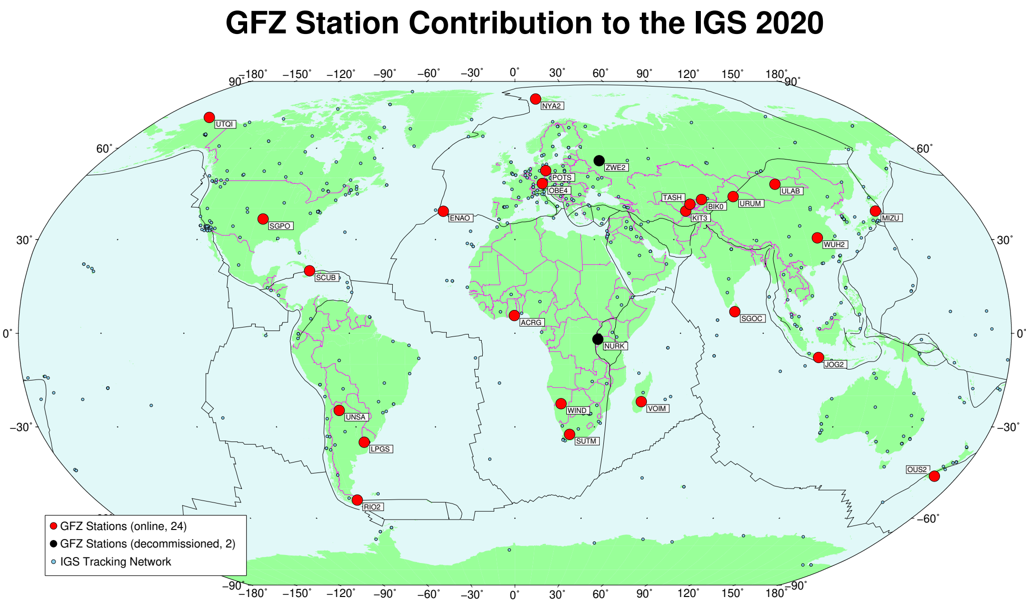

Figure 4: GNSS stations operated by GFZ (as of January 2020)

receivers and SEPCHOKE_B3E6 antennas. Due to the ongoing COVID-19 crisis several station visits had to be canceled. After many years of unsolved problems we decommissioned the stations NURK (Kigali, Rwanda) and ZWE2 (Zwenigorod/Russia) in 2020. However, ongoing negotiations for a new station in Kigali are promising.

Since 2020, 51 GFZ operated GNSS stations are available via the GFZ ISDC (https://isdc.gfz-potsdam.de/index.php?id=145). In addition to our IGS stations some of our backup stations but also project stations especially in Germany and the Near East are included. The RINEX data are sampled in 1s (@15minutes) and 30s (@1day). These data are included in our new data DOI (Ramatschi, M; Bradke, M; Nischan, T; Männel, B (2019): GNSS data of the global GFZ tracking network. V. 1. GFZ Data Services. doi.org/10.5880/GFZ.1.1.2020.001). Also our metadata system SEMISYS (https://semisys.gfz-potsdam.de) is now citable via Bradke (2020): SEMISYS - Sensor Meta Information System. V. 4.1. GFZ Data Services. doi.org/10.5880/GFZ.1.1.2020.005.

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Graz University of Technology (TUG) Analysis Center Technical Report 2020

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1 Introduction

In 2020, Graz University of Technology contributed to the International GNSS Service (IGS) for the first time as an Analysis Center by providing solutions for the third reprocessing campaign (repro3). We apply an uncombined and undifferenced (raw) observation approach in our GNSS processing (Strasser et al., 2019). Our software package GROOPS (Mayer-Gürr et al., 2020), which supports multi-GNSS processing among other features, has been released as open-source code on GitHub (`https://github.com/groops-devs/groops`).

2 Reprocessing campaign

Our contribution to repro3 was computed using GROOPS and covers the full time period from 1994 to 2020. Next to GPS, which spans the full period, GLONASS was introduced into the solutions starting from 2009 and Galileo from 2013. We included all available stations from the proposed repro3 station list (1212 stations), reaching more than 800 stations per day in the mid-2010s (see Fig. 1). All available code and phase observations on all frequencies (except Galileo E6) have been used at the full 30-second sampling rate. For a single day, this can result in more than 200 million raw observations, from which we estimate almost 5 million parameters. More details on how we adapted our processing setup to handle a computational challenge of this scale can be found in Strasser and Mayer-Gürr (2020).

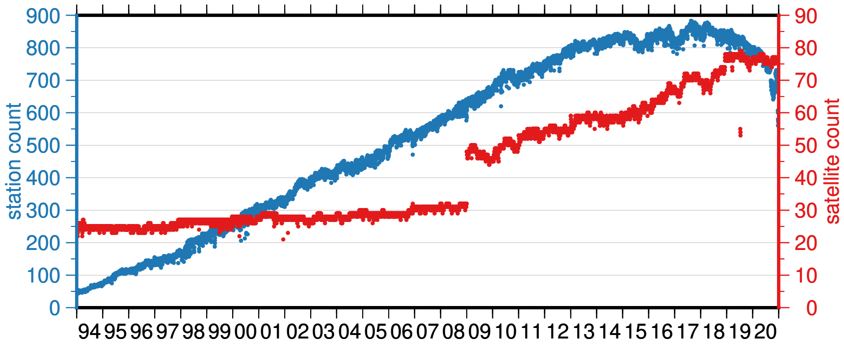

Figure 1: Number of processed stations and satellites per day.

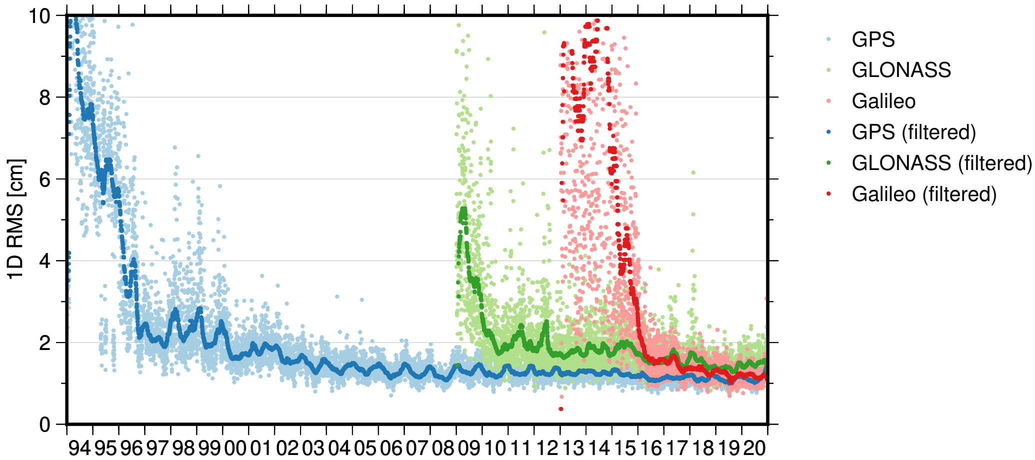

Figure 2: Median orbit midnight discontinuity RMS per GNSS.

Our repro3 products are listed in Tab. 1. They are going to be available on the IGS data centers and in a separate data repository (Strasser and Mayer-Gürr, 2021) in early 2021.

Results of preliminary analyses show that the orbit quality is very stable over time, except for the early periods per GNSS (see Fig. 2). GLONASS performs slightly worse than GPS and Galileo mostly due to some specific satellites showing a significantly higher than average discontinuity RMS (see Fig. 3). The source of these increased RMS values is still under investigation. TUG's station position residuals from a test combination of SINEX solutions by Paul Rebischung covering the years 2008–2019 were smallest among all included Analysis Centers, further confirming the high quality of our products.

Table 1: TUG's repro3 products

Product	Filename
Satellite orbits	TUG0R03FIN_*_01D_05M.ORB.SP3.gz
Satellite and station clocks	TUG0R03FIN_*_01D_30S.CLK.CLK.gz
Satellite attitude	TUG0R03FIN_*_01D_30S.ATT.OBX.gz
Satellite and station code and phase biases	TUG0R03FIN_*_01D_01D.OSB.BIA.gz
Station coordinates	TUG0R03FIN_*_01D_01D.CRD.SNX.gz
Troposphere estimates	TUG0R03FIN_*_01D_05M.TRO.TRO.gz
Earth rotation parameters	TUG0R03FIN_*_01D_01D.ERP.ERP.gz
Normal equations	TUG0R03FIN_*_01D_01D.SOL.SNX.gz

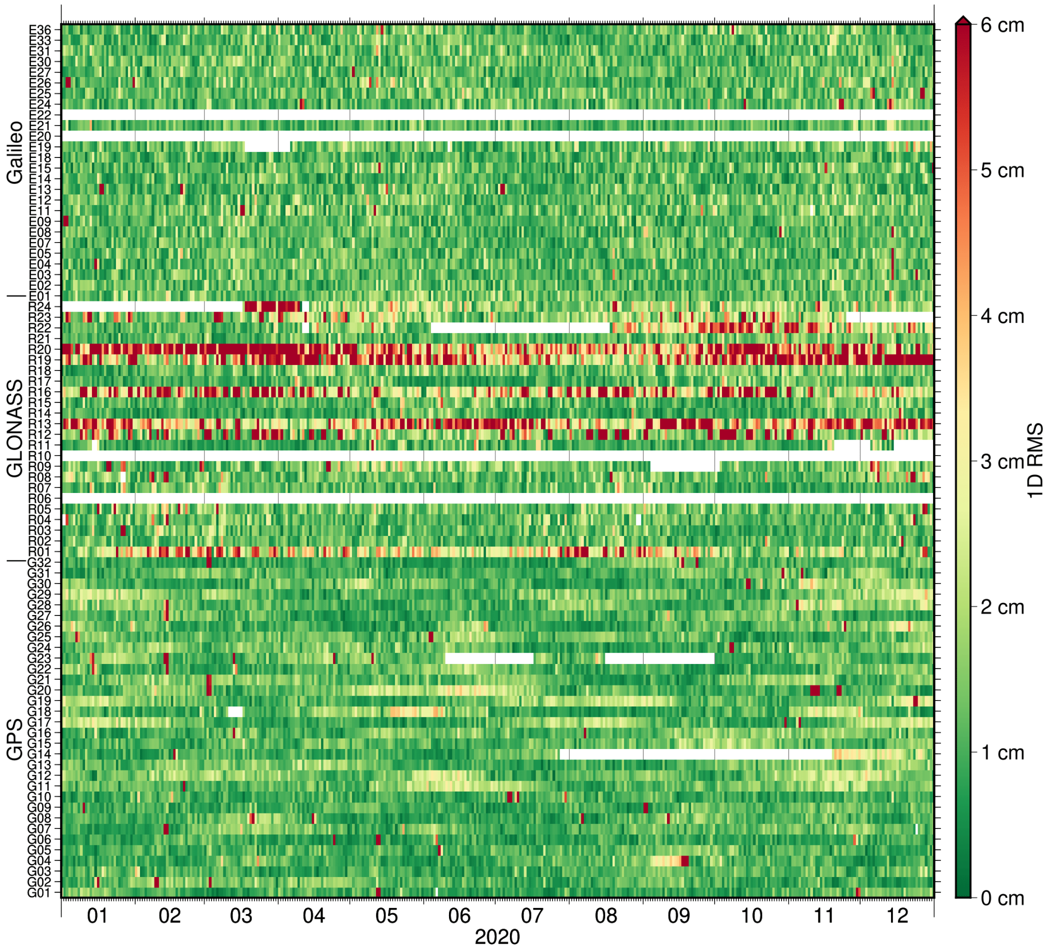

Figure 3: Orbit midnight discontinuity RMS per satellite for 2020.

3 Other activities

We have contributed to the satellite attitude comparisons conducted by some Analysis Centers in collaboration with the Precise Point Positioning with Ambiguity Resolution (PPP-AR) Working Group (Loyer et al., 2021). Based on the findings of this experiment, we re-implemented all known satellite attitude models for GPS, GLONASS, Galileo, BeiDou, and QZSS into our software in a generalized form, making them easier to maintain and less prone to errors. As GROOPS is open-source software, the source code and documentation of the attitude model implementations can be found in our GitHub repository.

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CNES-CLS Technical Report 2019

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1 Introduction

The CNES-CLS Analysis Center is being providing final products on behalf of the Groupe de Recherches de Géodésie Spatiale (GRGS) since 2010 using the GINS CNES software package. The formal "GRG" GPS-GLONASS products can be downloaded from the "gps/products/wwww" directory of the IGS archiving centers while MGEX "GRM" GPS-GLONASS-Galileo products are accessible through the "gps/products/mgex/wwww" directory. The main evolutions in the processing are summarized in Table 1.

More information can be found in the references section as well as at: https://igsac-cnes.cls.fr/.

2 Participation to the 3rd reprocessing campaign

In 2020, a large part of the CNES-CLS Analysis Center resources was dedicated to REPRO3 effort. Several processing model modifications have been implemented in a dedicated operational tool version in order to fulfil IGS recommendations (http://acc.igs.org/repro3/repro3.html). A set of 276 GNSS stations has been defined taking into

Table 1: Main processing changes

Date	GPS week	Change
2020/02/06	2093	Use of UT1 zonal terms in final orbits computations (only linear before)
2020/05/17	2106	According to IGSMAIL-7921 : Switch to IGb14 reference frame
2021/01/24	2142	Pole tide model correction (see section 3) SP3 sampling 300 s (900s before) Star delivering satellite attitude quaternions files (OBX files)

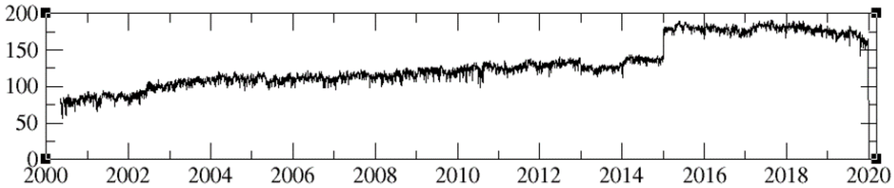

Figure 1: Daily number of stations.

account the different levels of priority provided by the IGS as well of the availability of GLONASS and Galileo tracking capability. Figure 1 illustrate the number of stations included in the daily processing as a function of time.

In terms of constellations, as shown in figure 2, GPS has been considered since DOY 124-2000 (Week 1060), while GLONASS has been included DOY 309-2008 and Galileo DOY 001-2017. The reprocessing period covers a time span until DOY 366-2020.

CNES-CLS REPRO3 products are called GRG6RE3FIN (table 2) and have been delivered to the IGS coordinators.

Alike final products delivered on a routine basis, REPRO3 GPS and Galileo products are compatible with an undifferentiated approach of phase ambiguity resolution. They can be used to process RINEX files in a PPP-AR mode.

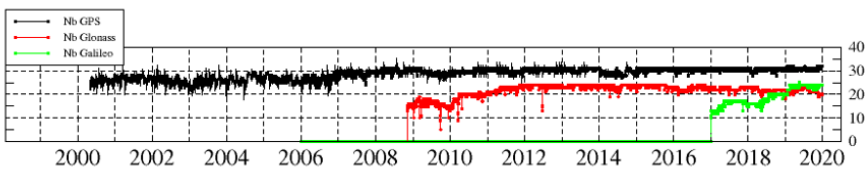

Figure 2: Number of GPS (black), GLONASS (red) and Galileo (green) satellites considered.

Table 2: Main processing changes

File	Type	Sampling
GRG6RE3FIN_yyyyddd0000_01D_000_SOL.SNX.gz	SINEX solution (satellite/station/ERP)	1/day
GRG6RE3FIN_yyyyddd0000_01D_02H_TRO.TRO.gz	SINEX Solution (Tropo)	Vert. (1/2h) Gradients (2/day)
GRG6RE3FIN_yyyyddd0000_01D_30S_ATT.OBX.gz	ORBEX Satellite attitude	30 seconds
GRG6RE3FIN_yyyyddd0000_01D_01D_ERP.ERP.gz	ERP solution	1 set/day
GRG6RE3FIN_yyyyddd0000_01D_05M_ORB.SP3.gz	SP3 Satellite orbit	5 minutes
GRG6RE3FIN_yyyyddd0000_01D_30S_CLK.CLK.gz	CLK satellite clock	30 seconds

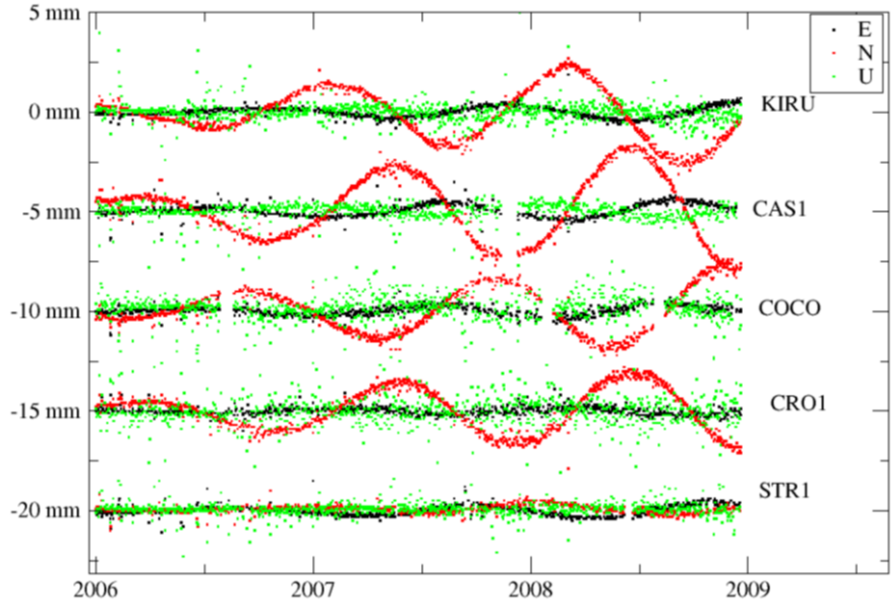

Figure 3: East, North, Up station coordinates differences before and after correcting the sign error in the North-South pole tide displacement model implementation

3 Station displacement due to pole tide

In the framework of the REPRO3 effort we participated in various product evaluation campaigns. Thanks to the feedback of the IGS Reference Frame Coordinator, an error in the pole tide correction implementation in the GINS software could be identified. In fact, a sign error of the North-East component (IERS conventions, equation 7.26) was a source of inconsistency on this particular component versus other ACs

This is illustrated in Figure 3 which compares on 5 different sites, station coordinate solutions before and after correcting the sign error on a 2006-2009 test period. The main impact was on the North-South component and was looking like an annual oscillation sometimes exceeding 5 mm at some stations. CNES-CLS REPRO3 products were produced using a corrected version of the GINS software. The operational GRG "final products" benefit from this improvement since 2021 January 24^{th}.

4 Satellite products and ORBEX files

For various reasons, some discrepancies in satellite attitude modeling implemented in the different IGS ACs processing tools still exist today in particular when satellites are crossing the Earth shadow. Nevertheless, users of orbit/clock products from a single AC can still fully exploit the quality of these products and preserve their properties (e.g. ambiguity resolution compatible) if the processing models is consistent as match as possible with the one used by that AC.

The REPRO3 campaign has been a great opportunity to encourage the different ACs to provide ORBEX files containing the satellite orientations as a function of time (`http://acc.igs.org/misc/ORBEX009.pdf`). As already mentioned in section 2, our AC has provided ORBEX file on the same period as of the REPRO3 orbit and clock products. Users of CNES-CLS IGS orbit/clock products are strongly encouraged to exploit the associated ORBEX files too.

5 ELIMSAT files

When the orbit/clock GRG products are generated, it can happen for various reasons that a given GNSS satellite is excluded from the global ambiguity fixing process. The (phase) clock solution for these particular satellite/day is not compatible with PPP-AR applications. On the user side, the corresponding phase data must be rejected from the ambiguity resolution process (but can be kept as un-fixed observations). This information is currently available in an internal format in this directory: `ftp://ftpsedr.cls.fr/pub/igsac/GRG_ELIMSAT_all.dat`

Figure 4 illustrate the occurrence of such events for GPS and Galileo satellites during 2020. The red dots correspond to clock products that are not compatible with un-differentiated ambiguity resolution. In 2021, we will start providing an additional product called Narrow-Lane Ambiguity Resolution (NAR) file in the bias IGS format in order to consolidate PPP-AR using GRG products.

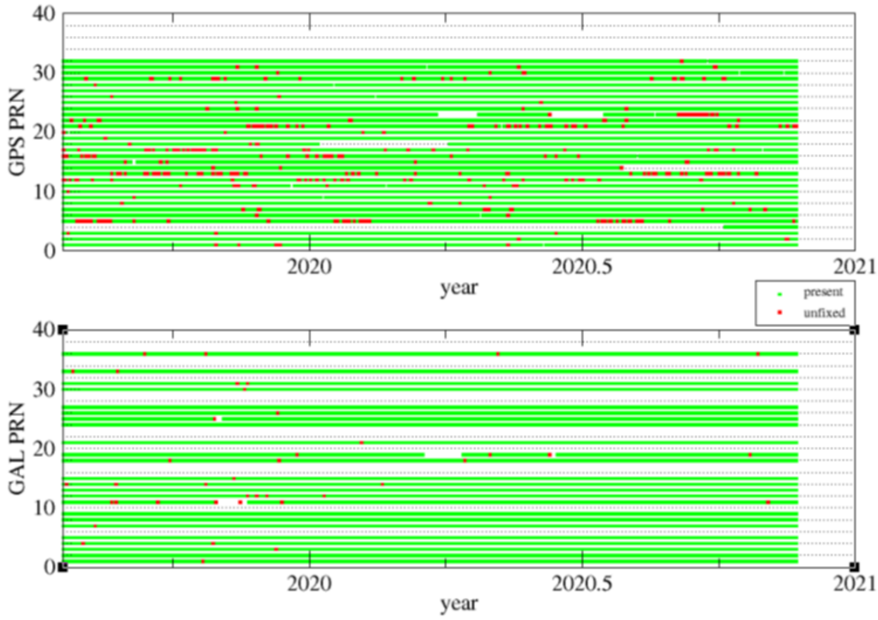

Figure 4: Matrix representation of the ELIMSAT file during 2020 for GPS (top) and Galileo (bottom) constellations

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JPL IGS Analysis Center Technical Report 2020

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1 Introduction

In 2020, 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 2020.

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

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

of our daily solutions is determined independently from neighboring solutions, namely 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)

Further details can be be found in the recent GipsyX/RTGx paper (Bertiger et al., 2020).

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

- Orbit and clock products: In March 2020 in response to the challenging Covid-19 situation we switched to producing our orbit and clock products with all personnel working from home with no interruption to the production or quality of these products.

- Third IGS global reprocessing campaign: We contributed to this campaign by conducting a complete re-analysis of GPS observations from 1994 onwards. This set of solutions were delivered in February 2021 in preparation for the future International Terrestrial Reference Frame, ITRF2020. As part of this campaign, JPL revisited its strategy for ground network selection and troposphere modeling (using the VMF1 model and mapping function instead of the GPT2 model). The reprocessed solutions also benefit from the latest updates to the IERS Conventions (newest recommended models including: linear mean pole convention, high-frequency Earth Rotation Parameter models along with EarthÕs libration model). It should be noted that, except for the ground network selection algorithm, none of the changes operated in the frame of the reprocessing effort will become operational settings until the ITRF2020 frame is released and an internal reprocessing is completed.

- Multi-GNSS: Progress towards an operational multi-GNSS product suite continued apace at JPL. Efforts included substantial code development, all based around our GipsyX software, and in May of 2020 resulted in the release of a test 6-month product set:

  https://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/MultiGNSS_Rapid_Test/

  As a first step towards publicly available operational products, our intent is to be able to release daily low-rate (5-min) Rapid multi-GNSS products by the end of 2021. Remaining development efforts are focused on ensuring that our code-base is robust, capable of producing operational multi-GNSS Final products, and that it is IGS repro-ready.

5 Future Work

We are currently developing the multi-GNSS capability of GipsyX and our longer term goal is to operationally generate high-rate (30s) rapid and final 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 and testing.

6 Acknowledgments

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MIT Analysis Center Technical Report 2017

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1 Introduction

In this report, we discuss results generated by the MIT analysis center (AC) both for submissions of weekly final IGS solutions and our weekly combination of SINEX files from MIT and the other eight IGS analysis centers that submit final SINEX files. We present here analysis of the networks we process, comparison between our position estimates and those from other IGS analysis centers and the impact of the IGS14 to IGb14 transition.

2 Overview of MIT processing

The MIT analysis for IGS final orbits, clocks and terrestrial reference frame uses the GAMIT/GLOBK software versions 10.71 and 5.34 (Herring et al., 2019). The GAMIT software uses a double-difference estimator. In order to efficiently process a large global network sub-networks are used. Each day, 350 stations are included in the combined network which is composed of seven individual networks each with 50 stations and pairs of stations that couple each sub-network to every other sub-network. These networks are generated independently each day and depend of the data that is available in the IGS and other data archives. We search CDDIS, UNAVCO, SOPAC, Geosciences Australia and BKG for RINEX data. Each network is seeded with four distant sites (not all sites need to be available) and the seven networks are sequentially filled, first from a list of 259 IGS sites in the IGb14.ssc and then from other sites around the world that will fill in regions not covered by the IGS sites. Sites are added one-at-time to each network rather than making one complete network before moving the next. The sequential approach makes each network as globally distributed as possible. Pairs of overlap stations are selected from the stations in each network to join the networks together. No station is used more than twice in this approach. The network solutions and parameterized orbit models are combined with the GLOBK software. The GAMIT solutions estimate parameters for the full set of Bernese Empirical Code Orbit models (Beutler et al., 1994; Arnold et al., 2015). The GAMIT implementation, referred to as ECOMC, uses 6 initial conditions, 3 constant radiation parameters and 3 pairs of once-per-revolution (OPR) radiation parameters in the direct, Y and B axes direction and 2 and 4 times-per-revolution terms in the direct solar-radiation direction. The parameters are scaled by the direct solar radiation force (i.e. the parameters fractional values). The apriori values for the 13 radiation parameters are all zero except the direct solar radiation parameter whose apriori value is 1. The parameters of the full model are poorly determined and in the GLOBK combination stage, we force the estimates of most of the periodic radiation parameters (PRP) to zero. The constant direct, B and Y axis and the once-per-rev B-axis and twice-per-rev direct terms are always estimated with an apriori constraint of 1 (i.e., 100% of the full solar radiation force). We check orbit overlaps and if these exceed 10 cm for any pair of days during the week we also allow estimation of the direct once-per-revolution and direct 4-times-per-revolution parameters. These additional parameters are only needed for 1-3 satellites per week and often no satellites. A weekly solution is then run with the radiation parameters loosely constrained between days. The RMS scatter of the radiation parameter estimates is then used to determine the random walk process noise to assigned to each radiation parameter still being estimated for each satellite. If the normalized RMS (NRMS, $\sqrt{\chi^2/f}$) is less than 0.5, the process noise is set to 0 (i.e., the radiation parameter will have a constant value for the week). For higher values of the NRMS, the process noise random walk value is set to allow changes of the value of the RMS in 1-day (i.e., RMS^2/day process noise value is used). The final weekly orbits and position SINEX files are generated from a "smoothing" Kalman filter run with large site position and earth orientation parameter process noise ($1\,\mathrm{m}^2$/day and $1\,\mathrm{mas}^2$/day). The orbit initial conditions are loosely constrained each day and use a white noise process noise model. The UT1 estimates track the integrated length-of-day estimates. The latest versions of GLOBK allow reference frame realization to applied during the back smoothing run.

In addition to weekly final processing, we also generate combined SINEX processing from the combination of all eight IGS ACs contributing to the IGS finals. We do this in our role as an associate analysis center (AAC). The procedures here are unchanged except for the transition to In Tables 1 and 2 we list the products submitted by MIT in our AC and AAC roles.

The network of stations processed by MIT in 2020 is shown in Figure 1. The figure shows the weighted root-mean-square (WRMS) scatter of the horizontal coordinates of nearly all of the stations included in the MIT finals processing. Stations that were used just a few times (15 stations in all) are not included in the plot. Only linear trends were removed from the time series. Figure 2 shows histograms of the WRMS in all three topocentric coordinates after the removal of linear trends from the time series. The median WRMS scatters of the 508 sites, measured more than five times, included in the statistics are 1.5 mm in North and East and 5.4 mm in height. No annual signals were removed.

Table 1: Table 1: MIT products submitted for weekly finals analysis

File	Description
mitWWWW7.sum.Z	Summary file. WWWW is GPS week number.
mitWWWW7.erp.Z	Earth rotation parameters for 9-days, IGS format
mitWWWWn.sp3.Z	Daily GPS satellite orbits (n=0-6)
mitWWWWn.clk.Z	Daily GPS satellite clocks (n=0-6)
mitWWWW.snx.Z	Daily GPS coordinate and EOP SINEX file.

