IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2021

EDITORS
ARTURO VILLIGER
ROLF DACH

ASTRONOMICAL INSTITUTE
UNIVERSITY OF BERN

International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

Astronomical Institute, University of Bern
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Editors: A. Villiger, R. Dach
Astronomical Institute, University of Bern

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IGS Central Bureau
Jet Propulsion Laboratory, M/S 238–540
4800 Oak Grove Drive
Pasadena, CA 91109–8099, USA

E–mail: cb@igs.org
Website: http://www.igs.org

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Abstract

Applications of the Global Navigation Satellite Systems (GNSS) to Earth Sciences are numerous. The International GNSS Service (IGS), a voluntary federation of government agencies, universities and research institutions, combines GNSS resources and expertise to provide the highest–quality GNSS data, products, and services in order to support high–precision applications for GNSS–related research and engineering activities.
This *IGS Technical Report 2021* 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 2021.

This report is available in electronic version at
https://files.igs.org/pub/resource/technical_reports/2021_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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Executive Reports

IGS in 2021: the IGS Governing Board Chair Report

F. Perosanz[1], A. Craddock[2], M. I. Oyola-Merced[2]

[1] IGS Governing Board Vice Chair
Centre National d'Études Spatiales (National Centre for Space Studies)
Toulouse, France

[2] NASA Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA

1 Introduction

As it draws near its 30th Anniversary the International GNSS Service (IGS, where GNSS stands for Global Navigation Satellite Systems) continues to evolve in its mission to advocate for and provide freely and openly available high-precision GNSS data and products. 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 incorporate a new strategy to achieve multi-GNSS excellence.

As such, we continue to engage with the International Community, including the Committee on Global Navigation Systems (ICG), the International Association of Geodesy (IAG), the Global Geodetic Observing System (GGOS). Accordingly, a number of the GB members participate in IAG and GGOS governance, bureaus, commissions and Working Groups (WGs), 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.

The IGS Workshop was postponed to Summer 2022 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 2021 we developed new IGS standards to include RINEX4.0 and the new Guidelines for IGS Real Time Broadcasters and Stations, completed the third reprocessing campaign (repro3) in support of the

ITRF2020. Moreover, we developed the Tour de l'IGS: virtual workshops on relevant topics to the IGS membership, stakeholders and GNSS community in general. These events will be hosted several times a year and will cover a wide range of topics including spaceborne and ground-based instrumentation, technology development, scientific and societal applications. Additionally, we released the 2021+ IGS Strategic Plan, a forward-looking addressing the role of IGS as facilitator, incubator, coordinator, and advocate on behalf of the community started in 2020.

2 IGS Membership and Governance

2.1 Membership Growth and Internal Engagement

In 2022, 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. The GB continues under the leadership of Dr. Felix Perosanz (CNES, France). In 2021, Dr. Pat Michaels (NASA Goddard/CDDIS, USA) took over as the new Data Center Coordinator, Dr. Elisabetta D'Anastasio (GNS, New Zealand) as the new IERS representative and Dr. Salim Masoumi (Geoscience Australia) as the new Analysis Center co-Coordinator. In December 2021, Dr. Paul Ries (NASA JPL), Dr. Rui Fernandes (SEGEL/U. , Portugal) and Jianghui Geng (Wuhan University, China) were elected by the Associate Members to fill in vacant positions as Analysis, Network and Data Center Representatives respectively. Dr. Laura Sanchez (DGFI-TUM/SIRGAS) and David Stowers (NASA JPL) reached end of their GB Appointments by 31 December, 2021.

Table 1 summarizes the Governing Board Membership at the end of 2021. Blue represents members of the GB who have transitioned into a new position. Purple are new members to the GB.