Table 2: MIT products submitted for daily combinations of IGS final AC SINEX files.

File	Description
migWWWWn.snx	Combined sinex file from all available analysis centers (n=0-6, WWWW GPS week number)
migWWWWn.sum	Name of this summary file (n=0-6)
migWWWWn.res	File of the individual AC position estimates residuals to the combined solution for the week. (n=0-6)

At the start of GPS week GPS week 2106 (May 17, 2020) we switched the reference frame from IGS14 to IGb14 which updated the coordinates of a number of refence sites used to define the frame. The impact of the change can be seen in Figure 4.

3 Position repeatability and comparison to other ACs

We can also compare the MIT daily position estimates with those of other analysis centers based on the AAC combinations performed at MIT. The MIG combined solution is used for comparison with the official IGS combination preformed at IGN and generally matches the IGN solution at the level of 0.1-0.2 mm in north and east (NE) and 0.7-1.0 mm in height (U). The two analyses use different methods to determine AC weighting and different selection of sites. In Figure 3, we show the WRMS scatter of the daily fits to 40 IGS14/IGb14 reference frame sites from each of the IGS ACs and the combined SINEX solution with the weights assigned to each AC consistent with the fit of the AC to combination of the other ACs. There is good consistency between the ACs. Figure 4 shows the WRMS scatter between the AC and either IGS14 (until week 2106) or IGb14 (after 2106). The transition to IGb14 can be clearly in the North and East components while not being so clear in the height. While the AC results look similar, there are differences in the mean of the RMS differences. Table 3 gives the mean RMS differences for each AC with respect IGS14/IGb14 and respect to the combination. This table shows that on average the MIT solution provides a very good match to the combined solution with sub-millimeter horizontal WRMS and 2.8 mm WRMS in height. We also compute the

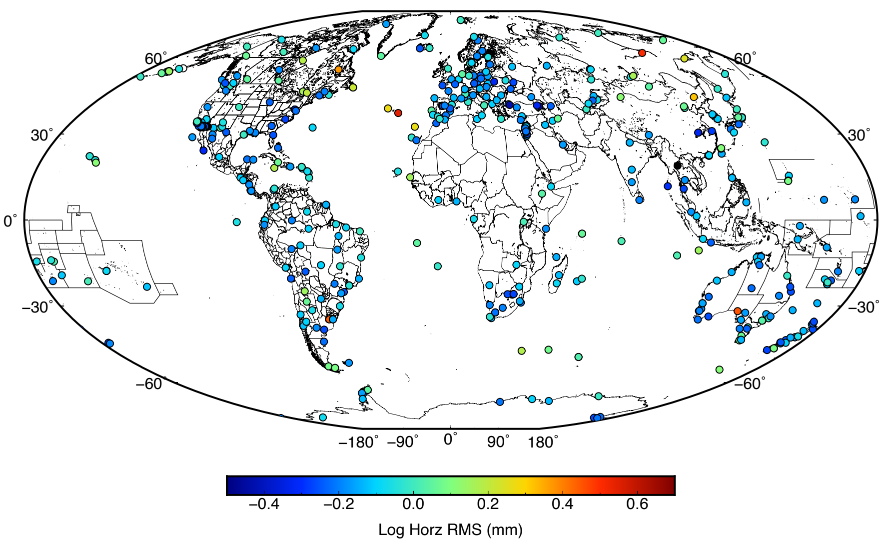

Figure 1: Log (base10) of the RMS scatter of the horizontal position estimates from the network of 508 stations processed more than 5 times by MIT in 2020. Each daily network has 350 station and the networks evolve with time depending on data availability and geometry. The cooler colors are all less than 1 mm RMS scatter while the warmer colors are greater than 1 mm scatter. The sites with the highest horizontal RMS scatters (sum square of N and E RMS scatters) are CEDU (5.12 mm) CHAN (5.29 mm) NAUS (5.33 mm) CN12 (6.01 mm) MARN (6.29 mm) SCH2 (6.30 mm) PDEL (6.94 mm) LPGS (7.31 mm) NETP (7.34 mm) TSK2 (7.45 mm) YAKT (9.40 mm) BILB (11.25 mm) AB07 (37.91 mm). The sites with the largest height RMS scatters are TRNT (12.20 mm) BILB (12.59 mm) KIRU (13.88 mm) GUUG (13.99 mm) RIO2 (14.38 mm) UNSA (16.25 mm) IPAZ (16.94 mm) HAMM (17.34 mm) CHAN (19.20 mm) CART (22.73 mm) NAUS (26.23 mm) CUIB (28.46 mm) IQQE (29.07 mm).

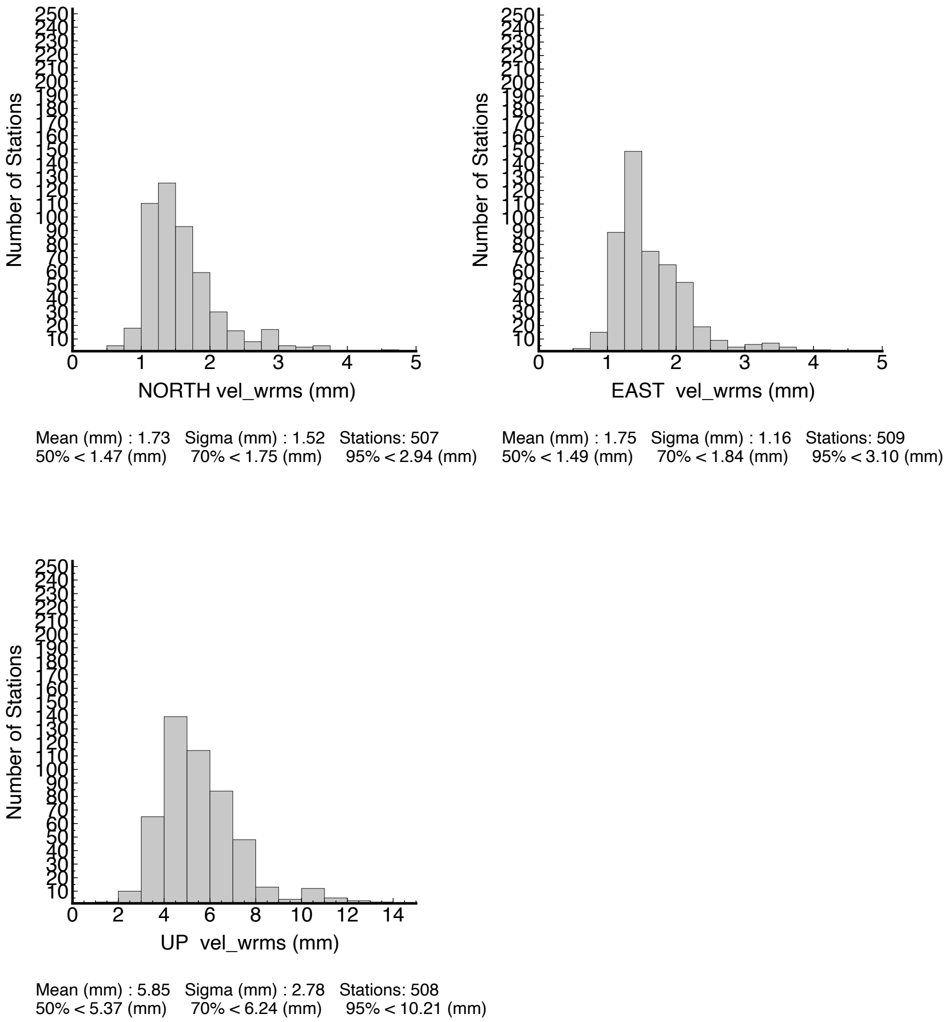

Figure 2: Histogram of the weighted root-mean-square (WRMS) scatter of daily position estimates of site used more than 5 times for 2020 after removal linear trends and elimination of gross outliers (5 times WRMS scatter). The median scatters are similar to last year with 1.5 mm horizontal and 5.4 mm vertical. These values are very similar to previous years.

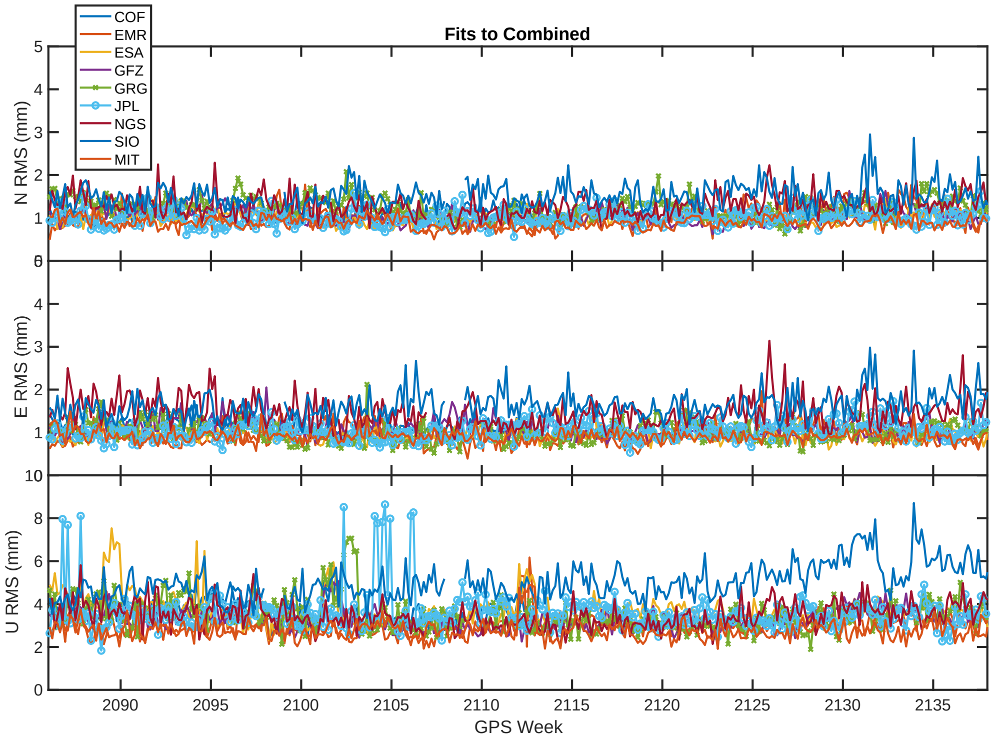

Figure 3: RMS scatters of the fits of the different IGS ACs to the MIG combined solution for 2020. It is not clear why the SIO heights show larger height scatters than the other ACs.

chi-squared per degree of the fits and all AC's have similar chi-squared values indicating that no one center dominates the combination.

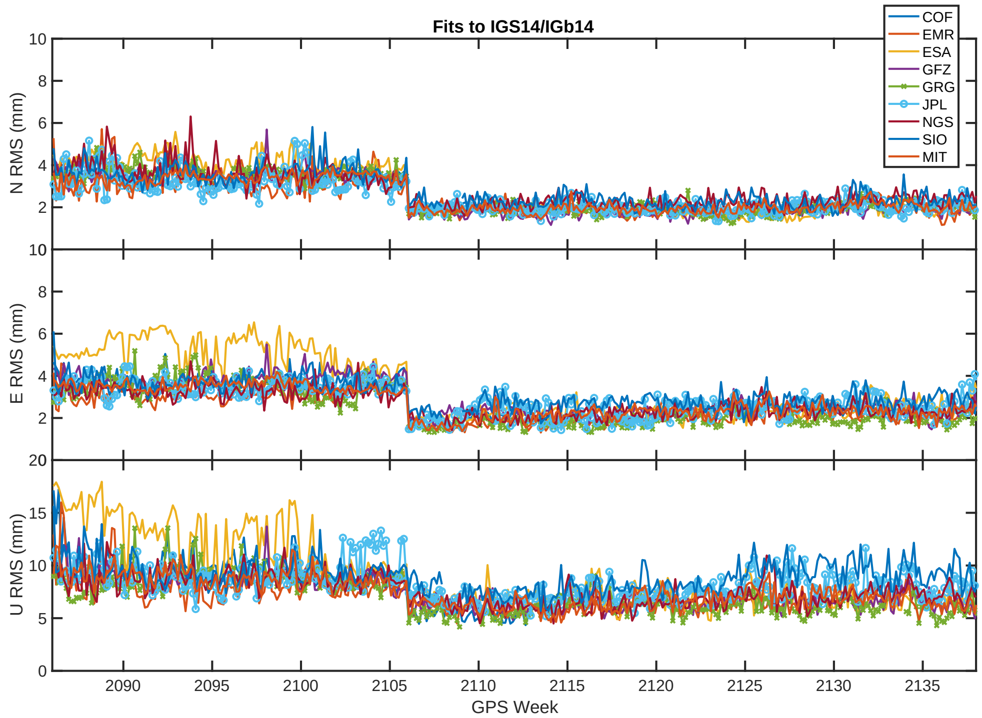

Figure 4: RMS scatters of the fits to IGS14, prior to GPS week 2106 (May 17, 2020), and IGb14 this week and after for the analyses in 2020.

Table 3: Comparison of the fits to the IGS14/IGb14 reference frame (RF) and daily combined solutions for RF sites in the MIT and other AC daily final SINEX files. Typically, 39 sites are used in the comparison for IGS14 and 43 sites for IGb14. The switch to IGS14 took place at the start of GPS week 2106 (May 17, 2020).

Center	IGS14/IGb14			Combined		
	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
MIT	2.48	2.70	7.40	0.88	0.91	2.79
COF	3.13	3.34	8.68	1.10	1.15	3.65
EMR	2.43	2.42	7.12	1.03	0.93	2.96
ESA	2.72	3.41	8.93	1.02	0.94	3.68
GFZ	2.47	2.94	7.37	1.02	1.09	3.28
GRG	2.58	2.51	7.04	1.24	1.00	3.50
JPL	2.49	2.83	8.28	1.02	1.05	3.62
NGS	2.82	2.67	7.64	1.30	1.48	3.49
SIO	2.84	3.15	9.13	1.59	1.70	5.25

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USNO Analysis Center Technical Report 2020

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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 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.

More information about USNO rapid, Ultra-rapid and UTGPS products can be found at the USNO website: 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, 2020

Figures 1-4 show the 2020 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 20 mm with respect to (wrt) the IGS rapid combined orbits. The USNO Ultra-rapid orbits had median WRMSs of 22 mm (24-h post-processed segment) and 40 mm (6-h predict) wrt the IGS rapid combined orbits. USNO rapid (post-processed) and Ultra-rapid 6-h predicted clocks had median 170 ps and 1040 ps RMSs wrt IGS combined rapid clocks.

USNO rapid polar motion estimates had (x, y) 25 and 24 microarcsec RMS differences wrt IGS rapid combined values. USNO Ultra-rapid polar motion estimates differed (RMS of x, y) from IGS rapid combined values by 392 and 396 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 728 and 850 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 2020, seven-parameter Helmert transformations computed between USNO and IGS Ultra-rapid GPS+GLONASS orbits had median RMSs of 53 and 88 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 453 and 266 microarcsec, respectively. USNO GPS+GLONASS Ultra-rapid 24-h predicted polar motion x and y values differed from the IGR values, RMS, by 635 and 382 microarcsec, respectively. These data are shown in Table 2 and Figs. 5–6.

All USNO AC official products were generated with the Bernese 5.2 GNSS Software in 2020.

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Table 1: Precision of USNO Rapid and Ultra-Rapid Products, 2020. 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	x	y	past 24 4 x	past 24 4 y	24-h predict x	24-h predict y			past 24 h	6-h predict
1/1/2020–12/31/2020	20	22	40	25	24	392	396	728	850			170	1040

Table 2: 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.

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
1/1/2020–12/31/2020	53	88	x: 453 y: 266	x: 635 y: 382

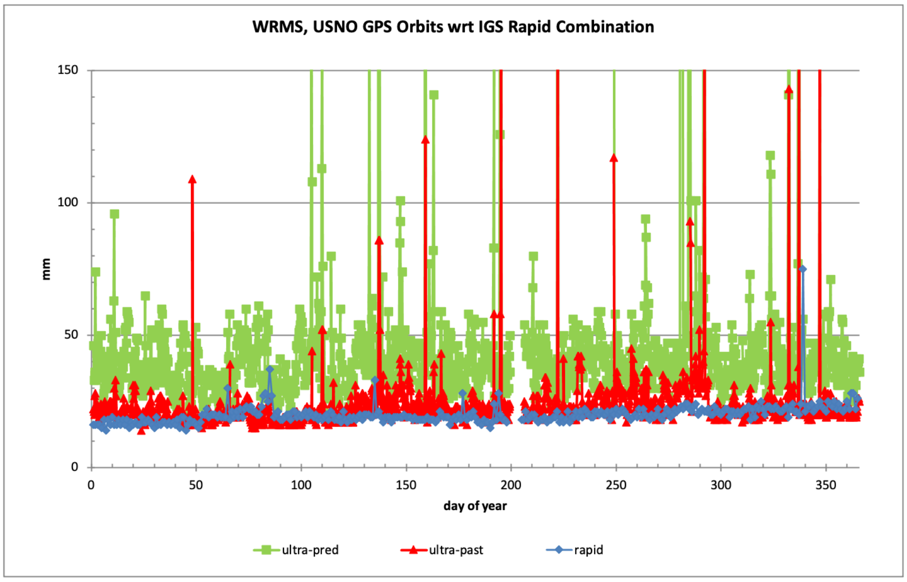

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2020. "Ultra-past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra-pred" refers to first six hours of Ultra-rapid orbit prediction.

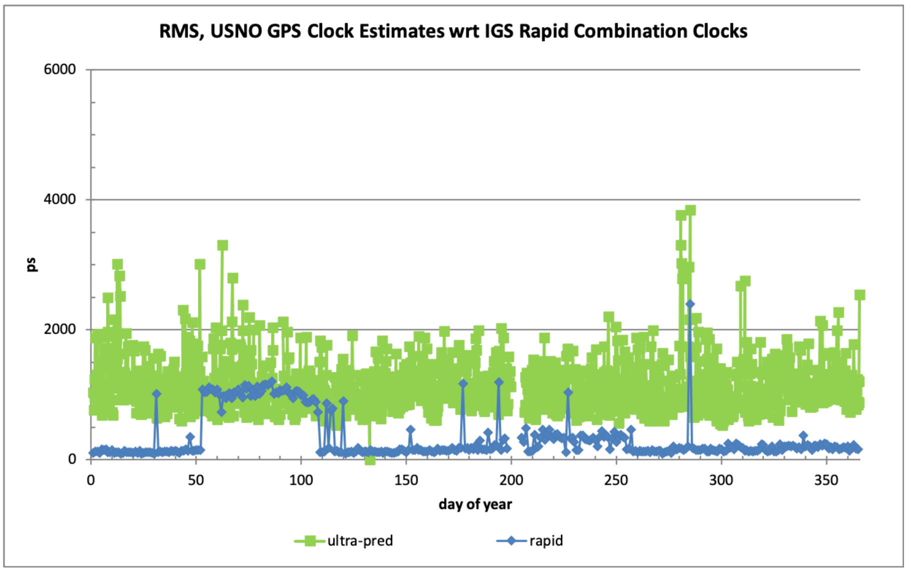

Figure 2: RMS of USNO GPS rapid clock estimates and Ultra-rapid clock.

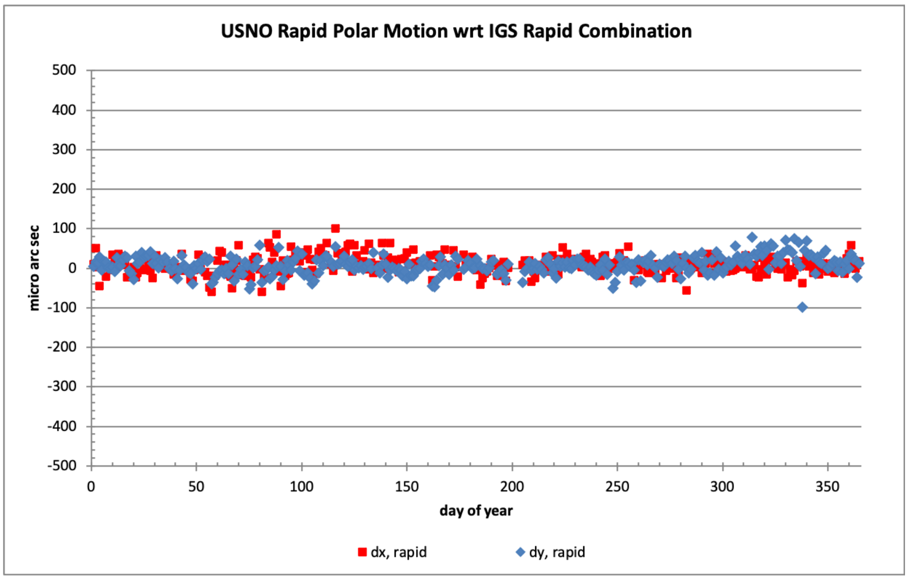

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2020. Note, scale kept same as in previous reports.

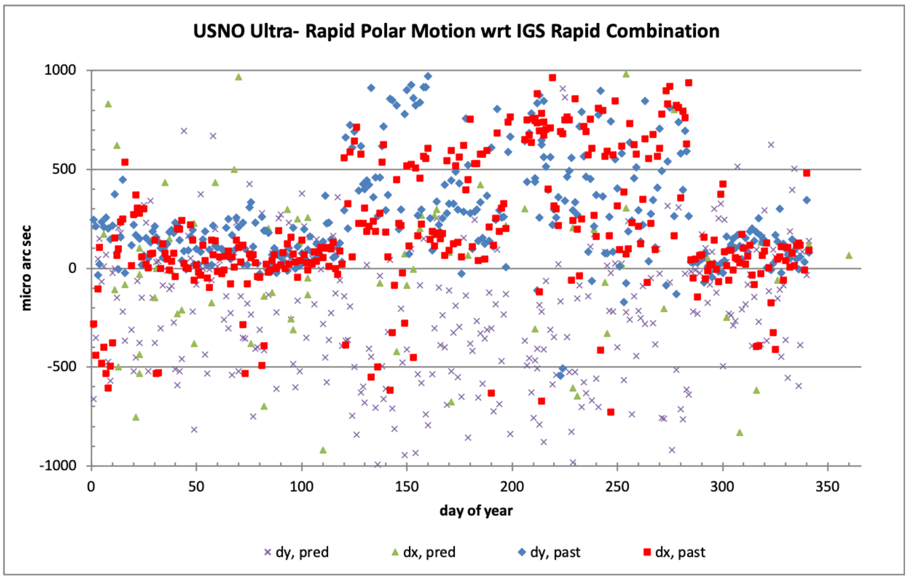

Figure 4: USNO Ultra-rapid polar motion estimates minus IGS Rapid Combination values, 2020

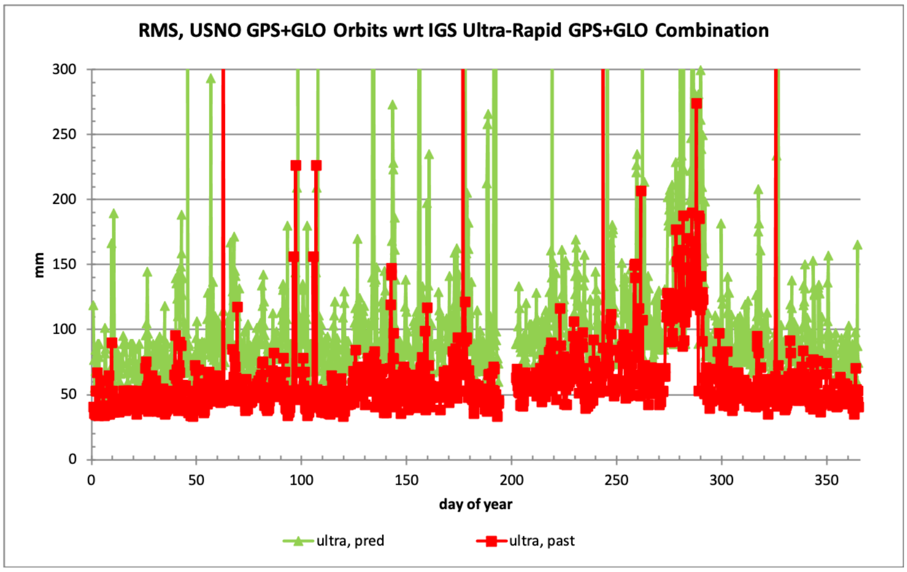

Figure 5: RMS of USNO Ultra-rapid GLONASS orbit estimates with respect to IGS Combined Ultra-rapid GLONASS orbits, 2020. "Ultra, past" refers to 24-hour

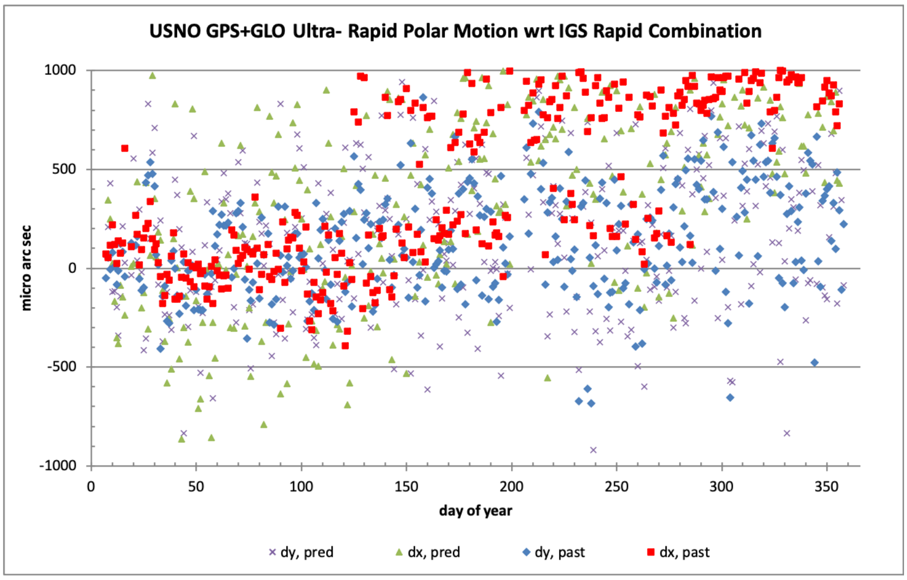

Figure 6: USNO Ultra-rapid GPS+GLONASS polar motion estimates minus IGS "IGR" GPS-only rapid solution, 2020.

WHU Analysis Center Technical Report 2020

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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 2020, WHU participated in the 3rd IGS Reprocessing campaign contributing the GPS/GLONASS orbit products and published very first WHU RT GIM products and multi-GNSS and multi-frequency observable-specific signal bias products.

2 WHU Analysis Products

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

3 RT-Clock Activities

3.1 WHU integer satellite real-time clock for GPS

Besides the float solution of real-time multi-GNSS satellite clock, we have implemented the integer satellite clock in real-time with the mount point ‘CLK17’. Up to now, the RT integer satellite clock is only generated for GPS only. As from our experience, though the STD of our integer clock solution was slightly improved and facilitate precise point positioning ambiguity resolution (PPP-AR) applications, it had a large RMS when compared

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
IONO00WHU0	Real time GIM with 5-min GPS observations

to our float clock solution. As an example, Figure 1 presents the typical results of GPS for float clock solution (upper panel) and integer clock solution (bottom panel).

3.2 WHU GLONASS IFB products for real-time clock for GLONASS

A new GLONASS pseudo range IFB correction strategy has implemented in the real-time GLONASS satellite clock generation. In this strategy, the IFBs on each frequency of GLONASS satellite-receiver pair were corrected in advance with the weekly averaged value of IFBs in advance. The IFB on each individual frequency of different satellite-receiver pair were estimated based on the undifferenced and uncombined PPP. Fig. 2 presented the IFB on each individual frequency of IGS for March 2017 with the PPP ionospheric delay modeling solution. As we can see, the PPP solution turned out to have a STD of about 1.0 ns and 1.17 ns.

4 4. Ionosphere and OSB Activities

At the end of year 2020, the GNSS Research Center of Wuhan University has published the RT GIM products and the very first products have been incorporated in the experimental combined RT-IGS GIM. The WHU RT GIM can be accessible via Wuhan Real Time Data Center (http://ntrip.gnsslab.cn).

WHU use the spherical harmonic (SH) expansion model to map the global ionosphere in a solar-geomagnetic reference frame. Currently, both the GPS real-time data streams and

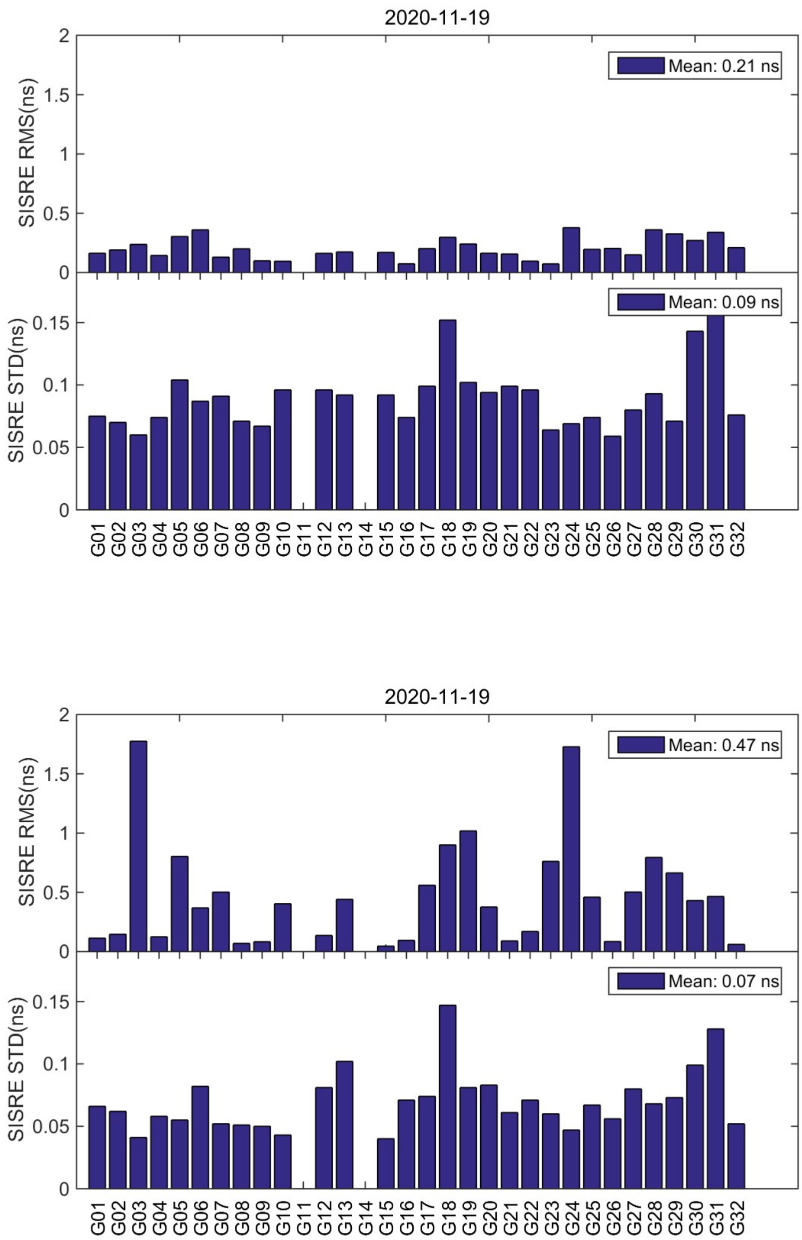
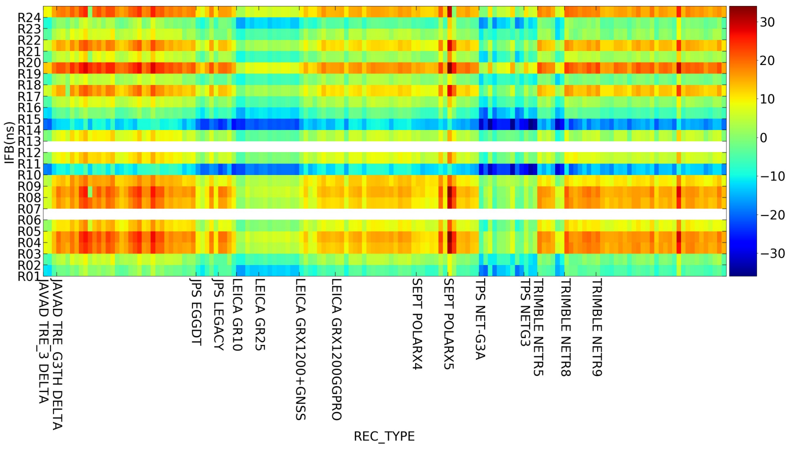
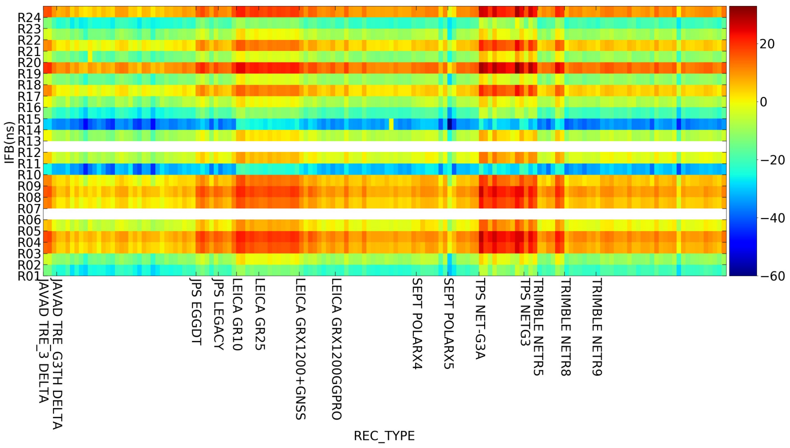


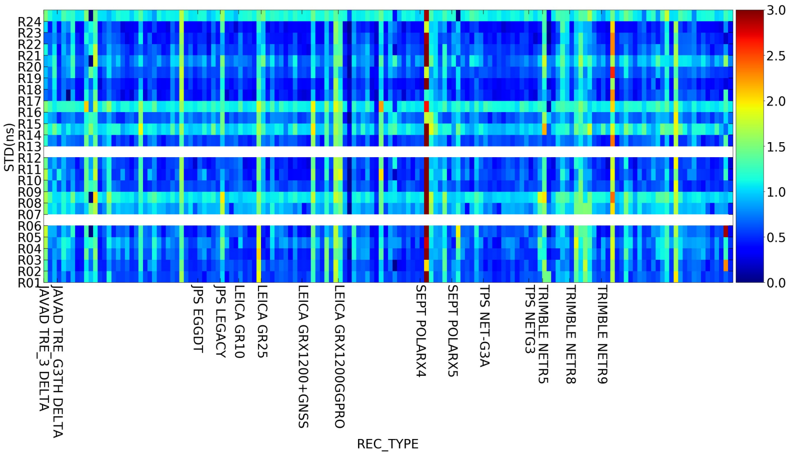
Figure 1: WHU real-time GPS clock precision with respect to IGS on day 6 - week 2141. Upper panel: float clock; Bottom panel: integer clock.


IFB(ns)
R24 R23 R22 R21 R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R09 R08 R07 R06 R05 R04 R03 R02 R01
30 20 10 0 −10 −20 −30
JAVAD TRE_G3TH DELTA
AVAD TRE_3 DELTA
JPS EGGDT
JPS LEGACY
LEICA GR10
LEICA GR25
LEICA GRX1200+GNSS
LEICA GRX1200GGPRO
SEPT POLARX4
SEPT POLARX5
TPS NET-G3A
TPS NETG3
TRIMBLE NETR5
TRIMBLE NETR8
TRIMBLE NETR9
REC_TYPE

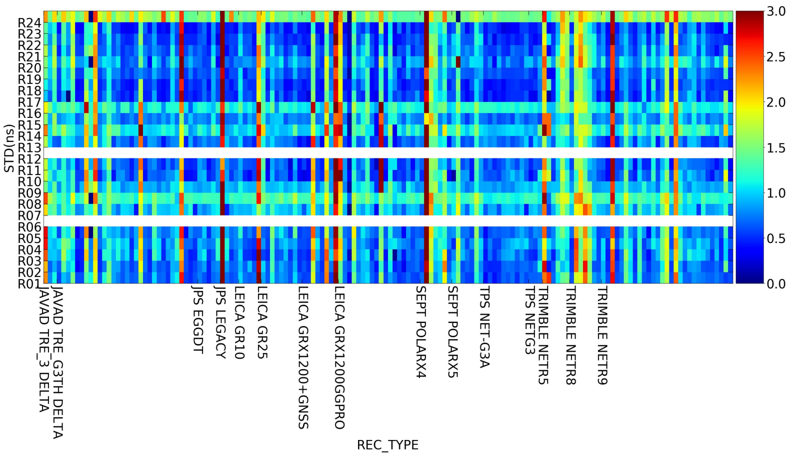
(a1)


IFB(ns)
R24 R23 R22 R21 R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R09 R08 R07 R06 R05 R04 R03 R02 R01
20 0 −20 −40 −60
JAVAD TRE_G3TH DELTA
AVAD TRE_3 DELTA
JPS EGGDT
JPS LEGACY
LEICA GR10
LEICA GR25
LEICA GRX1200+GNSS
LEICA GRX1200GGPRO
SEPT POLARX4
SEPT POLARX5
TPS NET-G3A
TPS NETG3
TRIMBLE NETR5
TRIMBLE NETR8
TRIMBLE NETR9
REC_TYPE

(a2)


STD(ns)
R24 R23 R22 R21 R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R09 R08 R07 R06 R05 R04 R03 R02 R01
3.0 2.5 2.0 1.5 1.0 0.5 0.0
JAVAD TRE_G3TH DELTA
AVAD TRE_3 DELTA
JPS EGGDT
JPS LEGACY
LEICA GR10
LEICA GR25
LEICA GRX1200+GNSS
LEICA GRX1200GGPRO
SEPT POLARX4
SEPT POLARX5
TPS NET-G3A
TPS NETG3
TRIMBLE NETR5
TRIMBLE NETR8
TRIMBLE NETR9
REC_TYPE

(b1)


STD(ns)
R24 R23 R22 R21 R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R09 R08 R07 R06 R05 R04 R03 R02 R01
3.0 2.5 2.0 1.5 1.0 0.5 0.0
JAVAD TRE_G3TH DELTA
AVAD TRE_3 DELTA
JPS EGGDT
JPS LEGACY
LEICA GR10
LEICA GR25
LEICA GRX1200+GNSS
LEICA GRX1200GGPRO
SEPT POLARX4
SEPT POLARX5
TPS NET-G3A
TPS NETG3
TRIMBLE NETR5
TRIMBLE NETR8
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REC_TYPE

(b2)

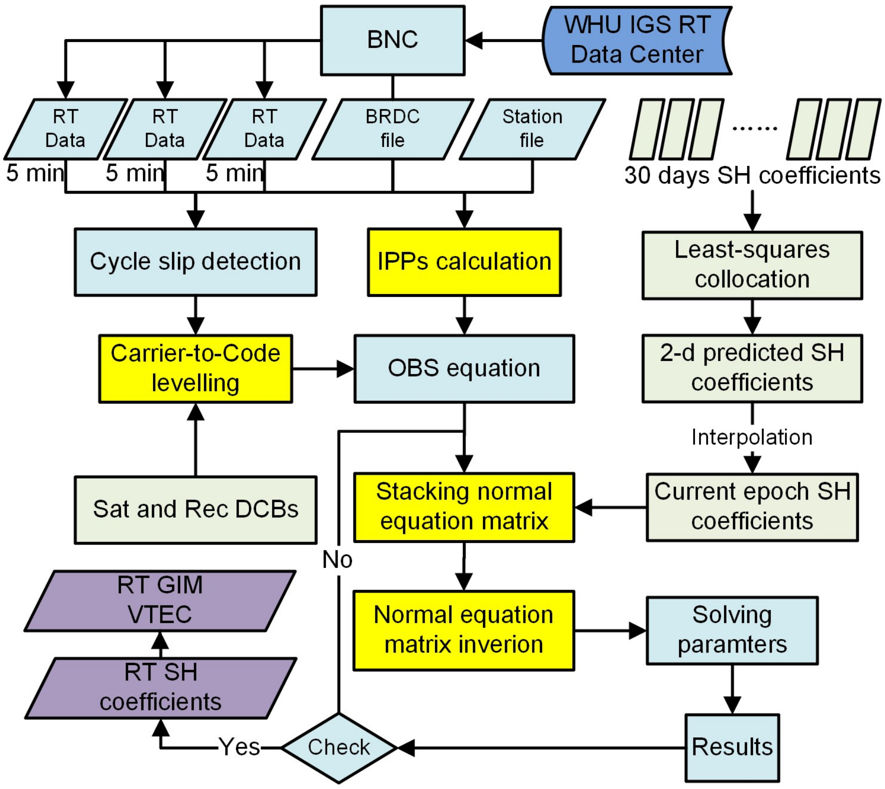

Figure 3: WHU RT GIM flowchart.

the predicted SH coefficients are used. The maximum degree and order are 15, and the time resolution is 5 min. According to the very first assessment conducted by Prof. Manuel Hernandez-Pajares, WHU RT GIM is close to the general results of other RT GIMs, and can be improved further. Now, we are focusing on improving our method in the next step. Figure 3 shows the flowchart of the generation of WHU RT GIM. The yellow rectangles represent the parallel computing with the OpenMP techniques which are incorporated in the GIMAS software (Zhang and Zhao, 2018).

In addition, we also published multi-GNSS and multi-frequency observable-specific signal bias (OSB) products. The products can be accessible via IGN FTP (ftp://igs.ensg.ign.fr) and WHU FTP (ftp://igs.gnsswhu.cn). The daily generated OSB products including GPS, GLONASS, Galileo, BDS and QZSS biases are computed using the MGEX data and several constrains or conditions are introduced in those computation.

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Shi C., Q. Zhao, J. Geng, Y. Lou, M. Ge, and J. Liu Recent development of PANDA software in GNSS data processing. In: Proceeding of the Society of Photographic Instrumentation Engineers, 7285, 72851S. 2008 doi: 10.1117/12.816261

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EUREF Permanent Network Technical Report 2020

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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 2020.

2 EPN Tracking Network

2.1 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. In 2020, the EPN CB started using the new Anubis version 2.3 (Vaclavovic and Dousa, 2015) for performing the EPN data quality checks. During this process, the monthly station skyplots have been revisted to allow visualisation for each satellite constellation separately, see for example http://www.epncb.oma.be/_networkdata/data_quality/skyplots/index.php?station=BRUX_13101M010

The development of the "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^{3}G, available from https://gnss-metadata.eu) continued in 2020 with the release of version 4.0 in November 2020. With this release, among other changes, M^{3}G introduced APIs to retrieve and submit metadata from EPN and EPN densification stations. In addition, the previous EPN CB site pictures submission tool as well as the complete EPN set of EPN site pictures have been migrated to M^{3}G. This was preceded by a cleanup of the EPN site pictures and the assignment of unique keywords to all pictures.

The EPN CB software to manage individual antenna calibrations was completely revised in 2020 to improve the naming of the individual antenna calibration files and switch to a new merged individual EPN antenna calibration file including recalibration values of the same antenna. The EUREF analysis centers switched to these new files in the spring of 2020.

Also the backend of the EPN Central Bureau information system has undergone several changes triggered by a redesign and optimization of its database. Finally, the code to provide information on the monitoring of the real-time data streams in the EPN CB web pages was rewritten to improve the consistency of the real-time information provided throughout several of the EPN CB web pages.

2.2 Network Changes

17 new stations were included in the EPN network in 2020: eleven stations in Belarus, one in Great Britain, one in Germany, one in Italy, two in France, and one in Portugal (see Figure 1 and Table 1). A couple of EPN stations were also decommissioned. At the end of 2020, 62% of the EPN stations were providing BeiDou data and 75% Galileo data (see Figure 2).

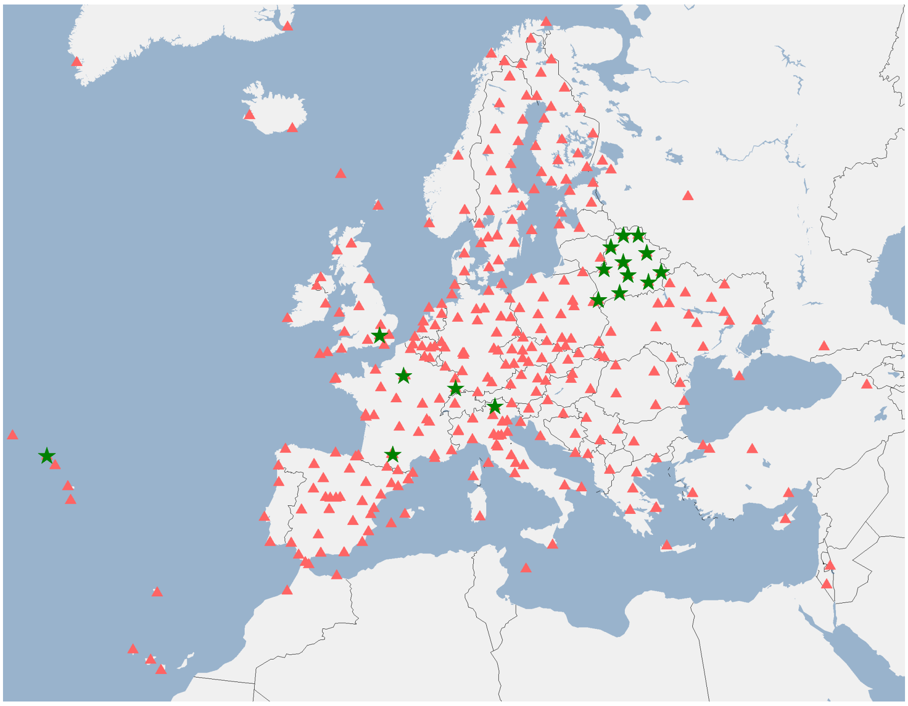

Figure 1: EPN GNSS tracking stations, status Dec. 2020. * indicate new stations included in the network in 2020.

Table 1: New stations included in the EPN in 2020 (stations indicated with * also contribute to the IGS, ** indicates calibration manually reduced to dual frequency GPS and GLONASS calibrations only) – G=GPS, R=GLONASS, E=Galileo, C=BeiDou, J=QZSS

9–char ID	City	Tracked Systems	Real–time	Antenna Calibration
BRMG00DEU	Bremgarten	GRECS		Indiv. chamber (GRECJS**)
BRTS00BLR	Brest	GR		IGS type mean
BZR200ITA	Bolzano Bozen	GREC	Y	Indiv. robot (GR)
ENAO00PRT*	Santa Cruz da Graciosa	GRECS	Y	Indiv. robot (GR)
GOML00BLR	Gomel	GR		IGS type mean
IGNF00FRA	Saint-Mande	GRECJS		IGS type mean
KLNK00BLR	Kalinkovichi	GR		IGS type mean
LICC00GBR*	London	GRECS	Y	IGS type mean
LIDA00BLR	Lida	GR		IGS type mean
MNKW00BLR	Minsk	GR		IGS type mean
MNSK00BLR	Minsk	GREC		IGS type mean
MOGI00BLR	Mogilev	GR		IGS type mean
NOVP00BLR	Novopolotsk	GR		IGS type mean
PINS00BLR	Pinsk	GR		IGS type mean
PSTV00BLR	Postavy	GR		IGS type mean
TLSG00FRA*	Toulouse	GRECS	Y	IGS type mean
VITR00BLR	Vitebsk	GR		IGS type mean

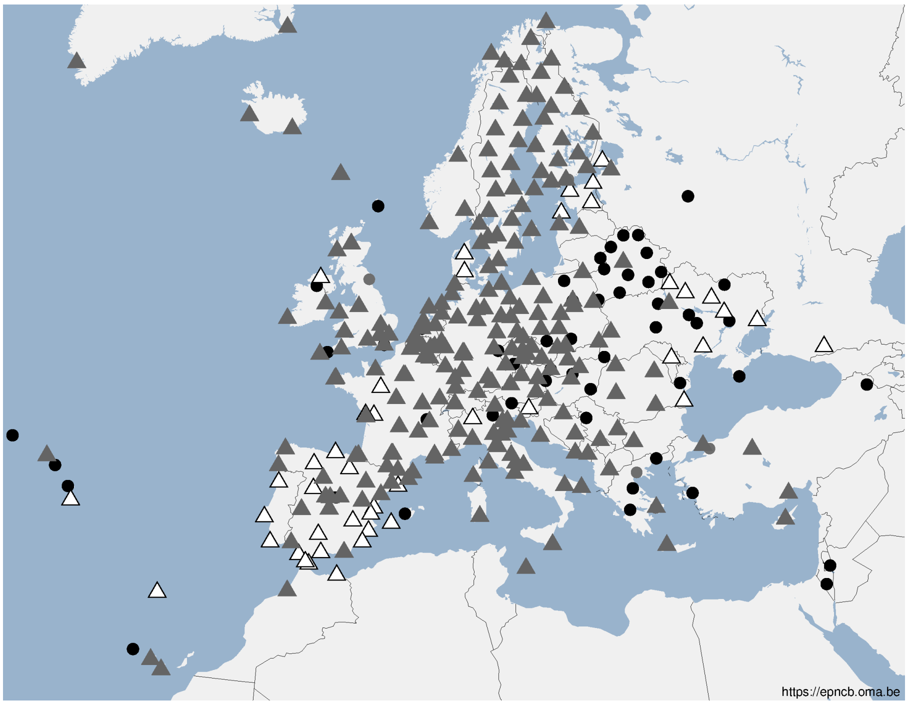

Figure 2: EPN tracking stations (status Dec. 2020). ●: tracking only GPS, ●: tracking GPS+GLONASS, △: tracking GPS+GLONASS+Galileo, and ▲: tracking GPS+GLONASS+Galileo+BeiDou.

2.3 EPN Data Flow

In 2020, EPN station managers have been strongly encouraged to stop submitting RINEX 2 and provide instead RINEX 3 data using the long file naming convention, as it is the case within the IGS. EPN station managers have done a large effort with 80 % of the EPN stations now providing RINEX 3 data. However still some station managers do not respect the new RINEX v3 naming conventions and are still using short filenames for their RINEX 3 data.

In addition, also to stay in-line with IGS, from December 1st, 2020, the EPN data centers started using .gz (instead of compress .Z) for publishing RINEX 2 data files. The EPN CB monitoring routines were consequently adapted to properly monitor EPN data availability taking these changes into account.

3 Data Products

3.1 Positions

The EPN Analysis Centers (ACs) operationally process GNSS observations collected at EPN stations. In 2020, all 16 ACs (Table 2) were providing final daily coordinate solutions of their subnetworks. Twelve ACs were providing also rapid daily solutions, and three ACs were providing ultra-rapid solutions. All AC solutions are regularly combined by the Analysis Center Coordinator (ACC). Details of the various combinations done by the ACC are given on `http://www.epnacc.wat.edu.pl`.

Since week 2106 (May 17, 2020) all EPN combined coordinate solutions (final, rapid, ultra-rapid) have been aligned to the new IGS reference frame – IGb14, which is an updated version of the previously used IGS14. The IGb14 reference frame contains 15 more EPN reference stations (49 stations in total) that can be used for the alignment of EPN combined solutions. After the switch, a slightly better agreement of EPN combined solutions with the IGS reference frame was observed, especially for the vertical component.

In 2019 EPN ACs were encouraged to use Galileo observations (in addition to GPS and GLONASS) for the generation of the operational products. At the end of 2019, there were 11 ACs including Galileo observations in their solutions (Table 2). In August 2020 also SGO AC started including Galileo observations in its final and rapid products.

In 2020, the ASI AC prepared test solutions using the new GipsyX software (Bertiger et al., 2020) based on observations of three GNSS (GPS, GLONASS, Galileo). The new PPP solutions (with full covariance matrix) were tested by the ACC in a combination with the other AC solutions. The RMSs of position residuals between the new ASI solutions and the combined solutions were: 1.07 mm for the north component, 1.96 mm for the east component, and 3.43 mm for the vertical component. For comparison, the RMSs of residuals of the corresponding operational ASI solutions (computed with the older

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: number of stations added/excluded in 2020), 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	75(4/2)	GOA 6.4.1	G
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	110(4/1)	BSW 5.2	GRE
BEV	Federal Office of Metrology and Surveying, Austria	WD	131(11/0)	BSW 5.2	GRE
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRU	135(6/0)	BSW 5.2	GRE
COE	Center for Orbit Determination in Europe, Switzerland	WD	41(0/0)	BSW 5.3	GR
IGE	Instituto Geografico Nacional, Spain	WDR	93(3/0)	BSW 5.2	GRE
IGN	Institut Géographique National de L'information Geographique et Forestiére, France	WDR	64(1/0)	BSW 5.2	GR
LPT	Federal Office of Topography swisstopo, Switzerland	WDRU	62(1/0)	BSW 5.3	GRE
MUT	Military University of Technology, Poland	WD	148(1/0)	GG 10.71	GE
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WDR	101(5/0)	BSW 5.2	GRE
RGA	Republic Geodetic Authority, Serbia	WD	53(0/1)	BSW 5.2	GR
ROB	Royal Observatory of Belgium, Belgium	DR	110(4/0)	BSW 5.2	GRE
SGO	Lechner Knowledge Center, Hungary	WDR	47(6/0)	BSW 5.2	GRE
SUT	Slovak University of Technology, Slovakia	WDR	58(0/1)	BSW 5.2	GRE
UPA	University of Padova, Italy	WDR	72(2/1)	BSW 5.2	GRE
WUT	Warsaw University of Technology, Poland	WDR	138(8/0)	BSW 5.2	GRE

GIPSY-OASIS software using only GPS observations) with respect to the combinations were: 1.61 mm, 1.10 mm, and 4.58 mm, for the north, east, and vertical component respectively. Slightly worse RMS of GipsyX solutions in the east component could be due to not fixing ambiguities in these solutions (as opposed to the operational ASI solutions). At the beginning of 2021, ASI AC started providing operationally rapid solutions computed using the new software. Final ASI solutions computed using GipsyX software are expected later in 2021.

3.2 Troposphere

Besides station coordinates, the 16 EPN ACs also operationally submit 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. The EPN combined solution provides ZTD estimates only for stations processed by more than three ACs. Therefore in 2020, the ZTD combined estimates are available, on average, for 341 stations (compared to 332 in 2019).

http://epncb.oma.be/_productsservices/sitezenithpathdelays/mean_zpd_biases.php shows for each AC the weekly mean bias (top) and the related standard deviation (bottom) of its 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. While the reprocessing part is based only on the solutions provided by five ACs and data cleaning was applied, the operational combination is based on 16 ACs and the individual AC solutions are not cleaned before the computation of the mean bias and standard deviation. In both cases, gross errors (i.e. ZPD with formal standard deviation $>$ 15 mm) and outliers, detected during the combination process, are removed thus not affecting the combined value.

In 2020, the conversion of the combined ZTD estimates to Integrated Water Vapour (IWV) has been implemented following the two-step approach. First, knowing surface air pressure, the hydrostatic part to the total delay (ZHD) is estimated by means of the Saastamoinen (1972) model. Then, ZHD is subtracted from ZTD to form the wet part of the delay that is converted to IWV knowing the weighed mean temperature of the atmosphere. The necessary auxiliary information, surface air pressure and weighted mean temperature of the atmosphere, are obtained from ECMWF operational products provided by the Technical University of Vienna . The data are distributed on a global grid with a horizontal resolution of 2° latitude and 2.5° longitude, and 6-hourly temporal resolution, and are valid on the model orography. A linear interpolation in time and a bilinear interpolation in space are applied to derive the surface air pressure and weighted mean temperature of the atmosphere at the station location with a sampling rate of one hour. For the IWV uncertainty we follow the analysis done by Ning et al. (2016).

IWV has been tested against NGL (Nevada Geodetic Laboratory, Blewitt et al. 2018) IWV estimates. For the whole 2019 and 270 EPN stations (Figure 3), it is found that the IVW bias ranges from -0,96 kg/m2 at station MARS00FRA to 0.41 kg/m2 at station CANT00ESP while the standard deviations are of the order of 0.4 kg/m2 with a maximum value of 0.91 kg/m2 at FLRS00PRT and a minimum value of 0.21 kg/m2 at OVE600SWE. We plan to disseminate the combined ZTD along with the derived IWV in SINEX_TRO v2.0 format (Pacione and Dousa, 2019) starting from the beginning of 2021.

The EPN multi-year tropospheric solution has been updated up to GPS week 2129 and covers the period 1996-10/2020. For each EPN station, ZTD time series, and comparison with radiosonde data (if collocated) plots are available at the EPN CB from `http://epncb.oma.be/_productsservices/sitezenithpathdelays/`. Starting from this cumulative solution high-resolution radiosonde data extracted from 01/2018 onwards are used.

3.3 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-year solutions with the CATREF software (Altamimi et al., 2007). In 2020, three solutions

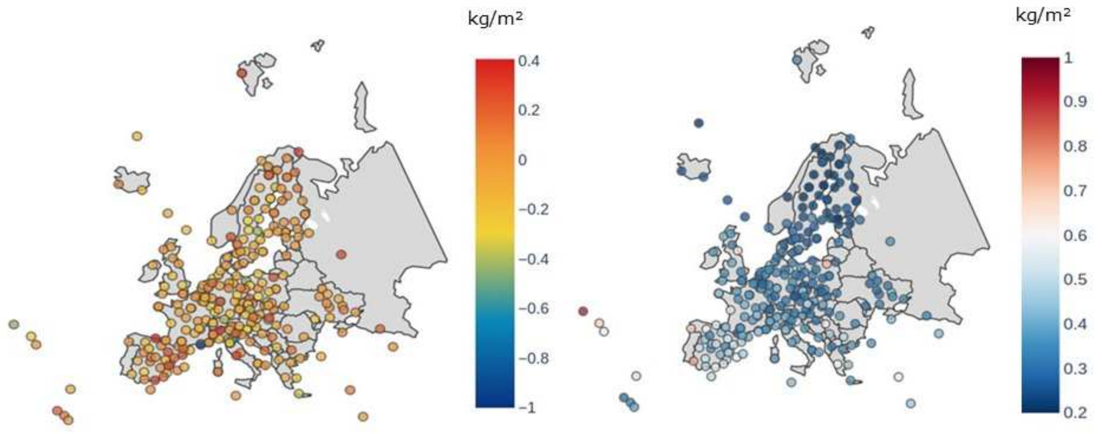

Figure 3: 2019 bias (left) and standard deviation (right) of EPN versus NGL IWV estimates for 270 EPN stations.

have been released: C2085 (March, 2020), C2100 (July, 2020) and C2115 (November, 2020). A Digital Object Identifier (DOI) has been issued for each solution (see Legrand (2020a,b,c)).The last solution C2115 was expressed in IGb14 (IGSMAIL-7921).

Thanks to the release of IGb14, we were able to use 48 reference stations among the 61common stations to align C2115 to IGb14 instead of 43 for the alignment of C2100 to IGS14. In addition, the agreement between the C2115 and IGb14 for the 48 reference stations used has been improved compared to the agreement with IGS14 solution. The standard deviations of the position differences between C2115 and IGb14 are 0.67, 0.69, 1.89 mm for resp. the north, east and up components compared to 0.94, 0.85 and 2.62 for the position differences between C2100 and IGS14. The standard deviation of the velocity differences between C2115 and IGb14 are 0.06, 0.08, 0.17 mm/yr for resp. the north, east and up components compared to 0.11, 0.09 and 0.23 mm/yr for the velocity differences between C2100 and IGS14.

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 IGb14 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.

A new station classification assessing the suitability of EPN stations as reference stations was developed for users of the EPN multi-year coordinate/velocity solution. This classification was applied in a web tool (http://epncb.oma.be/_productsservices/ReferenceFrame/) that provides, for an input observation time frame, a restricted list of EPN stations from which users can visualize on a map and interactively select the most suitable EPN reference stations to be included in their GNSS network processing. The web tool also includes additional information and plots (position and velocity discontinuities, collocated stations, detrended position time series, selection criteria values, and velocity variability).

Although its primary goal is to help users of the EPN multi-year position and velocity solution, the web tool is also useful to monitor the stations in the EPN multi-year solution. These web pages are updated at each release of the EPN multi-year solution.

3.4 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).

4 Working Groups

4.1 EPN Densification

The EPN Densification is a collaborative effort of 30 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 metadata, 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 October 2008 to April 2020 (GPS week 1500-2100) using inputs expressed in IGS14. Solutions based on the IGb08.atx antenna calibration model prior to GPS week 1934 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 complete solution includes 31 networks with positions and velocities of 3500 stations, well covering Europe. However not all of them are published, stations with shorter than 3 years observation series are kept internally and also low quality stations are filtered out. The positions

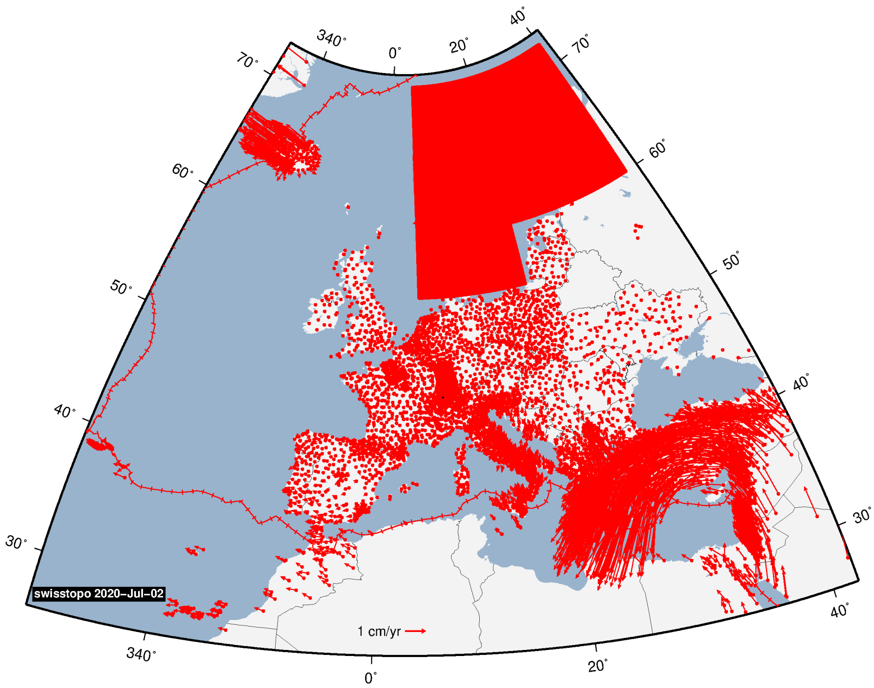

Figure 4: Horizontal velocities derived by the "European Dense Velocity" Working Group (status July 2020).

and velocities are expressed in the ITRF2014 and ETRF2014 reference frames and are tied to the reference frame using minimum constraints on a selected set of reference stations. The description of the EPN Densification, station metadata, and results are available from the newly established EPN Densification product portal (https://epnd.sgo-penc.hu).

4.2 European Dense Velocities

The velocity estimates in ETRF2000, derived by currently 31 contributors, are the direct input for 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. in the Nordic countries, velocity models are already in use. They can be integrated to indicate possible differences between modeled and observed velocities. Today, about 7000 individual station velocities (6200 in the previous year) are available for Europe and more than 3500 sites (2000 sites status last year) 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). Especially, for central Europe (mainly Germany and Benelux), NGL (Nevada Geodetic Laboratory) contributed a velocity estimation with more than 700 not yet analysed stations. Furthermore, the NKG velocity model got a major update.

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. Figure4 shows the horizontal velocity field in its current status. The web page was furthermore enhanced with dynamical visualizations (velocities as a wind field: (http://geolabpasaia.org/gnss/agi/maps/EU-DenseVelocities.html#4/50.04/14.99). 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. Another enhancement of the web page are strain calculations (http://pnac.swisstopo.admin.ch/divers/dens_vel/000.html#STRAIN). Since June 2020 the WG chair participates to an OGC working group "Deformation Models" which is focusing on standards and formats. We hope that these developments will soon lead to a European deformation model which is available for all European partners.

4.3 EPN Reprocessing

The WG on Reprocessing observes closely the IGS Repro3 activities as its products will enable the EPN to start its third EPN reprocessing campaign. Nevertheless, the third reprocessing of the entire EPN must be prepared very carefully. The use of Galileo signals in the reprocessing calls for consistent correction models for ground and satellites antennas. These are not widely available, especially since many EPN stations provide individual calibration models that do not contain corrections for Galileo signals. Therefore, an intensive discussion during the preparation of the third EPN reprocessing campaign is required to ensure the consistency of the operational analysis and a new EPN reprocessing campaign.

5 Stream and Product Dissemination

End of 2020, 193 EPN stations (i.e., mount-points) provided real-time data (after 188 end of 2019) which corresponds to 53 % (after 54 % in 2019) of the EPN stations. The relative decrease can be explained by Table1, where only some of the new EPN stations are also providing real-time 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 only two stations still providing RTCM 2.x. The number of streams supporting the RTCM 3.3 Multi Signal Messages (MSM) has still been growing, resulting in many Galileo and BeiDou data streams available. The number of stations providing MSM messages, which are delivering MSM4 (message type 1074 etc.) or MSM5 (message type 1075 etc.), increased to 66 whereas the MSM7 (1077 etc.) was available for 83 stations. Hence, the stations providing the "legacy" messages 1004 (GPS) and 1012 (GLONASS) significantly reduced from 50 to 27. Big improvement was made concerning the source of the data: only three stations are left which provide the data using an intermediate software. All other streams are coming (directly) from the receiver.

The visibility of the real-time data streams and the monitoring of the three EPN broadcasters at the EPN CB was maintained. 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 metadata 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 further improved. In particular, the ASI caster successfully implemented a large portion of missing stations, so that 95 % (was 85 % in 2019) of the real-time data is available at all EPN casters. For the remaining 9 real-time stations, the caster administrators have been encouraged to check the missing connectivity information.

Concerning real-time products, the EPN is mainly following the activities in the IGS and the standardization efforts in RTCM and in the IGS. Within the IGS, for the first time so-called broadcaster guidelines will be published soon, which follow to a large extent the strategy that has been developed in the EPN guidelines. The IGS is also pushing the development of the SSR format.

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SIRGAS Regional Network Associate Analysis Centre Technical Report 2020

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1 Introduction

The Geocentric Reference System for the Americas (SIRGAS) is presently realised by a network of continuously operating GNSS stations distributed over Latin America (Cioce V. et al., 2020). 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 and Drewes, 2016; 2020). 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 and Seitz, 2011; Sánchez et al., 2016)

2 SIRGAS reference network

The SIRGAS continuously operating network is at present composed of 410 continuously operating GNSS stations (Fig. 1). 66 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. 88% of the SIRGAS

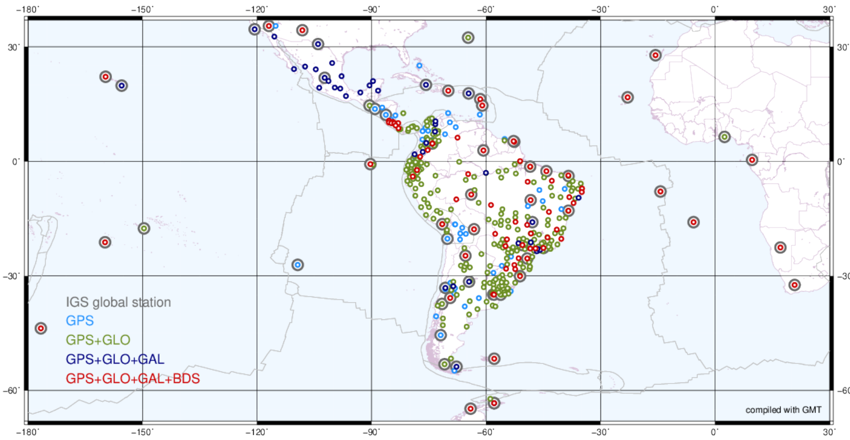

Figure 1: SIRGAS reference frame (as of Dec 2020). It is composed of 410 GNSS stations (100% GPS, 88% GLONASS, 30% Galileo, 20% Beidou). 66 of these stations belong to the IGS global network and some of them are used for the datum realisation in the operational SIRGAS reference frame computation.

stations track GLONASS, 30% Galileo and 20% 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.
- ational 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 the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS, see e.g. Sánchez (2018a)). The SIRGAS-N networks are computed by the SIRGAS Local Processing Centres, which operate under the responsibility of national Latin American organisations. At present, the SIRGAS Local Processing Centres are:

- CEPGE: Centro de Procesamiento de Datos GNSS del Ecuador, Instituto Geográfico Militar (Ecuador)
- 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 Rozas et al. (2019).
- 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 Mosquera 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).

In August 2020, a new SIRGAS experimental processing centre was installed at the Instituto Geográfico Nacional of Peru (IGN-Pe). Experimental processing centres are candidates to become SIRGAS Local Processing Centres. During a specified time period, they align their processing strategies to the SIRGAS requirements and demonstrate their capacity for timely and continuous delivery of weekly solutions of high quality. Once they satisfy these requirements, they are appointed as official processing centres. During the test period (usually one year), they process a set of SIRGAS reference stations, but their solutions are not included in the computation of the final SIRGAS products. With this new experimental processing centre at IGN-Pe, SIRGAS is approaching the goal of having a scientific GNSS data analysis centre in each country in the region.

4 Routine processing of the SIRGAS reference frame

The SIRGAS processing centres follow unified standards for the computation of the loosely constrained weekly 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

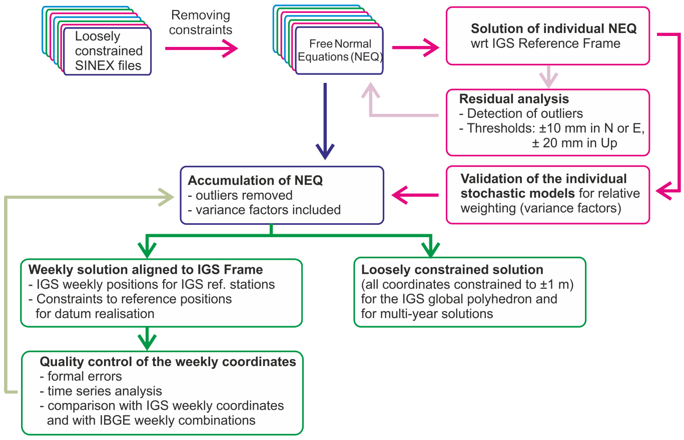

Figure 2: DGFI-TUM strategy for the combination of the weekly solutions delivered by the SIRGAS processing centres.

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 of the weekly solutions, 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/IGb14 reference stations. Station positions obtained for each sub-network are compared to each other to identify possible outliers. Stations with large residuals (more than ±10 mm in the N-E component, and more than ±20 mm in the Up component) are removed from the normal equations (NEQ). 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/IGb14. The datum realisation in the final SIRGAS combination is achieved through the IGS weekly coordinates (igsyyPwwww.snx) of the IGS14/IGb14 reference stations. Normal equations are added and solved using the Bernese GNSS software Version 5.2 (Dach et al., 2015). Figure 2 summarises the strategy applied by DGFI-TUM for the combination of the weekly individual SIRGAS contributing solutions.

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).

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

6 Reprocessing of the SIRGAS reference frame in ITRF2014 and geocentric realisation of the geodetic datum in the regional network

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 the 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: from week 1934 (Jan 29, 2017) to week 2105 (May 16, 2020).
- IGb14: since the GPS week 2106 (May 17, 2020).

In order to evaluate the long-term stability of the SIRGAS reference frame, a new reprocessing of the SIRGAS GNSS historical data from Jan 2000 to Dec 2019 based on the ITRF2014 (IGS14/IGb14) was accomplished. 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 explore the possibility of realising the regional geocentric reference frame directly and epoch-wise, without the usual transformation onto a global reference frame, but by combining GNSS with SLR and VLBI data using a minimum network configuration on a weekly basis (Kehm et al., 2019a). In our analyses, the datum is realised directly by a combination of SLR (origin realised by SLR only), VLBI (contributing to the scale, together with SLR), and GNSS (orientation realised via NNR condition over a global selection of stations). Since the epoch-wise realisation entails a variable SLR-network configuration from epoch to epoch, one central aspect of this study is to investigate the effect of the variable station network on a stable datum realisation (Kehm et al., 2017, 2019b). The combination of the different techniques is performed at NEQ level, as this is the most flexible but – given harmonised geophysical background models – also a rigorous approach for the combination. The input data are IGS14-based NEQs from GNSS, SLR (re-processed datum-free weekly NEQs from ILRS standard processing with DOGS-OC, see Bloßfeld and Kehm, 2020) and VLBI (session-wise datum-free NEQs from IVS standard processing with DOGS-RI, see Kwak et al. (2017). As orbits and EOPs are fixed in the GNSS processing, datum-free GNSS NEQs are reconstructed by introducing and reducing 7 datum parameters (three translations, three rotations and one scale factor) as a first step. The combination is performed by introducing local ties (LTs) at co-location sites as weighted condition equations. Based on the LT table generated for the DTRF2014 (Bloßfeld et al., 2020), the local ties are selected and weighted by comparing the weekly coordinate differences of the single-technique solutions to the measured LT.

Figure 4 shows the translation of the SLR-only solution (left) and of the technique-specific subnetworks of the combined solution with respect to ITRF2014 (weekly coordinates, post-seismic deformation applied). A seasonal variation at sub-cm level (amplitude 0.8 cm) can be seen. This represents the variation of the origin of ITRF2014 with its, in general, linear station velocities with respect to the actual geocentre, which is better represented in the epoch-wise solutions of the regional reference frame. The good agreement between the SLR-only and the combined solution confirms a good datum transfer. As the subnetworks of the combined solution have been transformed separately, we can clearly see that the datum transfer between the techniques is successful.

Figures 5, 6 and 7 show the translations, the scale and the rotations between the SIRGAS regional operational solution (old solutions transformed to IGS14) and the epoch-wise solutions of the regional reference frame based on the combination with SLR and VLBI. The translations are in a good agreement, the seasonal variations in x- and y-translation are reduced due to the fact that the variations of the stations coincide with those in the epoch-wise solutions. However, an offset and a seasonal variation are visible in the

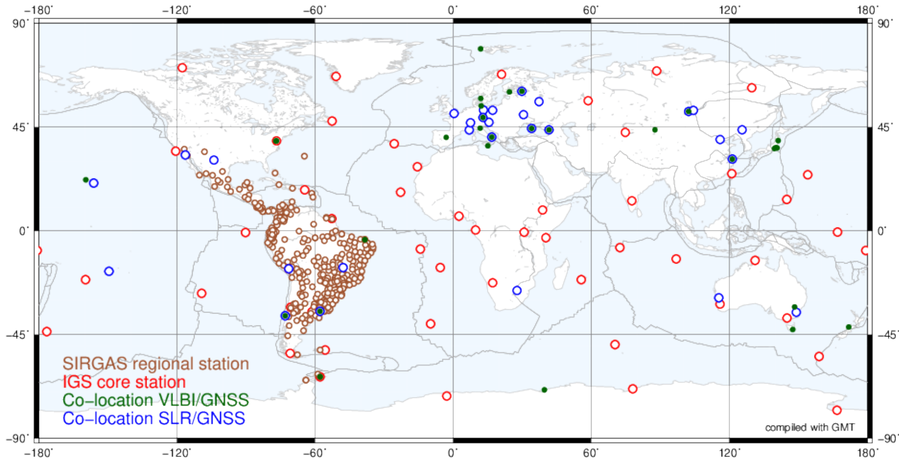

Figure 3: GNSS network configuration for the combination of GNSS, SLR and VLBI normal equations in the realisation of a geocentric geodetic datum in the regional reference frame SIRGAS. VLBI/GNSS (green dots) and SLR/GNSS (blue circles) co-located stations are necessary for the normal equation combination.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

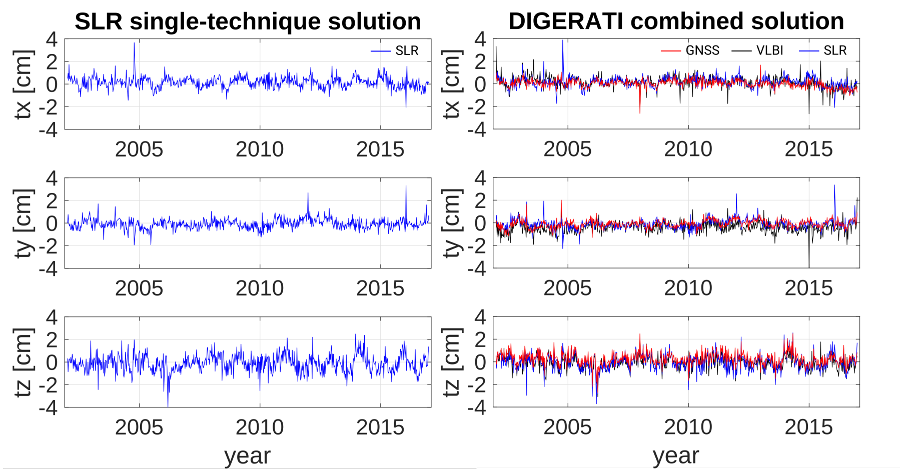

Figure 4: Translations of the SLR single-technique solution (left panel) and of the technique-specific subnetworks of the combined solution (right panel) w.r.t. ITRF2014. Blue: SLR, black: VLBI, red: GNSS.

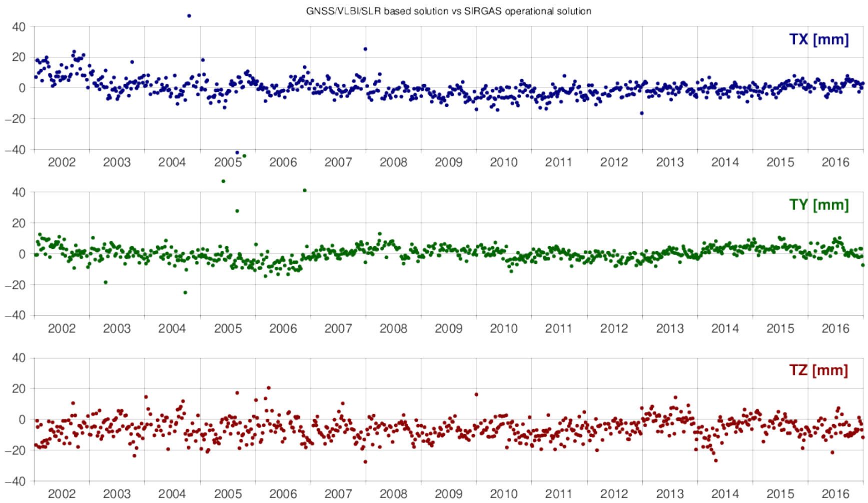

Figure 5: Translations between the GNSS/VLBI/SLR based solution and the SIRGAS operational solution.

z-translation. The offset confirms that the origin of the SIRGAS regional operational solution does not coincide with the geocenter since 90 % of the stations of the network are located in the southern hemisphere. The seasonal variation in z can be related to seasonal variations in the Amazon basin, leading to the conclusion that the datum of the current SIRGAS operational solution is affected by the instability of its datum stations. Consequently, the complete reference frame performs a periodic North-South displacement. The large translations and rotations in 2002 occur since a sufficient number of reliable IGS stations is lacking. After 2010, the better agreement is due to an extension of the SIRGAS network to a larger area with more fiducial points for an improved datum definition of the network. Jumps in the time series of the scale are due to the change of the modelling of antenna phase centre variations between ITRF realisations.

Current efforts concentrate on the stabilisation of the datum by means of filtering. It is planned to implement an information filter, which means that the filtering shall take place in the normal equation domain. In view of a potential operational application, the filtering shall not be applied to the station positions themselves but to the datum information contained in the NEQ in order to cope with changing network geometries. The treatment of the measured local ties at co-location stations is one of the critical points and different strategies are being investigated in relation with the chosen filtering approach.

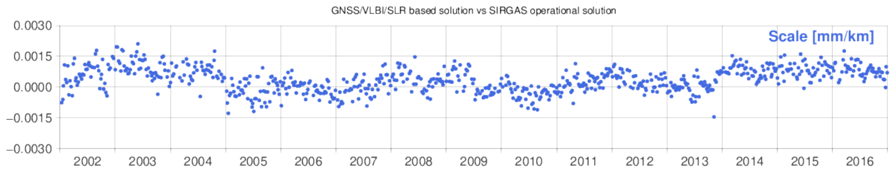

Figure 6: Scale difference between the GNSS/VLBI/SLR based solution and the SIRGAS operational solution.

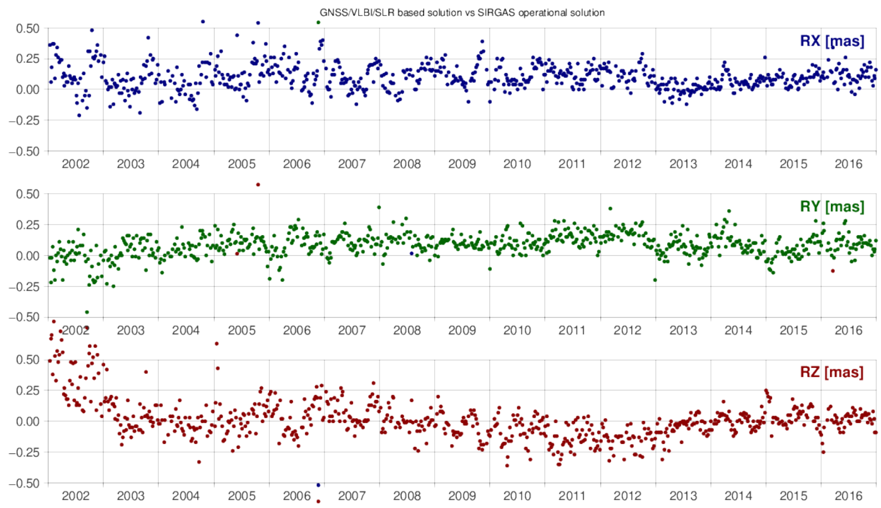

Figure 7: Rotations between the GNSS/VLBI/SLR based solution and the SIRGAS operational solution.

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Part III

Data Centers

Infrastructure Committee Technical Report 2020

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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 ensure 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 fulfils 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.

2 Members

The Committee consists of ex-officio members (those holding active roles in other IGS Working Groups), representative members (nominated and accepted by ex-officio members) and a representative from each of the active global data centers.

Table 1 shows the current membership as of January 1, 2021. New members wrt the

Table 1: List of IGS Infrastructure Committee Members (as of January 1, 2021)

	Member	Affiliation	Role
	Current Members (7):		
N	Bradke, Markus	GFZ	Infrastructure Committee Coordinator (ICC)
	Bruyninx, Carine	ROB	EPN Network Coordinator
N	D'Anastasio, Elisabetta	GNS	IERS Representative
	Donahue, Brian	NRCan	NRCan Network Representative
N	Ruddick, Ryan	GA	IGS Network Representative
N	Sanchez, Laura	TUM	IGS Network Representative
	Söhne, Wolfgang	BKG	IGS Network Representative
	Ex-officio Members (10):		
	Coleman, Michael	NRL	Clock Product Coordinator
	Craddock, Allison	JPL	Central Bureau (CB) Director
	Hauschild, André	DLR	Real-Time Working Group Chair (RTWG)
	Herring, Tom	MIT	Analysis Center Coordinator (ACC)
	Maggert, David	UNAVCO	Network Coordinator
N	Masoumi, Salim	GA	Analysis Center Coordinator (ACC)
N	Michael, Benjamin P.	CDDIS	Data Center Coordinator (DCC)
	Oyola, Mayra	JPL	Central Bureau (CB) Deputy Director
N	Rebischung, Paul	IGN	Reference Frame Coordinator (RFWG)
N	Romero, Ignacio	ESA/ESOC	RINEX Working Group Chair
	Data Center Representatives (6):		
	Duret, Anne	IGN	
	Geng, Jianghui	WHU	
	Michael, Benjamin P.	CDDIS	Data Center Coordinator (DCC)
	Navarro, Vicente	ESA	
	Sullivan, Anne	SIO	
	Yoo, Sung-Moon	KASI	

last report are marked as (N)ew. Ignacio Romero (ESA/ESOC), former chair of the IC, took over the role as RINEX Working Group chair and handed his duties over to Markus Bradke (GFZ) in Summer 2020. The former member Nicholas Brown got replaced by Ryan Ruddick (both from GA), the former Reference Frame Coordinator Bruno Garayt got replaced by Paul Rebischung (both from IGN) and Salim Masoumi took over the role as the Analysis Center Coordinator (ACC) from Michael Moore (both GA). Furthermore, a replacement for Carey Noll as Data Center Coordinator (DCC) has been elected with Benjamin P. Michael (both CDDIS).

3 Summary of Activities in 2020

Over 2020 the IC has supported the Network Coordinator on answering questions from IGS product and data users, plus adding 5 stations to the network and removing 5 long-standing absent stations from the network as stated in Table 2.

Table 2: List of approved and decommissioned Stations in the IGS Network in 2020.)

Station	Location	System(s)	Agency
Approved Stations (5):			
ACRG00GHA	Accra, Ghana	GRE	GFZ
KUJ200CAN	Kuujjuarapik, Canada	GRE	NRCan
LICC00GBR	London, Great Britain	GRECS	ICL
STPM00SPM	Saint Pierre, France	GRECS	IGN
USP100FJI	Suva, Fiji	GREC	BHU
Decommissioned Stations (5):			
AZU100USA	Azusa, United States	G	UNAVCO
BZRG00ITA*	Bolzano, Italy	GRE	STPOS
NRL100USA	Washington, United States	G	NRL
NURK00RWA	Kigali, Rwanda	GRES	GFZ
ZWE200RUS	Zvenigorod, Russian Federation	G	GFZ

* The station BZR2 is already proposed as a replacement.

The IC Coordinator has participated in several Working Group teleconferences over the year to ensure the coordination in terms of station needs and infrastructure across all the different IGS activities.

The latest version of the IC charter got approved by the Governing Board which includes the role change of the IC chairman to an IC coordinator with voting permissions in the Governing Board. With the approval of the charter, the former Data Center Working Group got merged into the IC.

We set up a task force "IGS Stations" that evaluates new station proposals. The team consists of the IC Coordinator, the IGS Network Coordinator as well as the three network representatives. The task force ensures that new stations are compliant to the IGS Site Guidelines (check for accepted hardware, monumentation, Multi-GNSS and Real-Time capabilities and general data quality) and coordinate the integration of such stations to regional GNSS networks (e.g. EPN, APREF, SIRGAS) prior to their acceptance on the IGS level.

In close collaboration with the Global Data Centers, recommendation 2018-4 from the 2018 Wuhan Workshop got implemented as of December 1, 2020 through all global data centers. This recommendation contains the transition of Z-compressed RINEX v.2 files to the gzip compression algorithm. Recommendation 2018-2 that describes the merge of 15-minute high-rate data to a combined daily station TARball has been discussed. CDDIS got the permission to follow this recommendation at their convenience but with a two months' notice to the community. Those files will be merged after 6 months of their nominal arrival time to a single TARball.

The ICC reached out to the Analysis Centers, the ACC and Reference Frame Coordinator to request that all IGS stations should be included in the IGS Final products. Beginning with GPS week 2132, GFZ included all missing stations in their Final products.

4 Current and planned Activities

In 2021, the Committee will put its focus on closing network gaps (e.g. in the North-American region) with Multi-GNSS and Real-Time stations by active outreach.

We will create and revise some elementary guidelines relevant for the IGS infrastructure. This includes the generation of a guideline for Real-Time Broadcasters in collaboration with the Real-Time Working Group as well as updates to the existing but outdated Site and Data Center Guidelines. Additionally, we will look into the development of policy and procedures for acceptance of new data and product types to the data centers.

We will work in close collaboration with the Global Data Centers to initiate quality check metrics for the stations in the IGS network. In addition, we will work with the Central Bureau to make these quality metrics visible on the central IGS website. Furthermore, we are targeting to initiate web-based systems to make station and satellite metadata more discoverable. This will include the implementation of GeodesyML as a new geodetic standard to maintain the station metadata.

Last but not least, we will work on setting up receiver firmware test beds between several station operators in the IGS network to evaluate the latest firmware releases of the most common vendors. The tests will follow defined and consistent

Acronyms

BKG	Bundesamt für Kartographie und Geodäsie
BHU	Beihang University
CDDIS	Crustal Dynamics Data Information System
DLR	German Aerospace Center
ESA	European Space Agency
ESOC	European Space Operations Centre
GA	Geoscience Australia
GFZ	GeoForschungsZentrum Potsdam
GNS	GNS Science New Zealand
ICL	Imperial College London Centre for Transport Studies
IGN	Institut national de l'information géographique et forestière
JPL	Jet Propulsion Laboratory
KASI	Korea Astronomy and Space Science Institute
MIT	Massachusetts Institute of Technology
NRCan	Natural Resources Canada
NRL	United States Naval Research Laboratory
ROB	Royal Observatory of Belgium
SIO	Scripps Institution of Oceanography
STPOS	Autonome Provinz Bozen - Sudtirol
TUM	Technical University Munich
WHU	Wuhan University

CDDIS Global Data Center Technical Report 2020

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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 geodetic 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 2020 are summarized below; this report also includes any recent changes or enhancements made to the CDDIS.

2 Archive Contents

As a global data center for the IGS, the CDDIS is responsible for archiving and providing access to GNSS data from the global IGS network as well as the products derived from the analyses of these data in support of both operational and working group/pilot project activities. The CDDIS archive is approximately 45 TBytes in size (over 370 million files) of which over 90% is devoted to GNSS data (40 TBytes) and GNSS products (2.1 TBytes). All these GNSS data and products are accessible through subdirectories of ftps://gdc.cddis.esdis.nasa.gov/gnss and https://cddis.nasa.gov/archive/gnss.

The CDDIS archive of IGS data and products are globally accessible through encrypted anonymous ftp (address: gdc.cddis.esdis.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 GNSS Data

2.1.1 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. However, this is not a formal mirroring of the other GDCs and as such it is possible that GDCs are not in a one-for-one agreement on holdings. 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

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 2020.

	Number of sites						
Data type	V2	V3	V2&V3	Unique	Vol.	#file	Directory
Daily	519	357	296	586	1856 GB	1.2 M	/gnss/data/daily
Hourly	351	289	239	401	542 GB	14.9 M	/gnss/data/hourly
High-rate	284	214	172	327	6,850 GB	26.7 M	/gnss/data/highrate

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 now use gzip (.gz) as of 1 December 2020. 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. Over 267K daily station days from 586 distinct GNSS receivers were archived at the CDDIS during 2020; of these sites, 296 sites supplied both RINEX V2 and V3 data (see Table 2). A complete list of daily, hourly, and high-rate sites archived in the CDDIS can be found in the yearly summary reports at URL https://cddis.nasa.gov/reports/gnss/. All incoming files for the CDDIS archive are now checked for conformance to basic rules, such as valid file type, non-empty file, uses correct compression, consistency between filename and contents, uses correct file naming conventions, and other logic checks. After incoming files pass these initial checks, content metadata are extracted and the files undergo further processing based on data type and format.

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

Within minutes of receipt (typically less than 30 seconds), the hourly GNSS files are archived to subdirectories by year, day, and hour. Although these data are retained online, the daily files delivered at the end of the UTC day contain all data from these hourly files and thus can be used in lieu of the individual hourly files.

2.1.2 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.gz`, 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.gz` and `brdcDDD0.YYg.gz`, 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 f¨ur 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.

2.1.3 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.

2.2 IGS Products

The CDDIS routinely archives IGS operational products (daily, rapid, and ultra-rapid orbits and clocks, ERP, and station positions) as well as products generated by IGS working groups and pilot projects (ionosphere, troposphere, real-time, MGEX). Table3 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.

Six AACs (CODE, GFZ, GRGS, JAXA, 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

Table 3: GNSS Product Summary for 2020.

Product Type	Number of ACs/AACs	Volume	Directory
Orbits, clocks, ERP, positions	14+Combinations	1.4 GB/week	`/gnss/products/WWWW` (GPS, GPS+GLONASS) `/glonass/products/WWWW` (GLONASS only)
Troposphere	Combination	5.5 MB/day, 2 GB/year	`/gnss/products/troposphere/YYYY`
Ionosphere	7+Combination	9.9 MB/day, 3.7 GB/year	`/gnss/products/ionosphere/YYYY`
Real–time	Combination	18 MB/week	`/gnss/products/rtpp/WWWW`
MGEX	6	1.3 GB/week	`/gnss/products/mgex/WWWWY`

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

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.

2.3 Real-Time Activities

The CDDIS real-time caster has been operational since early 2015 in support of the IGS Real-Time Service (IGS RTS). By the end of 2020, the CDDIS caster broadcasts 28 product and more than 350 data streams in real-time. The caster runs the NTRIP (Network Transport of RTCM via Internet Protocol) format. A full updated listing of all the streams CDDIS provides can be found at this URL - https://cddis.nasa.gov/Data_and_Derived_Products/Data_caster_streams.html.

The CDDIS caster serves as the third primary caster for the IGS RTS, thus providing a more robust topology with redundancy and increased reliability for the service. User registration, however, for all three casters is unique; therefore, current users of the casters located at the IGS/UCAR and BKG are required to register through the CDDIS registration process in order to use the CDDIS caster. 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.

2.4 Supporting Information

DailDaily 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 2 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.

3 System Usage

Summarizing the retrieval of GNSS data and products from the online archive in 2020, Table 4 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 1.4 billion files (nearly 350 TBytes) were transferred in 2020.

Table 4: GNSS Data Retrieval Summary

Data Type	# of Files	Total Bandwidth
Daily	209.8M	186.5GB
Highrate	283.5M	80.2GB
Hourly	852.8M	33.8GB
Products	124.3M	43.7GB

4 Recent Developments

4.1 Updates to Archive Access

The CDDIS has a large international user community; over 600K unique hosts accessed the system in 2020. Today, users access the CDDIS archive through encrypted anonymous ftp and https. On 1 November 2020, unencrypted anonymous ftp was terminated at CDDIS as per US government regulations.

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 Section6 below and https://cddis.nasa.gov/Publications/Presentations.html).

4.2 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 Future Plans

5.1 RINEX V3 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.

5.2 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.

5.3 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 past 6 months will remain in the standard, submitted 15-minute file format. CDDIS has been given permission to implement this change with a two month notice to the community. CDDIS intends to implement this change during fall of 2021.

5.4 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 such, repro3 will be archived similarly. Final acceptance of repro3 data is expected by mid-May 2021.

6 Publications

The CDDIS staff attended several virtual conferences during 2020 and presented, or contributed to, papers on their activities within the IGS, including:

B. P. Michael, C. Noll. Technology Changes and User Community Reaction – An Example from CDDIS, presented at the 2020 Fall Virtual AGU meeting, San Francisco, CA, USA, December, 2020. https://agu2020fallmeeting-agu.ipostersessions.com/Default.aspx?s=35-80-29-3D-28-C9-10-43-B7-56-F5-C7-54-80-9C-32

S. Blevins, L.Tyahla, B. P. Michael, C. Noll. DOIs for Geodetic Data and Derived Product Collections at the NASA GSFC CDDIS, presented at the 2020 Fall Virtual AGU meeting, San Francisco, CA, USA, December, 2020. https://agu2020fallmeeting-

agu.ipostersessions.com/Default.aspx?s=E4-B7-6E-0A-70-94-F8-C6-58-73-58-C1-9E-EE-3B-65

J. Woo, B.P. Michael. Improving Archive Completeness and Timeliness of Data Product Availability at Crustal Dynamics Data Information System (CDDIS), presented at the 2020 Fall Virtual AGU meeting, San Francisco, CA, USA, December, 2020.

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.

7 Contact Information

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

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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.

8 Acknowledgments

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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.

Additional Resources

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.

GSSC Global Data Center Technical Report 2020

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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.

3 2020 Developments

During 2020, GSSC developments have focused on releasing the first version of the GSSC Discovery and Analysis Platform. This new platform, preliminary presented at ION 2020, extends the large range of public datasets available through GSSC's FTP repository, with advanced search and analysis services. These services allow users to search IGS data using keywords, worldwide maps and filters like:

- Start and End Date
- In Space or Ground receivers
- Sampling Rate
- Observables
- Asset Type
- Collection
- Constellation
- Organisation
- Tags
- Processing Level
- Satellites
- Files Format
- Station
- Mission
- Class
- Service Domains

Combination of these filters offers a flexible mechanism to act upon millions of files matching the selection criteria (e.g.: data from LEO satellites, with Galileo constellation, with satellites G04 and G07 with L1 and L2). Selections can be used to download the data, explore their properties or trigger analysis on a JupyterLab. This approach saves time and resources to the final users who do not need to download the files in their computer to analyse GNSS data.

Additionally, 2020 has continued with the steady evolution of GSSC (gssc.esa.int) repository and ingestion services supported by following developments:

- Migration to HTTP ingestion services for CDDIS related collections.

- Assessment of additional GNSS collections for integration into the repository extension with new data collections for ESA projects (Galileo Environmental Monitoring Unit, EUREF, ILRS . . .) and GNSS In-Space (Swarm, Goce . . .).
- Improved security and monitoring capabilities to support the definition of dashboards with real-time information on alarms and KPIs.
- Improved load balancing capabilities.
- Web-portal re-design in line with new ESA Branding policy.

As shown in the following graphs and plots, IGS GDC hosted at GSSC has experienced considerable worldwide accesses from the GNSS community.

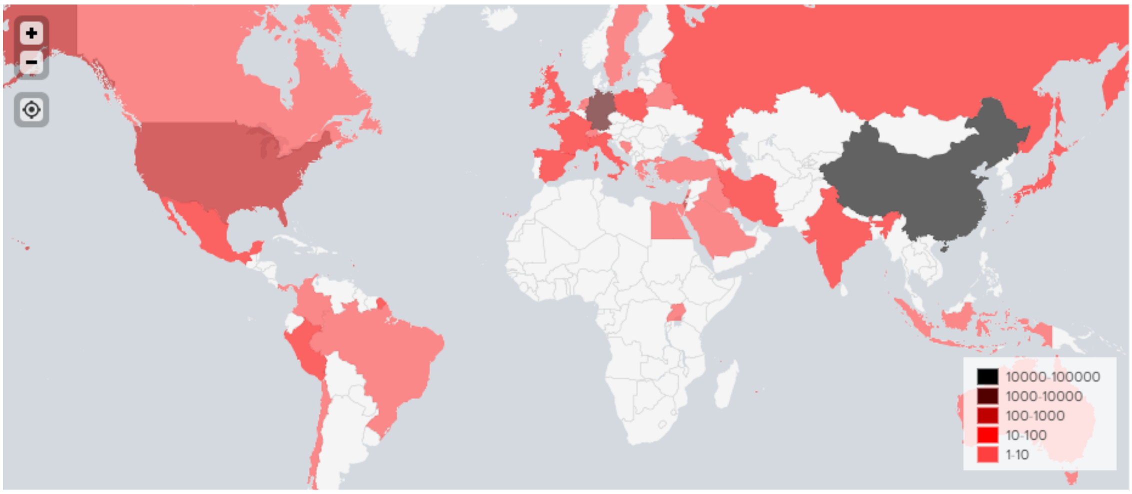

Figure 1: Worldwide Number of IGS File Downloads in 2020

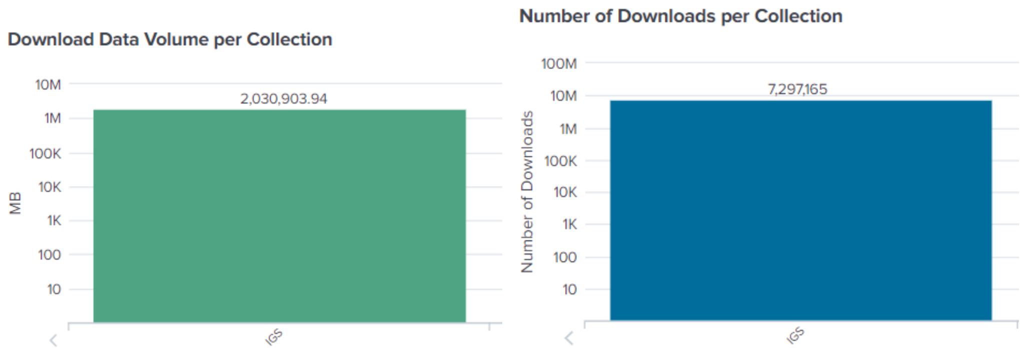

Figure 2: Volume and Number of IGS File Downloads

Figure 3: Volume and Number of IGS File Downloads

4 Planned 2021 Activities

Planned 2021 activities will include:

- Adaptive and evolutionary maintenance in line with IGS requirements.
- Public release of GSSC Discovery and Analysis Platform. Currently undergoing validation, this platform is expected to reach public release in Q2-2021.
- Integration of data processing pipelines for GNSS Science resulting from Galileo Science Office projects in the area of Machine Learning, IoT and Crowdsourcing.

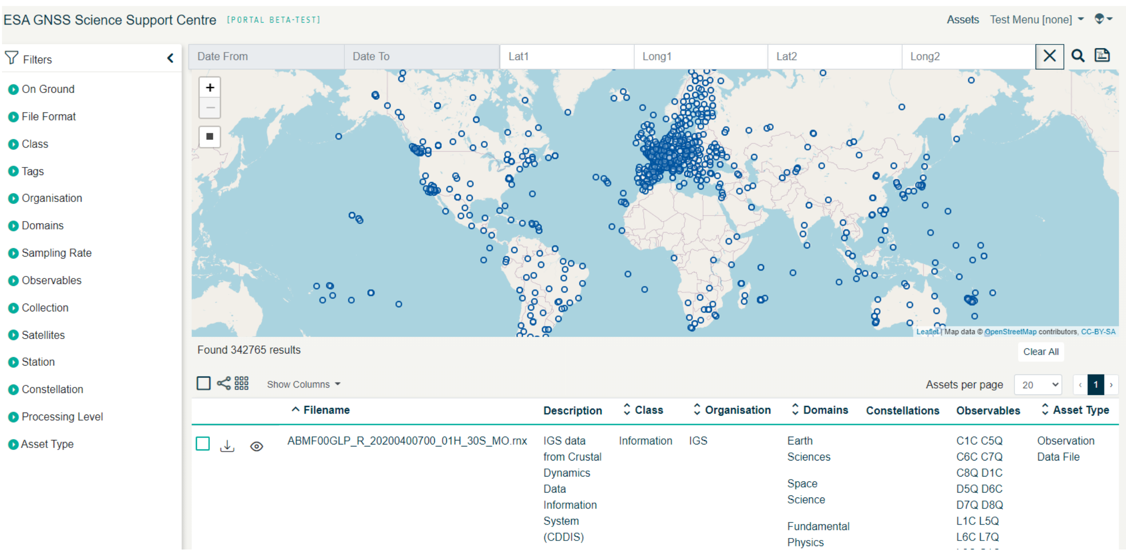

Figure 4: GSSC Discovery and Analysis Platform – Beta Environment

WHU Data Center Technical Report 2020

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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 2020 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/).

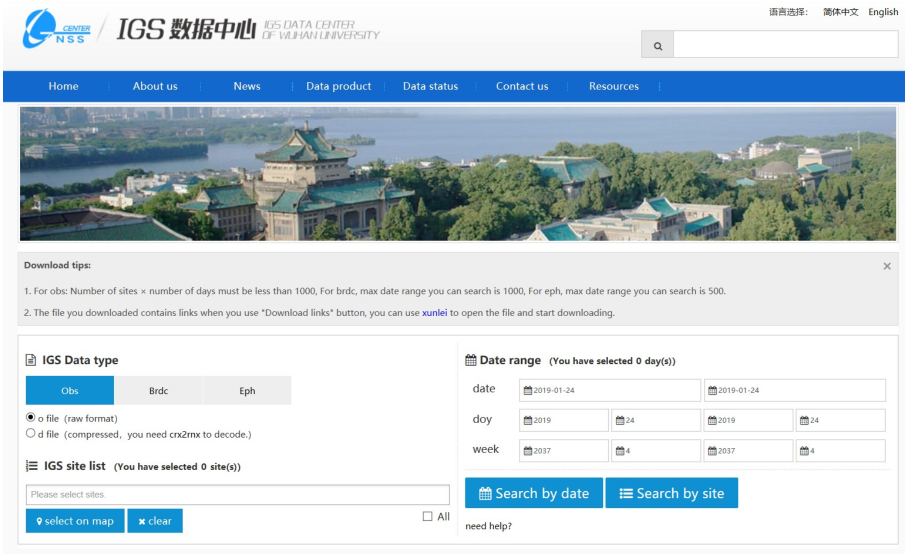

Figure 1: A snapshot of the website of WHU data center for data and products provision.

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

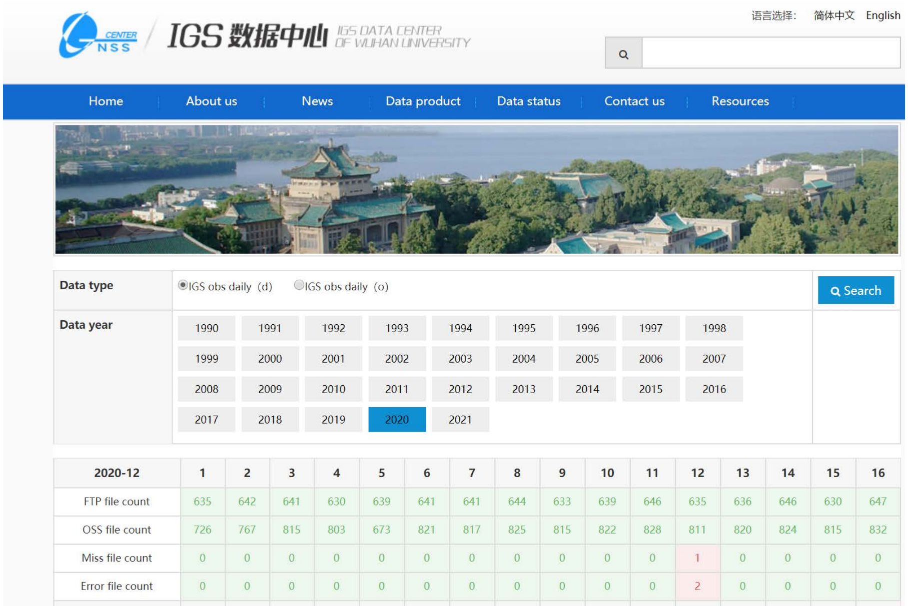

Figure 2: Data and products monitoring of WHU data center.

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. Two types of data are handled in the GDC: file-based (sec. 2) and real-time (sec. 3) data. 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 BKG GDC serves as the single point of access to the public and merges all kind of GNSS data and products, e.g. via one web interface. The GDC supports international projects referred to GNSS tracking networks by storing and transferring related data, for example the European project "Galileo Reference Center – Member States" (GRC-MS).

2 GDC File Archive

2.1 Infrastructure

Since many years, BKG‘s GDC is running on a server integrated in a virtual machine environment placed at BKG’s premises. It consists 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. A disaster recovery system for the GDC is not installed and not scheduled currently.

2.2 Access

The access to the file-based 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 automated 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 of approx. 550 globally distributed stations, roughly half of them belonging to project ‚IGS. 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 for storing files with the short names. After the introduction of the long file names in the IGS for the Rx3 files, Rx2 and Rx3 files could be stored both in the 'obs' sub-directory and the 'obs_v3' sub-directory will be obsolete in the near future.

Additionally, 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 19.3 million files are stored in the GDC with approx. 8.6 TByte of storage needed. We are facing with approx. 100,000 uploads and 1,100,000 downloads per day. There was an increase in number of downloaded files of 10% with respect to 2019. The volume of downloads also increased from 130 GB to 135 GB. The full number of users may reach 24,000 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.

To ensure an as much as possible correct download, the number of simultaneous users of the GDC has been limited to 190. In future, this number might not be sufficient and the mechanism may need some improvement.

3 GDC Real-Time Streaming

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). Information on the use of real-time data, such as registration and software, can also be found on the GDC homepage. 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 continuously improved. BKG is maintaining various broadcasters for global, regional and national purposes (IGS, EUREF, GREF). BKG's casters are still hosted by an external service provider and maintained by BKG staff. 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 GDC 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 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 2020):

- On the mgex-ip caster (`http://mgex.igs-ip.net`) are real-time data of approx. 63 streams provided (compared to 118 a year before). 51 streams are received in raw data format. Only two streams are still converted with the EuroNet software (Horváth , 2016) from receiver raw data into RTCM 3.2/3.3 Multiple Signal Message (MSM) format, one with NRCanRTCM software. On the MGEX caster, only two RTCM streams are coming directly from the receiver. Seven ephemeris data streams are generated with EuroNet software from raw data streams: 1 multi-GNSS and one each exclusively for BEIDOU, GALILEO, GLONASS, GPS, QZSS, SBAS.
- On the euref-ip caster (`http://www.euref-ip.net`) are approx. 199 data streams in RTCM3.0/1/2/3 format provided (compared to 178 a year before). There are still six streams available in the old RTCM 2.3 format.

- On the igs-ip caster (http://www.igs-ip.net) are approx. 272 data streams (compared to 244/216 one/two years before) in RTCM3.0/1/2/3 format provided. Meanwhile, 199 MSM streams are coming directly from the receiver. 22 streams are generated from EuroNet, three from RTKLIB, nine from NRCanRTCM. 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) are approx. 60 data streams in RTCM3.0/1/2 format provided. These streams divide in 49 clock & orbit correction streams from various organizations, one ionospheric correction stream and ten ephemeris data streams. There are various ephemeris streams available, mainly due to requests of specific user groups, e.g. constellation-specific data streams. The new products mountpoint scheme with ten characters which was discussed in 2019 in the RT Working Group has been fully introduced in 2020. The old names, which are still available by relaying, will be finally stopped in near future.

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 data 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 request for registration for BKG' casters 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 balance between the various IGS broadcasters and to keep the increase of the number of listeners and the amount of downloading at BKG small, 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 17, 23 and 17 GB per day for each caster and a download of 150, 530 and 55 GB per day, resp. The reduction of sent data of the MGEX caster (120 GB to 55 GB), however, is much smaller than the increase from 300 GB to 530 GB per day for the IGS caster. For the PRODUCTS caster, finally, we have a smaller upload of 3 GB per day and a download of 58 GB per day. This sums up to a traffic of more than 850 GB per day for the four caster - compared to 630/450 GB at the end of last 2019/2018 – or 17,5 TB each month.

4 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)

References

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

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

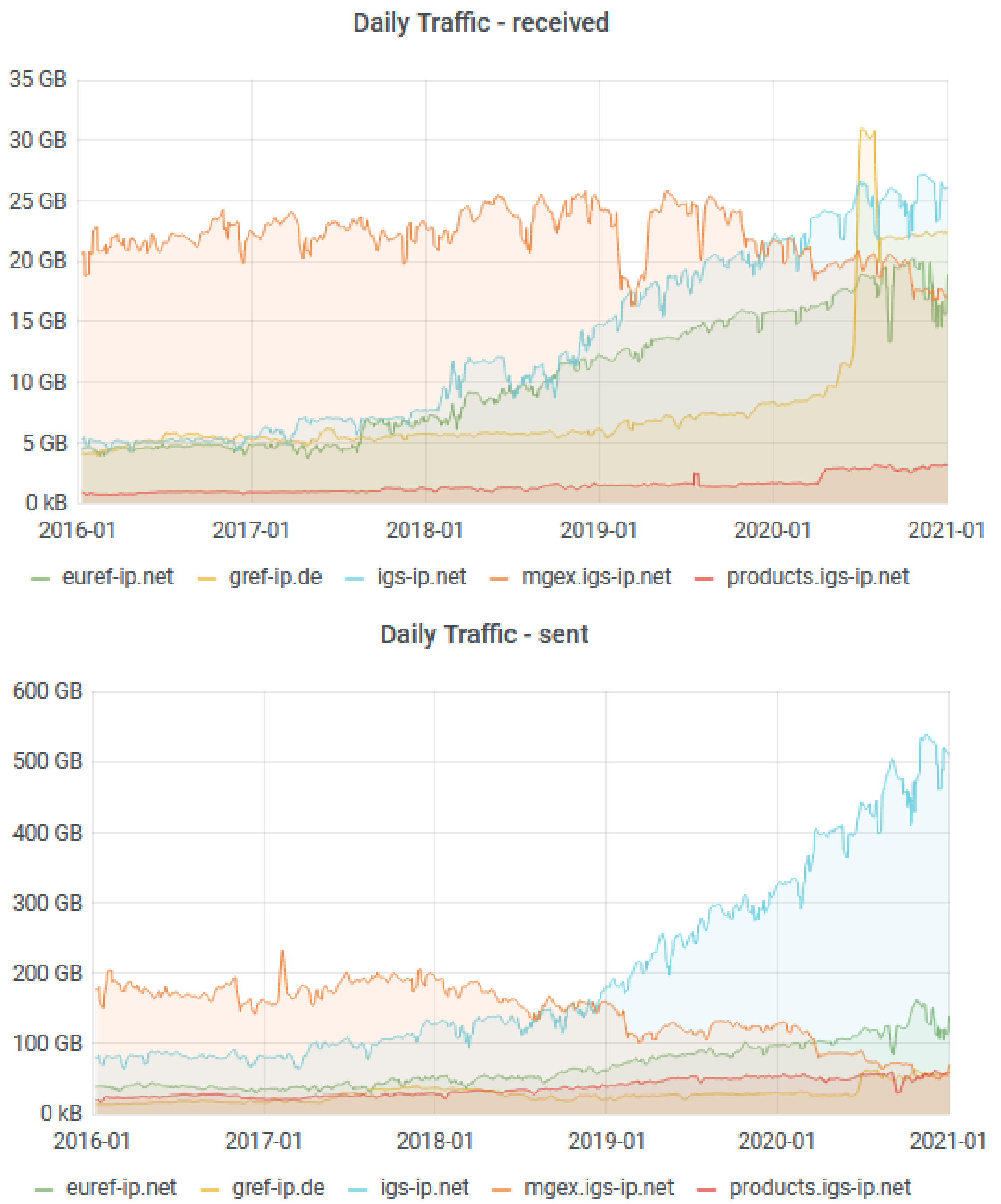

Figure 1: Daily received (i.e., upload to BKG, top) and sent (i.e., download from BKG) data volume at the BKG Broadcasters from 2016 to 2020.

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 2020

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1 Introduction

Geoscience Australia (GA) operates as a regional data centre for the IGS and serves as the primary data centre for the Asia-Pacific Reference Frame (APREF) project. The data centre platforms provide users with open access to data and metadata from over 1000 continuously operating GNSS reference stations in the region.

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 is focused on making improvements to data access, data accuracy and data automation.

2 Description and Access

The data centre provides a central location where users can access the data products and services from continuously operating GNSS reference stations across the Asia-Pacific region. The infrastructure consists of a data repository, station metadata database and a real-time service.

Access to the data centre is via a web portal (https://gnss.ga.gov.au), from the portal users can access a map of the network, a web application for finding and accessing RINEX data from the data repository, information on connecting to the real-time service and a web application for viewing and manipulating station metadata.

The GNSS data repository contains RINEX observations from over 1000 continuously operating GNSS reference stations, including all IGS stations in the Asia-Pacific region.

The dataset contains all standard IGS daily, hourly and high-rate RINEX observation files, alongside navigation and meteorological files for most stations. The dataset stretches from 1992 until present day and is growing by approximately 28,000 files per day.

Access to the GNSS data repository is via a web application, anonymous FTP server and secure web API.

- Web Application: https://data.gnss.ga.gov.au
- Anonymous FTP: ftp://ftp.data.gnss.ga.gov.au
- Web API: https://data.gnss.ga.gov.au/docs

Since 2018, a focus of the data centre has been enabling reliable access to real-time data streams for scientific and commercial applications. The real-time service is delivered through the AUSCORS real-time broadcaster. The broadcaster consists of two identical servers deployed to a highly-available environment hosted on Amazon Web Services (AWS). The servers are running the latest version of the BKG Professional NTRIP Broadcaster. At the end of 2020 the AUSCORS service provided access to 540 data streams and 16 product streams.

Access to the AUSCORS real-time service is free but does require an account. Data and products streams are delivered over NTRIP, which can be accessed and decoded by most common NTRIP clients and GNSS hardware. There are currently over 1500 register user to the service, this equates to about 5000 active connections (listeners) at any point in time.

- AUSCORS real-time service: https://auscors.ga.gov.au

3 2020 Developments

During 2020 the data centre team completed the migration of the systems and services to AWS hosted infrastructure. This transition, which was the culmination of over five years work, has streamlined the operational workflows, improved how users find and access the datasets and improved the reliability of the services through scalable and highly-available infrastructure.

The transition to cloud hosted infrastructure in 2020 enabled a number of additional improvements to be made to the data centre, these included:

- Enhancing our multi-GNSS capabilities by updating the workflows to accept RINEX v3 as the preferred observation data format.
- Reviewing and revalidating the historic datasets to ensure consistency between RINEX headers and station log files.

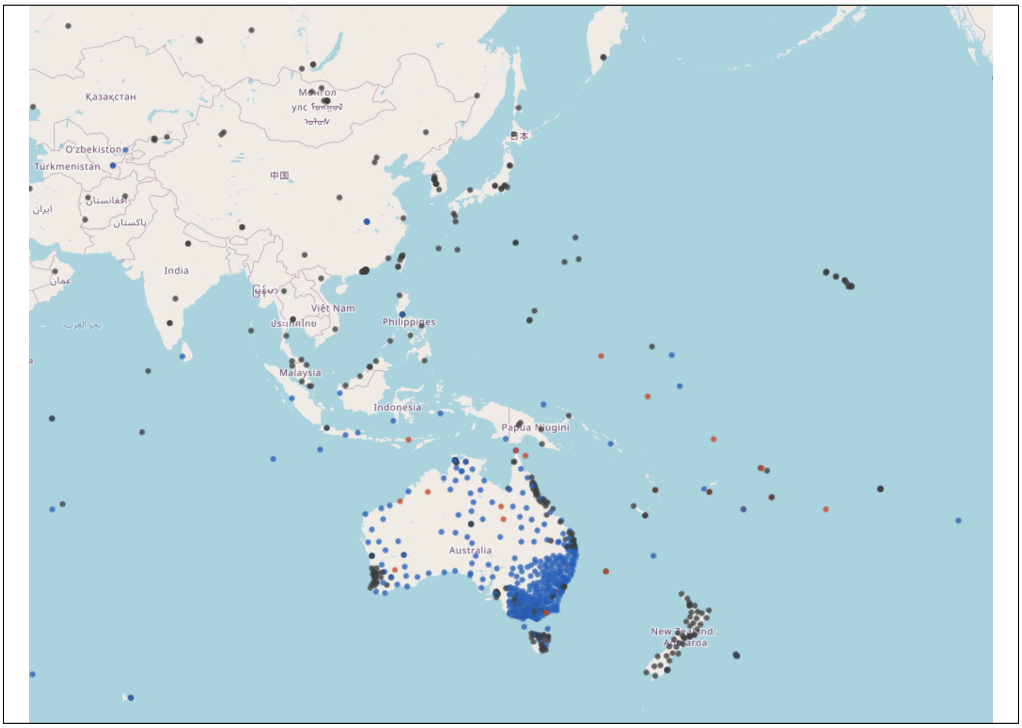

Figure 1: The GA regional data centre provides access to over 1000 GNSS stations from across the Asia-Pacific.

- Recompression of all RINEX v2 files to gzip to ensure that the datasets are interoperable with modern computing systems.
- Improving consistency of our data end-points by moving the FTP server to link directly to the primary data repository.
- Enhancing the station metadata application to accept photos, which has been included in the latest release of GeodesyML.
- Encouraging the sharing of real-time data across the Asia-Pacific region, through enabling the contribution of real-time data streams from APREF stations.

4 Planned Activities for 2021

The key focus of the data centre in 2021 is to release into production a new real-time broadcaster platform, which has been developed as part of our efforts to improve access to reliable real-time data streams across Australia. The platform is built on a cluster of servers which will improve the availability and performance of our broadcaster.

Centered around the deployment of the new real-time platform is the development of a real-time monitoring capability. This capability will allow the continuous monitoring of data streams for quality and accuracy, enabling the fast detection and alerting of station related issues.

Further enhancements and maintenance are scheduled to all components of the data centre, which will see improved reliability and security.

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2020

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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 Updates and content of the antenna phase center model

Table 1 lists all updates of the `igs14_wwww.atx` in 2020. 21 new antenna/radom combinations have been added. Moreover, the FOC satellite pattern where replaced with their chamber calibrations.

Table 1: Updates of the phase center model `igs14_wwww.atx` in 2020 (`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	Change
2136	17-Dec-2020	Added SEPVC6150L NONE
		SEPVC6150L SCIS
		SPP135000.00 NONE
2134	2-Dec-2020	Added R805 (R11)
		Decommission date R805 (R25), R853 (R11)
		Added LEICGA100 NONE
2132	17-Nov-2020	Added R805 (R25)
2131	12-Nov-2020	Added G077 (G14)
		Decommission date: G041 (G14)
		Added CNTAT600 CNTS
		HGGCYH8372 HGGS
		LEIFLX100 NONE
		TWIVSP6037L NONE
2129	29-Oct-2020	Added EML_REACH_RS2 NONE
		STXS900A NONE
		TIAPENG6J2 NONE
		TRMR12I NONE
2118	14-aug-2020	Added R735 (R22)
		Decommission date: R731 (R22)
		Added FOIA90 NONE
		HEMS631 NONE
2114	14-Jul-2020	Added G076 (G23), C230 (C61)
		Decommission date: G060 (G23)
2113		Corrected entries for TWIVC6050
	9-Jul-2020	Renamed antenna
		CNTT300+ to CNTT300PLUS
		Radom changed from CNTS to NONE for
		CNTAT340, CNTT30, CNTT300, CNTT300PLUS
2112	3-Jul-2020	Added C229 (C60)
		Updated PCO and PV of J003 (J07)
		TWIVC6050 NONE
		TWIVC6050 SCIS
		TWIVC6050 SCIT
2108	4-Jun-2020	Added STXS700A NONE
		STXS990A NONE
2101	14-Apr-2020	Added R860 (R24)
		Decommission date: R735 (R24)
2097	16-Mar-2020	Added G075 (G18)
		Decommission date: G034 (G18)
2091	6-Feb-2020	Added C225 (C44), C226 (C43), C227 (C41)
		C228 (C42)
		Added GMXZENITH16 NONE
		TRMR12 NONE
		Withdrawn TRM115000.00+S SCIT

Table 2: 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%
JAN 2021	**igs14.atx:**	**93.5%**	**1.8%**	**4.7%**

3 Calibration status of the IGS network

Table 2 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 increasement of 6% from igs08 to igs14 in 2017 another 2% of the IGS stations are covered by robot calibrations. In 2020 the situation has slightly improved but is very similar to the situation a year before.

4 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).

The current IGS repro3 ANTEX file has been updated to cover changes in the satellite constellations and adding newly launched satellites for 2020. No changes to the existing satellite antenna entries and receiver antennas have been made.

4.1 Update IGS repro3 ANTEX

Since the release of the first IGS Repro3 ANTEX file following changes have been made:

Table 3: Updates of the phase center model igsR3.atx in 2020 (`wwww`: GPS week of the release date)

Week	Date	Change
2136		`Added G076 (G23), G077 (G14), R735 (R22)`
		`R805 (R11),R805 (R25)`
		`Decommission date G041 (G14), G060 (G23)`
		`R731 (R22), R805 (R25)`
		`R853 (R11)`
2107		`Added G075 (G18), R859 (R04), R860 (R24)`
		`Decommission date G034 (G18), R742 (R04)`
		`R735 (R24)`

4.2 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

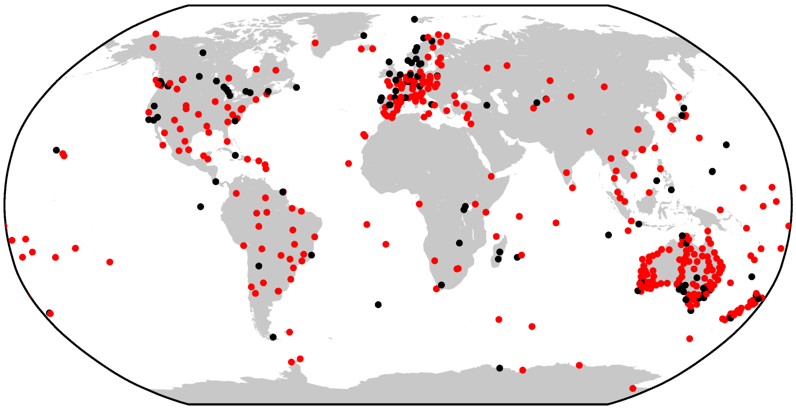

Figure 1: Repro-3 stations tracking Galileo (as of mid 2019). Red dots denotes sites with Galileo calibrations for their antennas and black dots antennas without Galileo pattern.

set (igsR3.atx). Figure 1 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.

4.3 Potential extensions (not part of official Repro3)

In addition to Galileo other system providers have disclosed metadata of the satellite antennas. Currently following information is publicly available:

GPS: Phase center offsets for the latest generation of GPS satellites (BLOCK IIIA) released by Lockheed Martin

GLONASS: not available

Galileo: Phase center offsets and variations (GSA, 2019)

BeiDou: Phase center offset

QZSS: Phase center offsets and variations (CAO, 2017)

References

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

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Bias and Calibration Working Group Technical Report 2020

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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 2020

- 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,

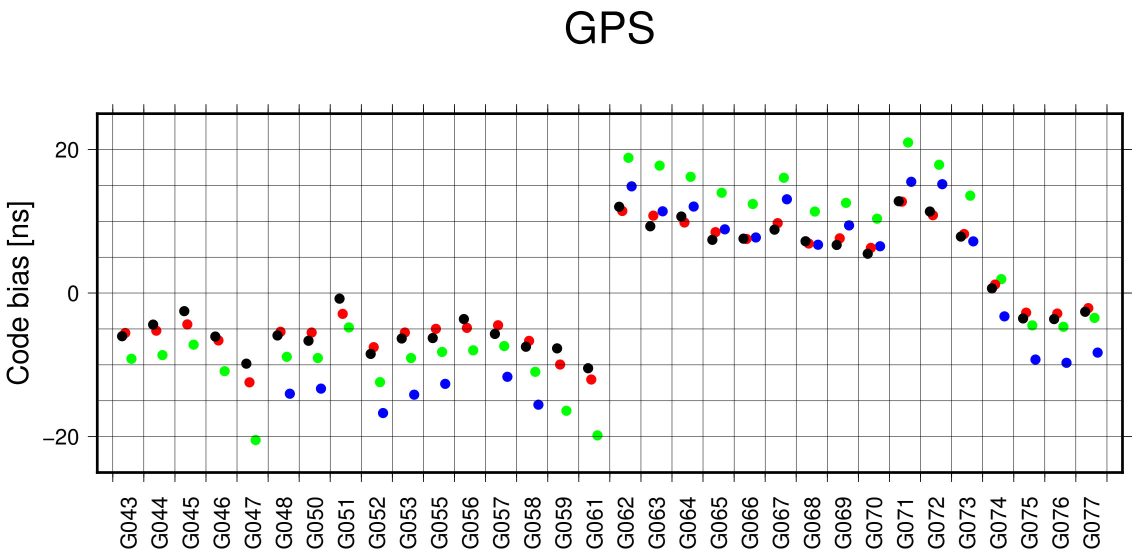

Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2021. Note that G043–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations and G074–G077 corresponds to Block IIIA@Legend: C1C (black), C1W (red), C2W (green), C2L/C2S (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-

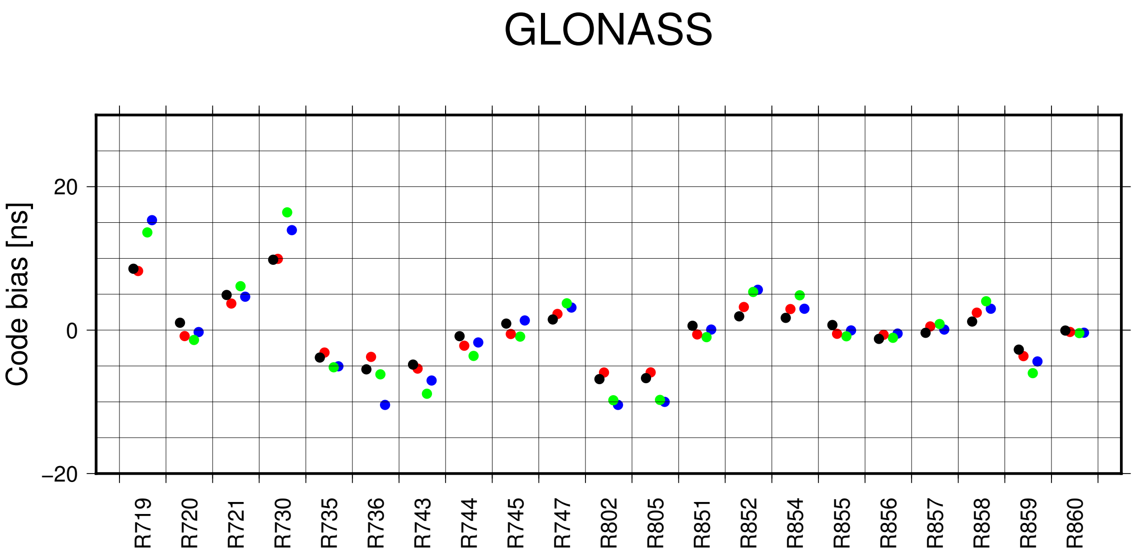

Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2021. Note that R719–R747 and R851–R860 correspond to GLONASS-M; R802–R805 correspond to GLONASS-K1 satellite generations. Legend: C1C (black), C1P (red), C2P (green), C2C (blue).

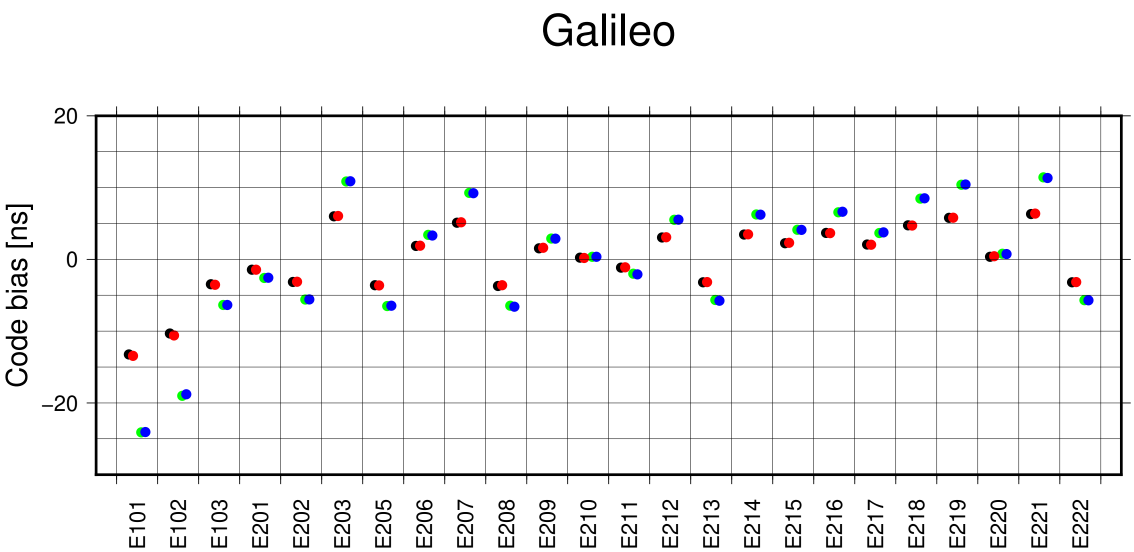

Figure 3: Observable-specific code bias (OSB) estimates for Galileo code observable types (using the RINEX3 nomenclature) and Galileo SV numbers, computed at CODE, for January 2021. Legend: C1X (black), C1C (red), C5Q (green), C5X (blue).

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 intersystem translation parameters, which are estimated and accumulated as part of CODE's IGS analysis (but completely ignored for all submissions to IGS).
- CODE's enhanced RINEX2/RINEX3 observation data monitoring was continued. Examples may be found at:
  ftp://ftp.aiub.unibe.ch/igsdata/odata2_day.txt
  ftp://ftp.aiub.unibe.ch/igsdata/odata2_receiver.txt
  ftp://ftp.aiub.unibe.ch/igsdata/odata3_gnss_day.txt
  ftp://ftp.aiub.unibe.ch/igsdata/odata3_gnss_receiver.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata2_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata2_d335_sat.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata3_gnss_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata3_gps_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata3_glonass_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata3_galileo_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata3_beidou_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/odata3_qzss_d335.txt
  ftp://ftp.aiub.unibe.ch/igsdata/y2020/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

Phase biases

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

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

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, 2020) 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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Ionosphere Working Group Technical Report 2020

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1 General goals

The Ionosphere Working group started tThe 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.

*Chair of Ionosphere Working Group

2 Membership

1. Mahdi Alizadeh (TU Berlin and K.N.Toosi University of Technology: Tehran)
2. Dieter Bilitza (GSFC/NASA),
3. Ljiljana R. Cander (RAL)
4. M. Codrescu (SEC)
5. Anthea Coster (MIT)
6. Patricia H. Doherty (BC)
7. John Dow (ESA/ESOC)
8. Joachim Feltens (ESA/ESOC)
9. Mariusz Figurski (MUT)
10. Pawel Flisek (UWM)
11. Adam Froń (UWM)
12. Alberto Garcia-Rigo (UPC)
13. Reza Ghoddousi-Fard (UNB)
14. Manuel Hernandez-Pajares (UPC)
15. Pierre Heroux (NRCAN)
16. Norbert Jakowski (DLR)
17. Attila Komjathy (JPL)
18. Andrzej Krankowski (UWM)
19. Kacper Kotulak (UWM)
20. Richard B. Langley (UNB)
21. Reinhard Leitinger (TU Graz)
22. Zishen Li (CAS)
23. Maria Lorenzo (ESA/ESOC)
24. Angelyn Moore (JPL)
25. Raul Orus (UPC)
26. Michiel Otten (ESA/ESOC)
27. Ola Ovstedal (UMB)
28. Ignacio Romero (ESA/ESOC)
29. Jaime Fernandez Sanchez (ESA/ESOC)
30. Stefan Schaer (CODE)
31. Michael Schmidt (DGFI-TUM)
32. Javier Tegedor (ESA/ESOC)
33. Ningbo Wang (CAS)
34. Rene Warnant (ROB)
35. Robert Weber (TU Wien)
36. Pawel Wielgosz (UWM)
37. Brian Wilson (JPL)
38. Yunbin Yuan (CAS)
39. 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 The cooperative IGS RT-GIMs: a global and accurate estimation of the ionospheric electron content distribution in real-time

The IGS combined Real-Time Global Ionosphere Map (RT-GIM) has been generated by applying the weights given by the real-time dSTEC assessment technique to RT-GIMs provided by the IGS real-time ionosphere centers: the Chinese Academy of Sciences (CAS), Centre National d'Etudes Spatiales (CNES), Universitat Politècnica de Catalunya (UPC), and Wuhan University (WHU) recently. Another recent improvement has been that one of the IGS RT-GIMs (UPC-IonSAT) has completely changed the RT-interpolation strategy, with a significant improvement. A new version of IRTG has been developed to improve the performance and also adapt to the newly updated IGS-SSR format.

The performance of global Vertical Total Electron Content (VTEC) representation in all of the RT-GIMs has been assessed by VTEC directly measured from Jason3-altimeter during one month over oceans and dSTEC-GPS technique with 2-day observations over continental regions. According to the Jason3-VTEC and dSTEC-GPS assessment, the real-time weighting technique is sensitive to the accuracy improvement of RT-GIMs, confirming in this way its suitability for the combination of RT-GIMs. During the recent testing period during beginning of 2021 (Fig. 1), the accuracy of IGS combined RT-GIM (irtg) is around 2.7 and 3.0 TECU over oceans and continental regions, respectively. This is slightly better or equivalent to the rapid GIMs like the IGS combined one (igrg), with latencies of 1-2 days, and just slightly worse than the final IGS GIM (igsg) with latencies of several days. These results indicates that the IGS RT-GIMs turn out to be reliable sources of real-time global VTEC information and has great potential for real-time applications including range error correction for trans-ionospheric radio signals, the monitoring of space weather and detection of natural hazards on a global scale.

6 Towards Cooperative Global Mapping of the Ionosphere: Fusion Feasibility for IGS and IRI with Global Climate VTEC Maps

In this study we introduced new VTEC products to GAMBIT Database and Explorer created and maintained at GIRO: global average (climate) maps of VTEC based on rapid

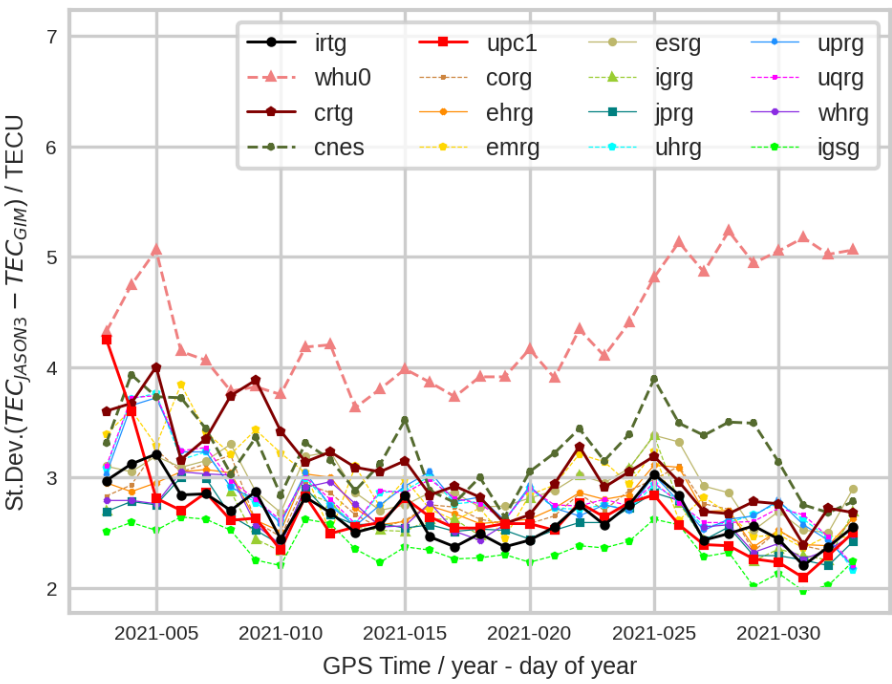

Figure 1: Daily standard deviation of GIM VTEC versus measured Jason3-VTEC (in TECU), from January 03 to February 02 in 2021, including the updated RT-IGS one (irtg), the rapid IGS GIM (igrg) and the final IGS one (igsg).

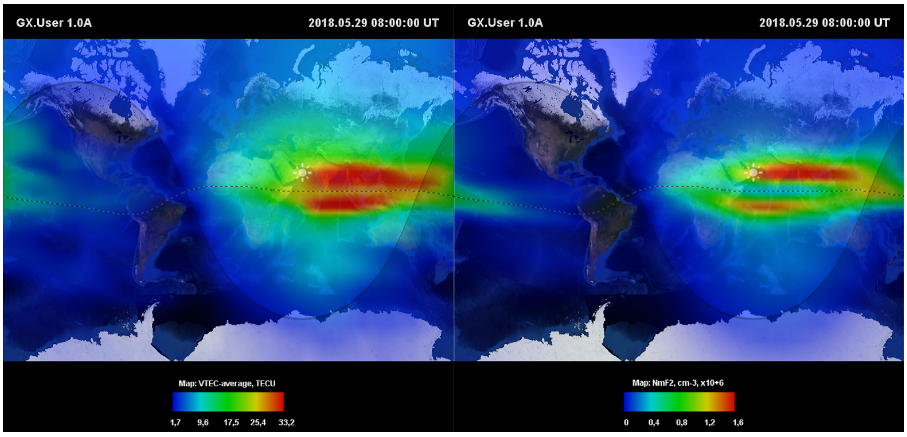

Figure 2: Comparison of climate VTEC and climate NmF2 as seen in GAMBIT Explorer. Climate VTEC derived from IGS network reflects expected quiet-time reference VTEC. Climate NmF2 from IRI model shows typical quiet-time plasma distribution.

15-minutes global UQRG maps on UPC and slab thickness based on climatological capabilities of IRI. Incorporation of the VTEC and slab thickness maps into the GAMBIT Explorer environment provided data analysts with nearly 10-year history of the reference average VTEC records and opened access to the GAMBIT toolkit for evaluation and validation of the slab thickness computations. This result is the first step towards establishing an infrastructure and the data workflow to provide GAMBIT users with the low latency and consistent quality and usability of the ionospheric weather-climate specifications. Combination of IGS-provided VTEC and GIRO-provided peak density of F2 layer NmF2 allows ground-based evaluation of the equivalent slab thickness t, a derived property of the near-Earth plasma that characterizes the skewness of its vertical profile up to the GNSS spacecraft altitudes. The cooperation between IGS and IRI over capabilities of joint ionosphere representation continues with ongoing works on introduction of real-time and rapid schedules global VTEC maps into GAMBIT that would extend the current climate VTEC capabilities on VTEC nowcast and allow for in-depth multiinstrumental insight of various ionosphere parameters both in actual and quiet-time climatological states (Fig. 2).

7 Climatology Characteristics of Ionospheric Irregularities Described with GNSS ROTI

In the study we have examined the long-term performance of the total electron content (TEC) fluctuations at mid and high latitudes. The study was based on the rate of tec index (ROTI) behavior within two sectors: North-American and European. GNSS stations distribution in North America allowed on insight to the higher magnetic latitudes (up to

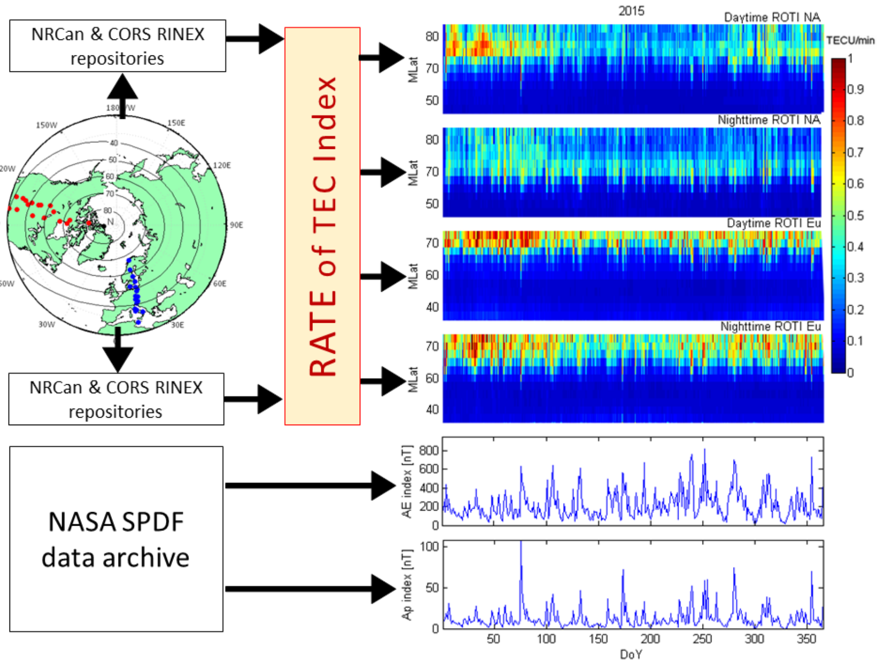

Figure 3: Block diagram of the elaboration and example results for the 2015 (day and night results for European and North-American sector atogether with AE and Ap indices)

85oN), whereas dense mid-latitude coverage in Europe gave closer view to the fluctuations sone behavior between (60 and 70°N). ROTI was elaborated based on the GNSS data located along two selected meridians for three years (2013, 2015 and 2017) selected as a representation for the whole solar cycle 24. We considered the different scale temporal signatures (daily, seasonal and solar cycle-long variation) and checked the general sensitivity to the solar and geomagnetic activity. We found and described the ROTI auroral oval equatorward spread triggered by the disruptions within the magnetic field. This was confirmed by a high correlation between ROTI and geomagnetic activity indices within mid latitudes (55-65oN) during more active periods. Mid-latitude correlation dropped during quiet conditions. Figure 3 presents the block diagram of the elaboration and example results for the 2015 The work also concluded a signifficant correlation between ROTI auroral and sub-auroral performance and empirical models. More detailed analysis of the geomagnetic storm-induces ROTI behavior is currently under preparation.

Multi-GNSS Working Group Technical Report 2020

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1 Working Group Charter and Composition

The new charter of the Multi-GNSS Working Group (MGWG) was approved by the IGS governing board on December 16, 2020. The key goals mentioned in the charter are:

- Conduct and supervise the Multi-GNSS Pilot Project (MGEX) with the near-term goal of a comprehensive integration of multi-GNSS tracking and analysis into all IGS components and activities.
- Consult and liaise with other IGS Working Groups to ensure adequate consideration of all GNSSs in standards and data formats. This includes, but is not limited to, receiver data, antenna information, biases, and conventions for precise point positioning.
- Coordinate and promote the generation of comprehensive multi-GNSS orbit and clock products, and support the build-up of a multi-GNSS orbit/clock product combination process within the IGS.
- Interact with GNSS providers and manufacturers to increase awareness of user needs in the field of precise multi-GNSS, and promote the release of relevant information and the proper support of new standards.
- Increase public awareness for multi-GNSS related work in the IGS and facilitate access to relevant information through the IGS multi-GNSS website.

Vladimir Mitrikas of the IAC joined the MGWG as IAC has started to contribute multi-GNSS orbit and clock products to MGEX in September 2020.

2 GNSS Evolution

The GNSS satellite launches of 2020 are given in Table 1. Following the launch of the first two GPS III satellites in 2019, the first satellite Vespucci was set healthy on January 13, 2020 (GPS World, 2020) and the second GPS III satellite Magellan started signal transmission on March 13, 2020, and was set healthy on April 1 (Steigenberger et al., 2020). Two further GPS III spacecraft were launched and set healthy in 2020 resulting in a mini constellation of four GPS III satellites. Flex power operations of Block IIR-M and IIF satellites continued in 2020 with frequent changes in the activation pattern and only one short period without flex power.

Table 1: GNSS satellite launches in 2020.

Date	Satellite	Type
09 Mar 2020	BeiDou-3	GEO
16 Mar 2020	GLONASS-M+	MEO
23 Jun 2020	BeiDou-3	GEO
30 Jun 2020	GPS III-3	MEO
25 Oct 2020	GLONASS-K1	MEO
11 Nov 2020	GPS III-4	MEO

On July 31, 2020, the BeiDou Navigation Satellite System (BDS-3) was formally commissioned. As of January 2021, the constellation of healthy BDS-3 satellites consists of 24 MEOs, 3 IGSOs and 2 GEOs. The most recently launched GEO satellite has still the status *testing*.

The first two Galileo satellites accidentally launched in an eccentric orbit (E201/E14 and E202/E18) were declared healthy on 30 November 2020. Due to the eccentricity of about 0.16, these satellites are not included in the almanac. After initial problems with the host platform, the EGNOS GEO-3 payload on Eutelsat 5 West B entered into service in February 2020 (GSA, 2020).

3 Network

As of December 2020, the IGS multi-GNSS tracking network comprises 325 stations, see Figs. 1 and 2. Five stations are completely dormant and did not provide any observations in 2020. The BDS-3 tracking capability was improved due to further deployment of updated firmware versions already mentioned in Steigenberger and Montenbruck (2020).

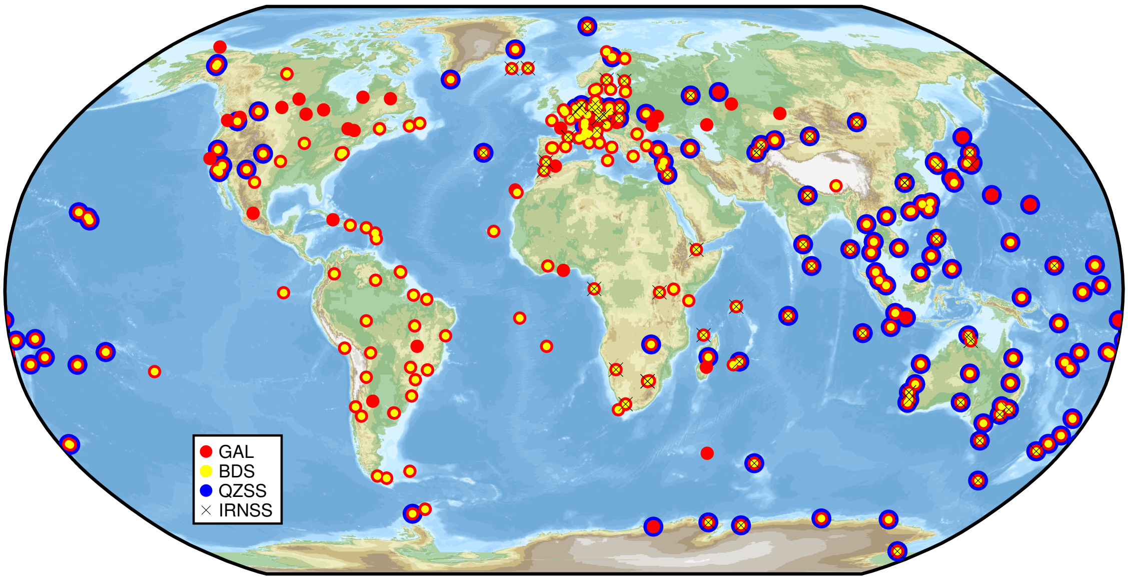

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of December 2020.

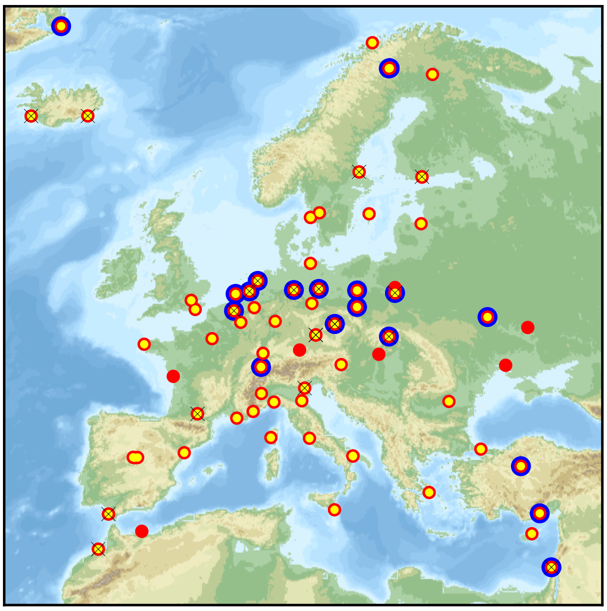

Figure 2: Distribution of European IGS multi-GNSS stations as of December 2020. See Fig. 1 for explanation of individual station labels.

4 Products

In 2020, IAC joined the MGWG and started providing orbit and clock products to MGEX covering all global navigation systems as well the regional QZSS (Table 2). Precise orbit and clock determination of BDS-3 PRNs > C37 was initially hampered by software limitations of several GNSS receiver types of the IGS network. As this situation improved in 2020, WU started to include these PRNs in their MGEX products. In 2020, GFZ and SHA also started to include BDS-3 in their products.

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	GRG0MGXFIN	GPS+GLO+GAL
CODE	COD0MGXFIN	GPS+GLO+GAL+BDS2+QZS
GFZ	GFZ0MGXRAP	GPS+GLO+GAL+BDS2+BDS3+QZS
IAC	IAC0MGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS
JAXA	JAX0MGXRAP	GPS+GLO+QZS
SHAO	SHA0MGXRAP	GPS+GLO+GAL+BDS2+BDS3
Wuhan University	WUM0MGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS

Changes in MGEX products:

- 148/2020: switch from 15 min to 5 min orbit sampling for SHAO
- 161/2020: inclusion of BDS-3 in SHAO products
- 166/2020: inclusion of BDS-3 in GFZ products
- 190/2020: switch from 30 s to 5 min clock sampling for SHAO
- 256/2020: start of IAC final orbit product submission
- 262/2020: start of IAC final clock product submission
- 279/2020: inclusion of BDS-3 PRNs > C37 in WU products

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 and GPS DCB types were included as soon as a sufficient number of IGS receivers provided these observations:

- Inclusion of BeiDou C2I-C8X DCBs in February 2020.
- Inclusion of GPS L1C-related DCBs (C1C-C1L, C1C-C1X) since March 2020.

As announced in Steigenberger and Montenbruck (2020), provision of DLR's broadcast ephemerides and CNAV products with short filenames was stopped in June 2020. Both products are available with long filenames (prefixes `BRDM00DLR` and `BRDX00DLR`) in the default data directories of the IGS data centers.

5 Satellite Metadata

In December 2020, Satellite Group Delay, Phase Center and Inter-Signal Bias Data for the first two GPS-III satellites were officially published on the website of the U.S. Coast Guard Navigation Center (NAVCEN, 2020a). The antenna gain pattern of the GPS Block IIR and IIR-M were officially released (NAVCEN, 2020b) although already available from Lockheed Martin since several years (Marquis and Reigh, 2015). On the basis of the presentation of Galileo metadata that could be published in the near future (Gonzalez and Dilssner, 2019), details of this publication have been discussed by the MGWG with ESA and GSA.

Following the switch to the new IGS website, the IGS satellite metadata file is now made available at https://files.igs.org/pub/station/general/ with an updated file naming scheme `igs_satellite_metadata_wwww.snx` where `wwww` stands for the GPS week of the release.

The latest satellite metadata file is also available with a static filename at https://files.igs.org/pub/station/general/igs_satellite_metadata.snx. Historic files can be found in the folder https://files.igs.org/pub/station/general/old_sat_meta/.

6 Proposal for new RINEX Navigation data format

The modernization and build-up of new GNSSs has greatly increased the variety of navigation data in use today:

- CNAV data are routinely transmitted on the L2C/L5 signals of GPS IIR-M/IIF/III satellites since 2015, and CNAV-2 data transmission on L1C is soon expected for the new set of GPS III satellites.
- QZSS transmits CNAV (on L2/L5) and CNAV-2 (on L1C) navigation messages since almost a decade.
- Along with the declaration of a global service, BeiDou-3 has started to transmit healthy CNAV-1 (on B1C), CNAV-2 (on B1a), and CNAV-3 (on B2b) navigation messages.

These navigation messages offer enhanced precision, full support of multi-frequency positioning with arbitrary signals, and a variety of new data such as inter-system time offsets and Earth orientation parameters. The practical availability of advanced navigation data contrasts sharply with the limited capabilities of the current RINEX navigation file format, which is confined to a single type of navigation message for most constellations. As an exception, Galileo FNAV and INAV messages can be handled in a joint record format, but no option exists to handle GPS/QZSS CNAV and CNAV-2 data along with legacy (LNAV) navigation messages. Likewise, RINEX support for BeiDou is limited to the BDS-2 D1/D2 navigation messages, whereas BeiDou-3 CNAV-1/2/3 navigation messages cannot be handled.

An update of the RINEX navigation data format has been developed, which supports the exchange of ephemeris data for all legacy and modernized navigation messages as well as time-dependent constellation data such as ionosphere model parameters, system time offsets, and Earth orientation parameters. A task force within the RINEX working group is currently discussing this format proposal.

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

IAC Information and Analysis Center for Positioning, Navigation and Timing

JAXA Japan Aerospace Exploration Agency

SHAO Shanghai Observatory

WU Wuhan University

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Precise Point Positioning with Ambiguity Resolution Working Group Technical Report 2020

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1 Introduction

The precise point positioning with ambiguity resolution (PPP-AR) working group (WG) aims at guiding the IGS towards offering combined satellite orbit, clock and bias products enabling ambiguity resolution at the user end. This feature is supported by the generation of phase biases to isolate carrier-phase ambiguities as integer parameters. Using this additional product, PPP-AR users can benefit from improved positioning accuracy, a shorter convergence period and enhanced derived products such as tropospheric and ionospheric delays and receiver clock offsets.

In the first phase of the PPP-AR WG, the interoperability of satellite clock corrections and bias estimates was assessed (Banville et al., 2020). Since analysis centers use different approaches to estimate phase biases, transformations were defined to convert estimates into observable-specific biases supported by the Bias SINEX format (Schaer, 2016). Using this format allowed defining a new combination strategy considering clock corrections and biases simultaneously and confirmed the interoperability of PPP-AR products generated by IGS analysis centers.

Even though products are interoperable, their consistency is affected by a lack of knowledge regarding the satellite attitude used while estimating satellite clock corrections. During satellite eclipses, differences in satellite attitude models among analysis centers can cause discrepancies in the clock combination. Furthermore, if satellite attitude implementation on the user end differs from the network solution, a degradation of estimated positions can occur. For these reasons, the PPP-AR WG promoted the exchange of satellite attitude information within the IGS.

2 Satellite Attitude Comparisons

As a part of the IGS repro3 campaign, analysis centers were encouraged to submit attitude information in the form of quaternions in the ORBit EXchange format (ORBEX) (Loyer et al., 2019). During the 2014 repro3 test period, seven analysis centers submitted attitude files as shown in Table 1.

Table 1: Analysis centers (AC) having provided satellite attitude information for the 2014 repro3 test campaign

AC	Agency	Interval (s)	GNSS
COD	Center for Orbit Determination in Europe	900	GRE
EMR	Natural Resources Canada	30	G
GFZ	German Research Centre for Geosciences	300	GRE
GRG	Centre National d'Etudes Spatiales Collecte Localisation Satellites	30	GR
JPL	Jet Propulsion Laboratory	30	G
NGS	National Geodetic Survey	900	G
TUG	Graz University of Technology	30	GRE

An extensive comparison of GPS attitude quaternions among all analysis centers revealed that approximately 3% of quaternions differed by more than 1 degree. Fortunately, the axis of rotation was always aligned with the satellite-body z-axis, meaning that all attitude differences were pure yaw angle differences. This finding is not surprising since, by definition, the z-axis points towards the center of the Earth. Since the maneuvers associated with GLONASS satellites are simpler to model, attitude discrepancies rarely exceed 50 degrees. For Galileo, for which the attitude model was released by the European GNSS Agency, no significant attitude differences were noticed over the study period.

Attitude differences correspond to a rotation of the satellite about its satellite-body z-axis and create carrier-phase wind-up discrepancies in satellite clock estimates. As an example, Figure 1 shows residuals from a GPS satellite clock combination for 29 April 2014 using four analysis centers. Residuals correspond to differences between the satellite clock estimates provided by analysis centers and the combined clocks after removing, for each analysis center, an epoch-specific timing offset and a satellite-specific offset. Each color represents a satellite, and residuals from most satellites are at the millimeter level, as expected from satellites in yaw steering conditions. However, residuals for satellite G25 in red are clearly larger as the GPS IIF satellite was observed at a beta angle between -0.7 and 0.0 degree, in which wrong noon-turn maneuvers can occur. Analysis centers modelled these turns differently, creating attitude differences and clock discrepancies.

When satellite attitude information is provided by analysis centers, it is possible to apply a correction for the wind-up effect, which is proportional to the attitude difference. Figure 2 shows the benefits of this correction, with residuals for G25 being clearly reduced.

Remaining inconsistencies likely originate from clock estimates having absorbed part of the non-zero satellite phase center offsets while the satellite was not oriented consistently. Removing this effect would only be possible if analysis centers adopted the same attitude models.

The study conducted by Loyer et al. (2021) also demonstrates the benefits of attitude information to PPP users. Over a one-week period in 2014, kinematic PPP position residuals for 10 IGS stations were reduced by 50% on average when using the attitude quaternions provided by the analysis center.

3 Open Source Attitude Models

Since it is not meaningful to combine satellite attitude information from analysis centers, a reference attitude must be adopted. This reference serves the purpose of aligning solutions from analysis centers during the clock combination process, and also needs to be provided to users to ensure consistency in PPP solutions.

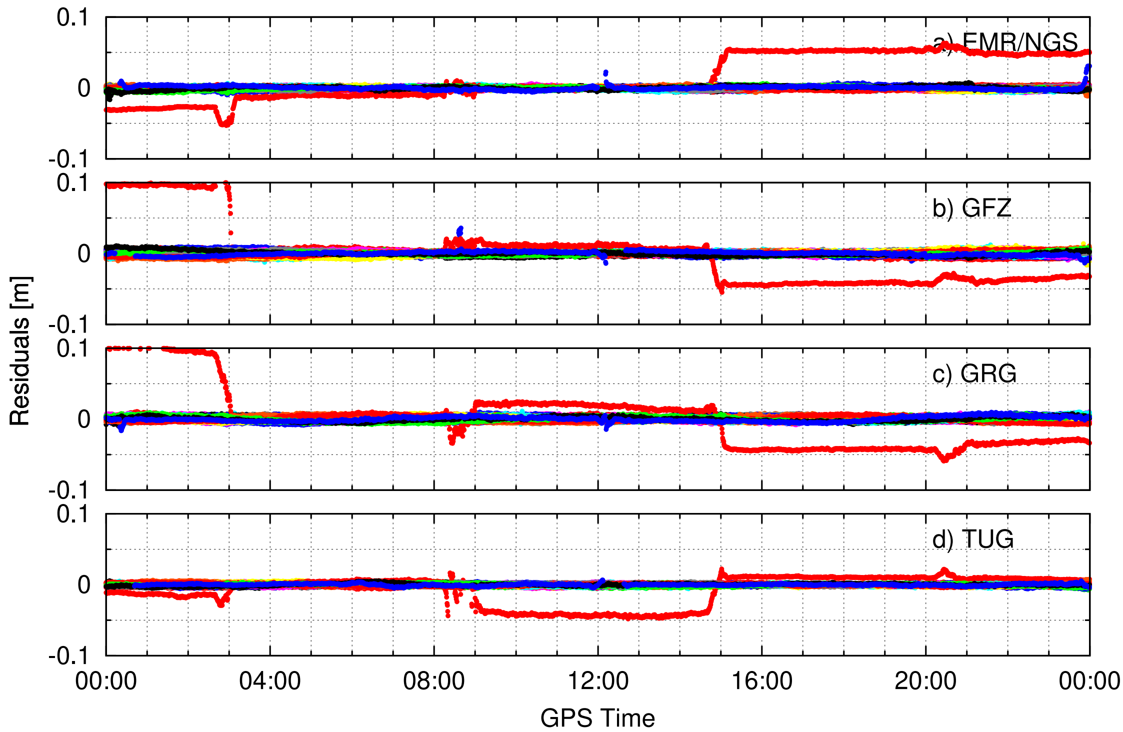

Figure 1: Satellite clock residuals for the combination of 29 April 2014 without using attitude information (from Loyer et al. (2021)).

To fulfill the need of a reference attitude for the IGS, attitude models should be available as open source code and represent attitude models as reliably as possible. The Gravity Recovery Object Oriented Programming System (GROOPS) is a software toolkit written in C++ enabling, among other features, processing of GNSS measurements (Mayer-Gürr et al., 2020). A careful implementation of attitude models for all GNSS constellations is available within the software (Strasser et al., 2021) and is currently being validated by some analysis centers of the IGS. The source code is available here: https://github.com/groops-devs/groops.

4 Future Work

As the repro3 campaign nears completion, the PPP-AR WG is planning on being actively involved in the satellite clock combination of repro3 solutions. The modernized clock combination software developed as a part of the WG initiative could allow for the combination of multi-GNSS satellite clocks and biases. Therefore, the resulting products would enable

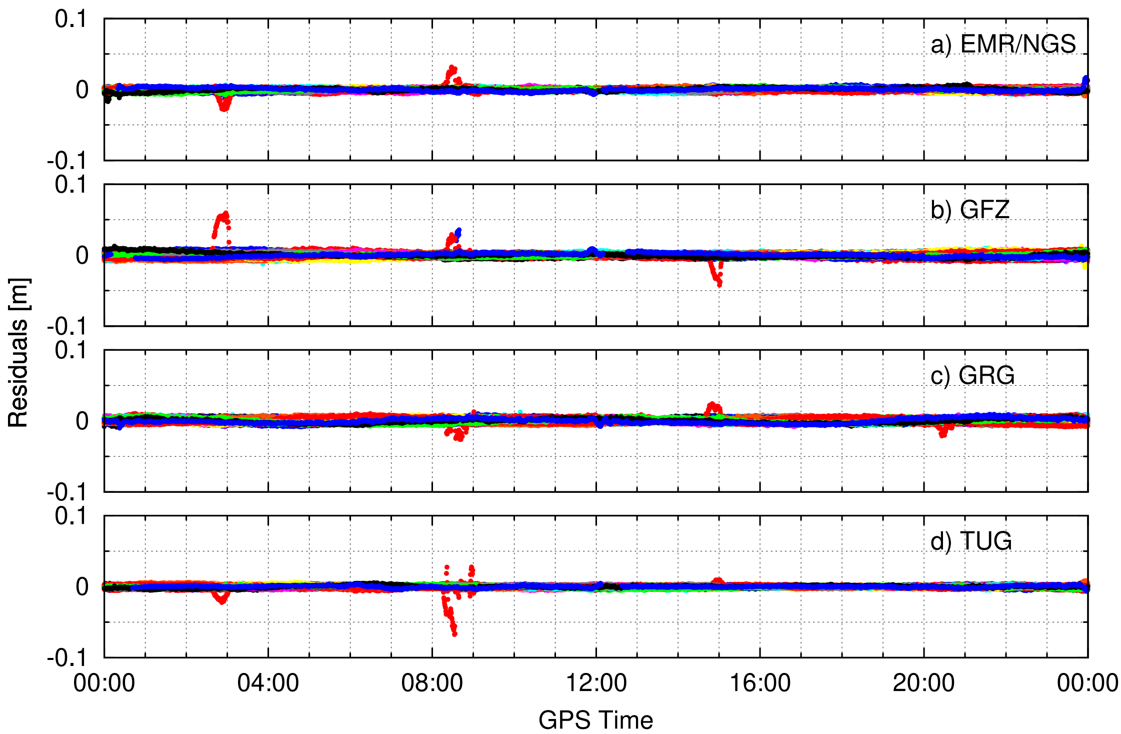

Figure 2: Satellite clock residuals for the combination of 29 April 2014 when using attitude information provided by analysis centers (from Loyer et al. (2021)).

PPP-AR solutions at the user end (at least for the GPS constellation). Attitude files provided by analysis centers would also be integrated into the clock combination process to improve the consistency of clock estimates during satellite eclipses.

Current data formats also lack a clear means of identifying clock and bias continuity/discontinuity, for instance, at day boundaries. If time allows, an extension of current data formats will 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.

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IGS Real-Time Working-Group Technical Report 2020

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1 Introduction

The IGS Real-Time working group continued holding regular telephone conferences in 2020 in February, April, July, October and December. A comprehensive summary of these telephone conferences is provided in this technical report.

2 Development of IGS SSR Format

It has been suggested by Loukis Agrotis (RT-ACC) to continue developing a real-time SSR format within the IGS. A task force under the lead of Gerhard Wübbena (geo++) and Martin Schmitz (geo++) has been formed from member of the RT-WG and started working immediately on the definition of a new format. IGS SSR format v1.0 was released on October 05, 2020 and is available at the IGS website. Topics for future developments are planned for antenna phase center corrections, satellite attitude and ionospheric corrections.

3 Experimental Real-time Ionospheric Product

Under the lead of Manuel Hernandez-Pajares and in collaboration with the IONO-Working group an experimental real-time ionospheric product has been set up and provided on a new mountpoint on the IGS products caster "products.igs-ip.net". The real-time ionospheric GIM combination software has been substantially upgraded and is processing contributions from CAS, WHU, UPC and CNES. The newest version of BNC has been installed to generate the streams in the new IGS-SSR format. An upgrade of the ionosphere correction messages in the IGS SSR format is currently being discussed in the ionospheric working group together with the SSR task force to better meet user needs.

4 Experimental Real-time Multi-GNSS SSR Product

A major revision of the real-time stream combination functionality of the BNC software by BKG now allows the timely combination of more than two GNSSs from the individual analysis center solutions. A first experimental multi-GNSS combination stream has been set up on the combination mountpoints provided by BKG at the IGS products caster “products.igs-ip.net”. The stream contains orbit and clock corrections for GPS, GLONASS, Galileo and BeiDou.

5 Real-time Working Group Broadcaster Guidelines

A final draft of the real-time working group broadcaster guidelines has been finalized by Markus and Wolfgang. The guidelines have been posted online for last inspection by the working group prior to finalization and publication. The guidelines cover real-time related aspects of reference stations and data centers, i.e. broadcasters. A publication of the finalized guidelines is anticipated in 2021.

6 Update to RT-WG Charter

The working group charter has been revised and updated. The new charter is attached in Appendix B of this report.

7 Switch to Long Mountpoint Names

All observation and product mountpoint names have been switched in the course of the year from short mountpoint names to long mountpoint names. A description of the new long mountpoint name convention is attached to Appendix A) of this report.

8 APC Coordinate Convention for GPS

A coordination effort has been done by the RTACCC to harmonize the antenna phase center reference convention among analysis centers. Some analysis centers have used the ionosphere-free L1/L2 combined phase center while others have used the L1 phase center. It has been agreed for all analysis centers to switch to the L1 phase center convention at the earliest opportunity to be consistent with the definition in the new IGS SSR format.

9 Deactivation of CB Caster and Transition to UCAR Caster

The UCAR team has taken over user-registration and other actions related to caster operations from the CB and become an official IGS caster for real-time observations and products.

10 Improving Broadcast Ephemeris Quality in IGS Combined Streams

Problems with GLONASS RTCM3-SSR orbit corrections have occurred frequency and could be traced down to problems with corrupted GLONASS broadcast ephemerides. Enhancements to BNCs quality control of the broadcast ephemerides have been implemented by Andrea and have successfully mitigated these issues.

Appendix A Long Product Mountpoint Format

The long product mountpoint names consist of 10 characters of the form "TTTTXXAAAF" with

TTTT:	stream type (SSRA, SSRC, IONO, BCEP, etc.)
XX:	2 digit solution ID
AAA:	3 letter agency code
F:	1 digit format ID (0: RTCM3, 1: IGS-SSR, 2-9: reserved)

The stream type (TTTT) is one of the following:

SSRA:	state space corrections (orbits, clocks, ...), orbits refer to APC
SSRC:	state space corrections (orbits, clocks, ...), orbits refer to COM
DCBS:	state space corrections (DCBs only)
IONO:	ionospheric corrections
TROP:	tropospheric corrections
BCEP:	broadcast navigation data (broadcast ephemeris)

Note that SSRA and SSRC may also contain differential code biases (DCBs), ionospheric corrections, tropospheric corrections and fractional phase-biases (FCBs).

The following agency codes (AAA) are defined

BKG:	Federal Agency for Cartography and Geodesy (BKG)
CAS:	Chinese Academy of Sciences
CNE:	National Centre for Space Studies (CNES)
DLR:	German Aerospace Center (DLR)
ESA:	European Space Agency (ESA)
GFZ:	German Research Centre for Geosciences (GFZ)
GMV:	GMV Innovating Solutions S.L. (GMV)
NRC:	Natural Resources Canada (NRCan)
UPC:	Polytechnic University of Catalonia (UPC)
WHU:	Wuhan University

Appendix B IGS Charter 2020

The use of real-time data in GNSS processing has gained a significant importance over the last decade. The applications using real-time data cover a wide range from scientific studies to commercial services: RTK and PPP positioning, tsunami or earthquake monitoring, ionospheric delay estimation, time dissemination or GNSS constellation monitoring are only a few examples. Real-time data streams with GNSS observations and broadcast ephemerides provide the necessary data to enable these various applications. Central servers for data distribution (NTRIP casters) are used to disseminate the data streams to users with low latency. Data formats capable of streaming real-time data are required to transport observations, broadcast ephemerides as well as derived products with low bandwidth requirements.

The IGS through its real-time working group (RTWG) is dedicated to provide open data, open products and open standards for real-time users to the GNSS community. The RTWG aims at maintaining high quality data and providing high precision products that are state-of-the-art. It supports their dissemination by improving existing data formats or by developing new standards. The RTWG provides a forum to discuss the development of new methods and algorithms, for example, to improve the performance of precise point positioning (PPP) techniques in terms of convergence, accuracy and reliability. The goals of the RTWG are defined as follows:

- Maintain and expand the multi-GNSS real-time reference station network of IGS stations in close cooperation with the Infrastructure Committee and the Network Coordinator
- Monitor and improve the quality of GNSS real-time observations and broadcast ephemerides in cooperation with the RINEX WG and give advice on stream configuration

- Provide precise real-time corrections for orbits, clock, biases and atmospheric delays
- Provide and monitor a combination of correction data streams for a robust and reliable IGS real-time product
- Develop new and improved RT products and work with the RT ACC to transition these products to the Real Time Service (RTS)
- Develop and improve open standards for real-time data and products
- Investigate new streaming technologies
- Provide users access to real-time data from reference stations and correction streams through the internet

RINEX Working Group Technical Report 2020

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1 Introduction

The IGS/RTCM RINEX Working Group was established in December 2011 to update and maintain the RINEX format to meet the needs of the IGS and the GNSS Industry. Since the RINEX format is widely used by the GNSS scientific community and industry it was decided that it should be jointly managed by the IGS and the Radio Technical Commission for Maritime Services – Special Committee 104 (RTCM-SC104). In this way the working group consists of IGS scientific and institutional members and RTCM-SC104 industry members.

2 Membership

Current membership has been revised during 2020 and is current and correct on the IGS website; https://www.igs.org/wg/rinex/#members

3 Summary of Activities in 2020

2020 has been a busy year for the RINEX WG; we have selected a new Chair, written a new WG Charter, revised the membership list and issued the new RINEX 3.05 format definition standard document.

Over 2020 the most important development has been the approval of the RINEX 3.05 format definition standard published on 1 December 2020. This version of RINEX modifies the signal table for the Beidou GNSS by adapting the signal definition to properly account for the BDS-2 & BDS-3 signals. Additionally, the GLONASS navigation message is enhanced by adding necessary health indicators and other parameters in a new line in the navigation message. The RINEX 3.05 document is also restructured and reformatted to simplify and clarify the text and explanations.

The RINEX Chair position had remained empty since May 2019 when the previous chair retired. In May 2020 two candidates had been identified and underwent a selection process amongst the RINEX WG members with the selection as stated above.

The updated RINEX WG Charter and Goals were renewed and approved without objection by the WG members in December 2020. The previous charter dated back to 2011 to the establishment of the WG and was out of date. The updated charter continues the commitment to maintaining RINEX into the future and to evolve the format as required to remain in-line with all the GNSS signal-in-space public interface control documents (ICDs). The new RINEX WG charter version is available here; https://www.igs.org/wg/rinex/#charter

The RINEX WG members list was reviewed and updated since it had not been since 2013. The previous members were contacted to test their email addresses. Several organizations and members expressed the need to change contact details, retire from the WG and other organizations added members to the group. The current list of members is in the link indicated above, the WG has around 60 members, as a mixed IGS and RTCM group this is as expected.

4 Planned 2021 Activities

During 2021 the RINEX WG will strive to complete the revision of the Navigation message format which has not seen a major update recently. This is necessary as currently some of the transmitted navigation data by the GNSS satellites is not properly captured in RINEX, for example for modernized and new messages. For this purpose, a RINEX WG Navigation taskforce has been assembled from the members and work will take place to fully upgrade the navigation messages.

Additionally, as new GNSS ICDs are updated, or newly published, they will be analyzed to check if there are any needed changes to RINEX, and a new RINEX version will then be created, discussed, approved and published.

Tide Gauge Benchmark Monitoring Working Group Technical Report 2020

T. Schöne, R. Bingley, A. Craddock, Z. Deng, M. Gravelle, M. Guichard, D. Hansen, T. Herring, A. Hunegnaw, M. Jia, M. King, M. Merrifield, G. Mitchum, M. Moore, C. Noll, E. Prouteau, L. Sánchez, A. Santamaría-Gómez, N. Teferle, D. Thaller, S. Williams, G. Wöppelmann

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 2020

- TIGA-AC's are actively participating in the IGS-repro3 or align TIGA activities with IGS-repro3 time line.
- The TIGA-WG participated in the GLOSS Data Center Meeting (Paris, March 2020) to better align the IGS-TIGA activities with the IOC/GLOSS activities
- TIGA Network operator continues to work 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 2020 in total 209 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 1047 (TIGA: 121 stations, with 18 decommissioned) stations (with 187 stations decommissioned). Still there are 163 stations where the GNSS data is not (yet) available for scientific research.

3 Related important Outreach activities in 2020 (selected)

- Participation GLOSS Data Center Meeting - 12 to 13 March 2020 (Paris, France)
- Participation IGS Governing Board Meetings, May, August and December 2020
- Reporting IGS Governing Board Meeting, 16 December 2020
- Contribution to the IOC Manual Quality control of in situ sea level observations: a review and progress towards automated quality control, volume 1 (IOC/2020/MG/83Vol.1)
- UNESCO/IOC: IOC Manual Quality control of in situ sea level observations: a review and progress towards automated quality control (IOC/2020/MG/83Vol.1) https://unesdoc.unesco.org/ark:/48223/pf0000373566
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4 TIGA Working Group Members in 2020

Working group members are listed in Table 1.

Table 1: TIGA Working Group Members in 2020

Name	Entity	Host Institution	Country
Guy Wöppelmann	TAC, TNC, TDC	University La Rochelle	France
Laura Sánchez	TAC	DGFI/TUM Munich	Germany
Minghai Jia		GeoScience Australia	Australia
Norman Teferle	TAC/TCC	University of Luxembourg	Luxembourg
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	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
Benjamin Männel	TAC	GFZ Potsdam	Germany
Elizabeth Prouteau	TNC	University La Rochelle	France
Médéric Gravelle	TAC/TDC	University La Rochelle	France
Daniela Thaller	IERS CB	BKG	Germany

IGS Troposphere Working Group Technical Report 2020

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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. Sharyl Byram has chaired the working group since December 2015 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 2020

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

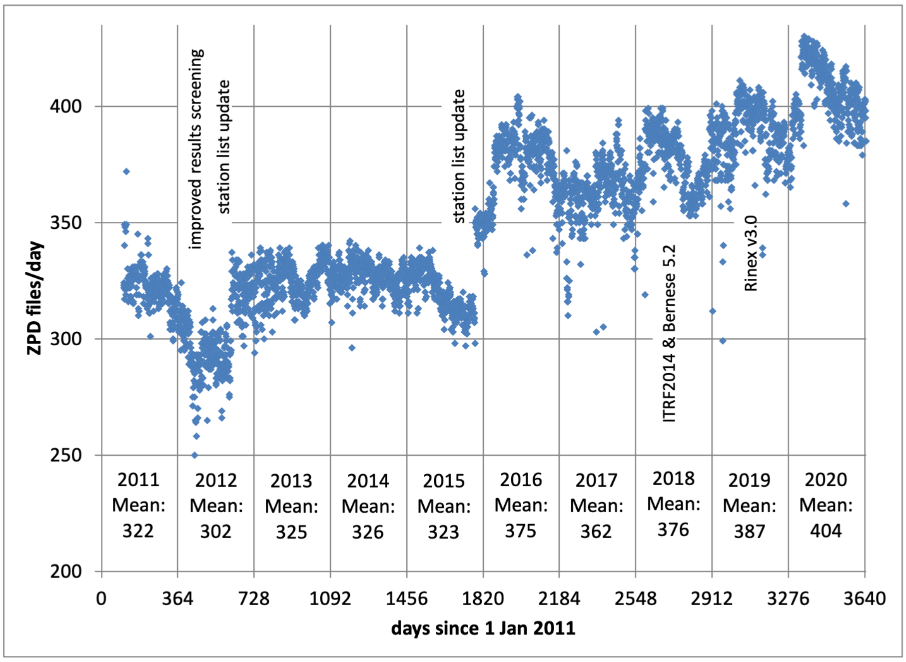

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011–2020. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011)

Fig. 1 shows the number of receivers for which USNO computed IGS FTEs 2011-2020. The average number of quality-checked station result files submitted per day in 2020 was 404, higher than the 2019 average value of 387 due to the implementation of improved observation file downloading scripts and quality checking. The result files are available for download from the CDDIS data server at https://cddis.nasa.gov/archive/gnss/products/troposphere/zpd/. The number of downloaded zpd files from CDDIS was 29.3 million in 2020.

3 IGS Troposphere Working Group Activities 2020

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 usually 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.

Due to COVID-19 health precautions, all TWG meetings were delayed to 2021. Communications on news and activities were distributed via the TWG mailing list.

3.1 Working Group Projects

3.1.1 Standardization of the tropo_sinex format

The IGS Troposphere Working group 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[1] organizations and other communities; its work is further supported by the EUREF Technical Working Group[2] as well as E-GVAP[3] 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. For more information, please contact Dr. Pacione at rosa.pacione@e.geos.it or Dr. Dousa.

3.1.2 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 Repro3 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).

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

4 How to Obtain Further Information

IGS Final Troposphere Estimates can be downloaded from: https://cddis.nasa.gov/archive/gnss/products/troposphere/zpd/.

For technical questions regarding the estimates, please contact the TWG Chair, 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

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Part V

Additional Contributions

Validation of GNSS orbits using SLR data and combined SLR+GNSS solutions at UPWr
IGS Technical Report 2020

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1 Introduction

In 2020, the Satellite Geodesy Department at the Wroclaw University of Environmental and Life Sciences (UPWr) conducted research involving the validation of GNSS orbit products using Satellite Laser Ranging (SLR) data, the development of the strategy for multi-GNSS data processing and determination of global geodetic products, e.g., Earth Rotation Parameters (ERPs) and geocenter coordinates (GCC), and the combination of the GNSS and SLR techniques using the co-location onboard the Galileo satellites for the orbit determination. The short 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., 2019), is placed in Section 2. Section 3 provides a quality assessment of the very first IGS experimental multi-GNSS combined orbits based on SLR. Section 4 gives an overview of the independent orbit validation based on SLR of the real-time IGS orbits. Section 5 summarizes the recent achievements in the determination of global geodetic parameters using GPS, GLONASS, and Galileo. Finally, Section 6 describes the GNSS orbits derived using the combined SLR and GNSS observations.

The latest information about the research activities conducted at IGG UPWr can be found in the given references as well as at: www.igig.up.wroc.pl/igg/.

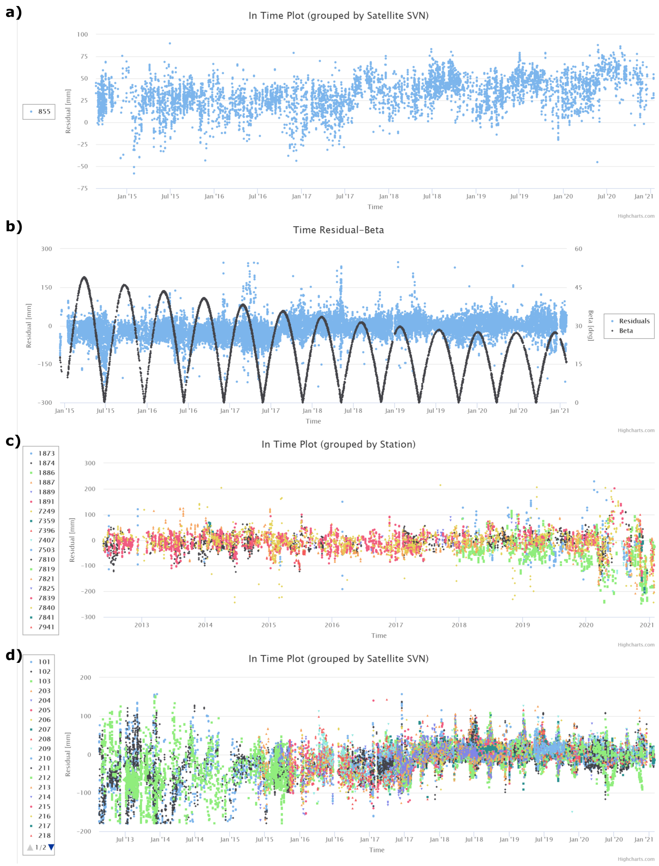

Figure 1: Examples of the plots from the GOVUS service; a) Time series of SLR residuals for GLONASS M+ (R21); b) Time series of SLR residuals to Galileo E14 on eccentric orbit with the change of the elevation of the Sun above the orbital plane (β); c) Time series of SLR residuals to GLONASS-M (R20) with the distinction between individual SLR stations; d) Time series of SLR residuals to Galileo satellites for the period 2012-2021.

2 ILRS Associated Analysis Center (ACC)

In 2017, a new service was established at UPWr, which became an ACC of the ILRS (Otsubo et al., 2019). The center provides products for validating orbits of Galileo, GLONASS, BeiDou, and QZSS satellites generated by the Center for Orbit Determination in Europe (CODE, Prange et al., 2020) with respect to laser observations collected by SLR stations distributed worldwide. The service also provides information about GNSS satellites and the characteristics of laser stations. The GOVUS service (Zajdel et al., 2017) is addressed to users of multi-GNSS orbit products and SLR stations belonging to the ILRS, which track GNSS satellites (Sośnica et al., 2019). The center generates daily reports with the features of the quality of the orbits of GNSS satellites and the quality of laser observations provided by stations. Moreover, the web service (www.govus.pl) enables performing online analyzes and data visualization. The validation results may be analysed in the form of the descriptive statistics or the advanced plots of SLR residuals enabling to, e.g., monitor misbehaving satellites (see Fig. 1a,b), investigate the differences in the SLR residuals from individual SLR stations (see Fig. 1d) or check the overall quality of the selected group of satellites (see Fig. 1c). The high quality of GNSS orbits is important for the high-quality positioning and navigation based on new GNSS systems (Hadas et al., 2019; Katsigianni et al., 2019) as well as for the realization of the geodetic reference frames and determination of global geodetic parameters (Zajdel et al., 2019). The service is available through a dedicated website: www.govus.pl (see Fig. 1).

3 Experimental IGS combined orbits

In 2019, the IGS established an experimental multi-GNSS orbit combination service. The combination is conducted by adapting the legacy methodology used for many years for the combination of GPS and GLONASS orbits. The combined orbits are based on products generated by MGEX ACs and IGS ACs. We assessed the quality of the experimental IGS multi-GNSS combined orbits based on SLR observations and the mean combination position errors (Sośnica et al., 2020). The BeiDou-3 CAST and SECM are characterized by opposite SLR residual dependencies with respect to the Sun elongation angles. GLONASS-M+ has the mean bias of +29 mm. The smallest SLR residuals are obtained for Galileo, GLONASS-K1, and GLONASS-M+. The mean RMS of SLR residuals is 23, 29, 40, 50, 87 and 72 mm for Galileo, GLONASS, BeiDou MEO, BeiDou IGSO, BeiDou GEO, and

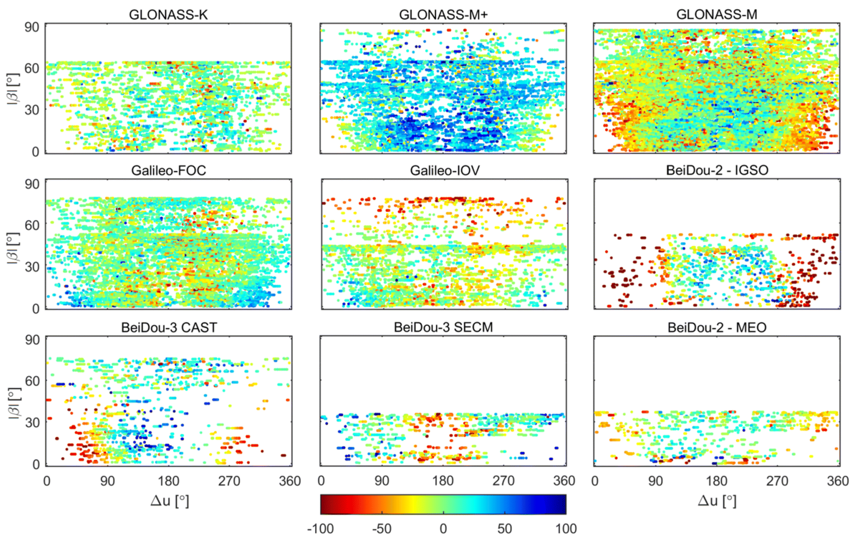

Figure 2: SLR residuals in millimeters as a function of the Sun elevation angle above the orbital plane (absolute value of β) and the satellite argument of latitude with respect to the latitude of the Sun (Δu), after Sośnica et al. (2020).

QZSS, respectively (see Fig. 2). From the combination, the orbit errors for MEO satellites are four times lower than those for GEO and IGSO. The IGS combinations are available at: igs.org/acc/experimental-multi-gnss-combinations/

4 Orbits and clocks for real-time multi-GNSS solutions

To take advantage of the multi-GNSS constellation in real-time (RT), users need to employ streamed data transmitted in RTCM messages via the Internet. Centre National d'Études Spatiales (CNES) is one of the RT ACs that supports quad-system positioning. The quality of the orbit and clock is inhomogeneous (Kazmierski et al., 2018). Precise Point Positioning (PPP) fully relies on the products that are introduced to the normal equation system. The quality of RT products is not constant and still evolves for new GNSS. We check the evolution of the CNES RT orbit and clock quality for the three years between 2017 and 2020 (Kazmierski et al., 2020). Additionally, SLR residuals were employed as the second independent quality indicator for tested products.

SLR validation results are shown in Figure 3, whereas the values of standard deviation and mean offsets for particular satellite blocks and types are given in Table 1. The obtained results show that RT orbits of the best quality are delivered for GLONASS and Galileo. It is hard to observe any satellite block/type dependency for GLONASS and Galileo satellites for which standard deviation equals about 25 mm. The mean offset for GLONASS K1 is almost 0 mm. This value is for only one spacecraft R09 because R26 is not supported by the RT CNES streams. The remaining GLONASS blocks have opposite shifts, which are −8 and +32 mm for M and M+, respectively. Galileo IOV and FOC satellites have very

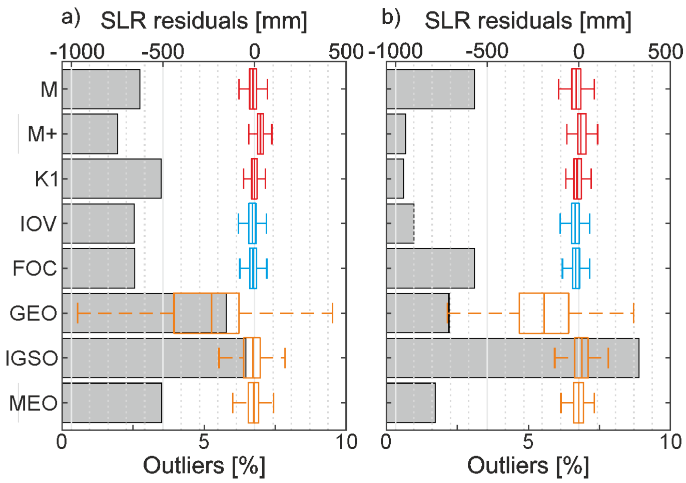

Figure 3: SLR residuals from the validation of RT orbits divided into specific GNSS blocks and types (boxplots; top) and corresponding outliers (bars; bottom); a) January 2017–November 2019, b) November 2019, after Kazmierski et al. (2020).

Table 1: SLR residuals standard deviation (STD) and mean offset for real-time CNES orbits, after Kazmierski et al. (2020).

system	GLONASS			Galileo		BeiDou		
satellite block/type	M	M+	K1	IOV	FOC	GEO	IGSO	MEO
STD [mm]	28	23	22	27	26	254	67	38
Mean offset [mm]	-8	32	-1	-13	-8	-260	-15	-6

consistent SLR residuals distribution with the offset of −10 mm. Results for BeiDou GEO residuals are an order of magnitude higher than for the other satellite types and exceed 250 mm both for standard deviation and for mean offset. BeiDou MEO and IGSO results are inferior when compared to GLONASS and Galileo with the standard deviations higher by 60 and 170%, respectively.

Figure 4 illustrates the SLR residuals for the specific GNSS as a function of the absolute height of the Sun above the orbital plane (β) and the argument of the latitude of the satellite with respect to the argument of the latitude of the Sun (Δu). SLR residuals for GLONASS and BeiDou have smaller values when the observations are collected closer to the Sun and for Galileo, residuals have opposite signs. Additionally, the pattern of increased SLR residuals for Galileo IOV is observed when the β is close to the maximum values. The dependency of SLR residuals on the argument of latitude is present for most of the RT orbit products. The analysis of the signal-in-space ranging errors (SISRE) revealed that the Galileo high-accuracy clocks are able to correct the orbital errors and thus the total SISRE is lower than the orbital SISRE. In the case of GLONASS, the total SISRE is higher than the orbital SISRE because of the clocks of inferior quality. The GPS

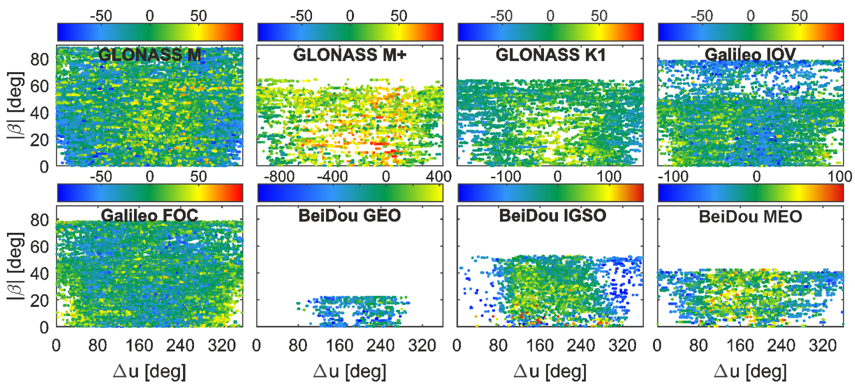

Figure 4: SLR residuals for GNSS-specific types as a function of the absolute height of the sun above the orbital plane (β) with respect to the argument of the latitude of the Sun (Δu). All values are expressed in mm, after Kazmierski et al. (2020).

and BeiDou MEO clocks neither reduce nor increase the total SISRE when compared to orbital SISRE (Kazmierski et al., 2020).

5 GNSS-based global geodetic parameters

Precise GNSS orbits need proper modeling of the impact of non-gravitational forces, especially the solar radiation pressure (SRP). Three types of orbit models are typically employed: empirical, physical, and hybrid. We propose a hybrid model that employs the a priori box-wing model for GNSS and the estimation of a small number of empirical parameters to absorb these forces that cannot be well captured by the a priori box-wing model. The model was described by Bury et al. (2019, 2020) for Galileo satellites, because the precise metadata with satellite surface properties have been released by GSA and thus allow for the establishment of precise a priori box-wing models for Galileo.

High-quality GNSS orbits are needed for the realization of geodetic terrestrial reference frames and deriving high-quality parameters, such as station coordinates, ERPs including the pole coordinates and length-of-day (LOD), GCC, and many other parameters that have a fundamental meaning in space geodesy. Zajdel et al. (2021a) studied the impact of the SRP modeling on the GCC estimates derived using GPS, GLONASS, and Galileo satellites. The addition of a priori information about the SRP-based forces acting on the satellites using a box-wing model mitigates a great majority of the spurious signals in the spectra of GCC. Despite the possible improvement in the GLONASS-based GCC-Z parameter, some significant power can still be found at periods other than annual. The GPS- and Galileo-based estimates are less affected; thus, a combination of GPS and Galileo leads to the best geocenter estimates.

Zajdel et al. (2020) derived the ERPs: pole coordinates and LOD using three GNSS constellations: GPS, GLONASS, and Galileo. The GPS-derived LOD turned out to be affected by a deep resonance 1:2 between the Earth rotation and the satellite revolution period, which caused a large secular drift of the accumulated LOD values (which correspond to UT1-UTC). Much smaller secular variations are for the GLONASS and Galileo solutions and the multi-GNSS combinations. Three types of systematic errors were identified in GNSS-based series: related to the common periods of constellation repeatability and Earth rotation (individual for each constellation), harmonics of the draconitic year, and aliasing errors with sub-daily ERP models (Zajdel et al., 2020, 2021b). Zajdel et al. (2021b) derived an empirical model of the sub-daily polar motion based on the multi-GNSS processing incorporating GPS, GLONASS, and Galileo observations. The sub-daily polar motion model is based on a 3-year multi-GNSS solution with ERPs estimated with a 2 h temporal resolution. The sub-daily estimates, which are derived from system-specific solutions, are inherently affected by artificial non-tidal signals with an amplitude up to 30 μas for GLONASS. After the recovery of the tidal coefficients for 38 tides, we infer better consistency of the GNSS-based empirical models with the new Desai–Sibois model

(Desai and Sibois, 2016) than the model recommended in the IERS 2010 Conventions (Petit and Luzum, 2010). The consistency of the combined multi-GNSS solution with the Desai–Sibois model reaches the level of 1.6, 1.2/2.1 μas for the prograde diurnal, and prograde/retrograde semi-diurnal tidal terms, respectively.

6 Determination of precise Galileo orbits using combined GNSS and SLR observations

SLR observations to GNSS satellites are typically used as an independent validation tool of the microwave-based GNSS orbits. However, the laser observations can be combined with the microwave-GNSS data to determine the GNSS orbits. Thanks to observations provided by the ILRS stations it is possible to conduct the combined SLR and GNSS orbit determination with an appropriate weighting between the two techniques, i.e., with a ratio of 1:4 for optical-SLR:microwave-GNSS data (Bury et al., 2021). Despite a relatively lower number of SLR observations to GNSS satellites as compared to the GNSS data, the addition of the laser observations diminishes the formal error of the determined orbit semi-major axis by up to 62%.

In terms of the orbit accuracy, the highest improvement is visible for the high β angle when the Sun is almost perpendicular to the orbital plane, and for the lowest β angles during the eclipsing periods (see Fig. 5). The threshold of the improvement starts for

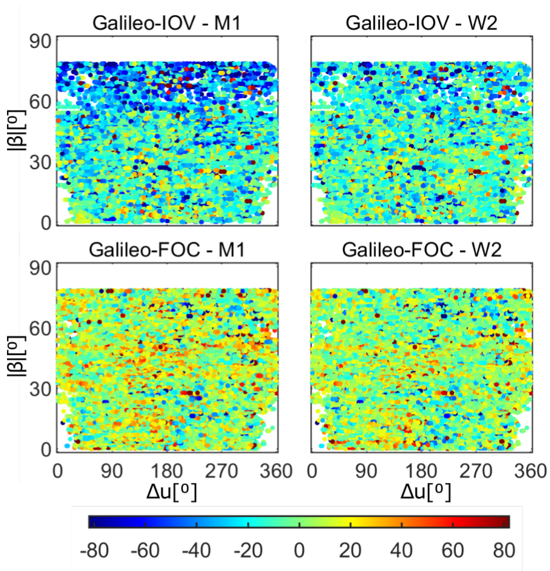

Figure 5: SLR residuals as a function of $|\beta|$ and Δu for Galileo-IOV (top) and Galileo-FOC (bottom) for the microwave (left) and combined solutions (right). All values in mm, after Bury et al. (2021)

$|\beta| > 60°$. Considering SLR residuals, the STD of SLR residuals obtained for the combined SLR+GNSS solution is at the level of 24.4 mm when compared to 26.6 mm for the GNSS-only solution. Moreover, for the combined SLR+GNSS solution for $|\beta| > 60°$, the STD of SLR residuals for Galileo-IOV is at the level of 29.6 mm when compared to 36.3 mm for microwave GNSS solution. Finally, the drift of the accumulated LoD parameter is diminished by 20% for the combined SLR+GNSS solution when compared to the microwave-only GNSS solution.

Due to a modest number of SLR observations the orbit improvement is still limited. More SLR observations of GNSS satellites would be beneficial for the identification of remaining inconsistencies and, eventually, for the full exploitation of the SLR-GNSS co-location in space (Bury et al., 2021).

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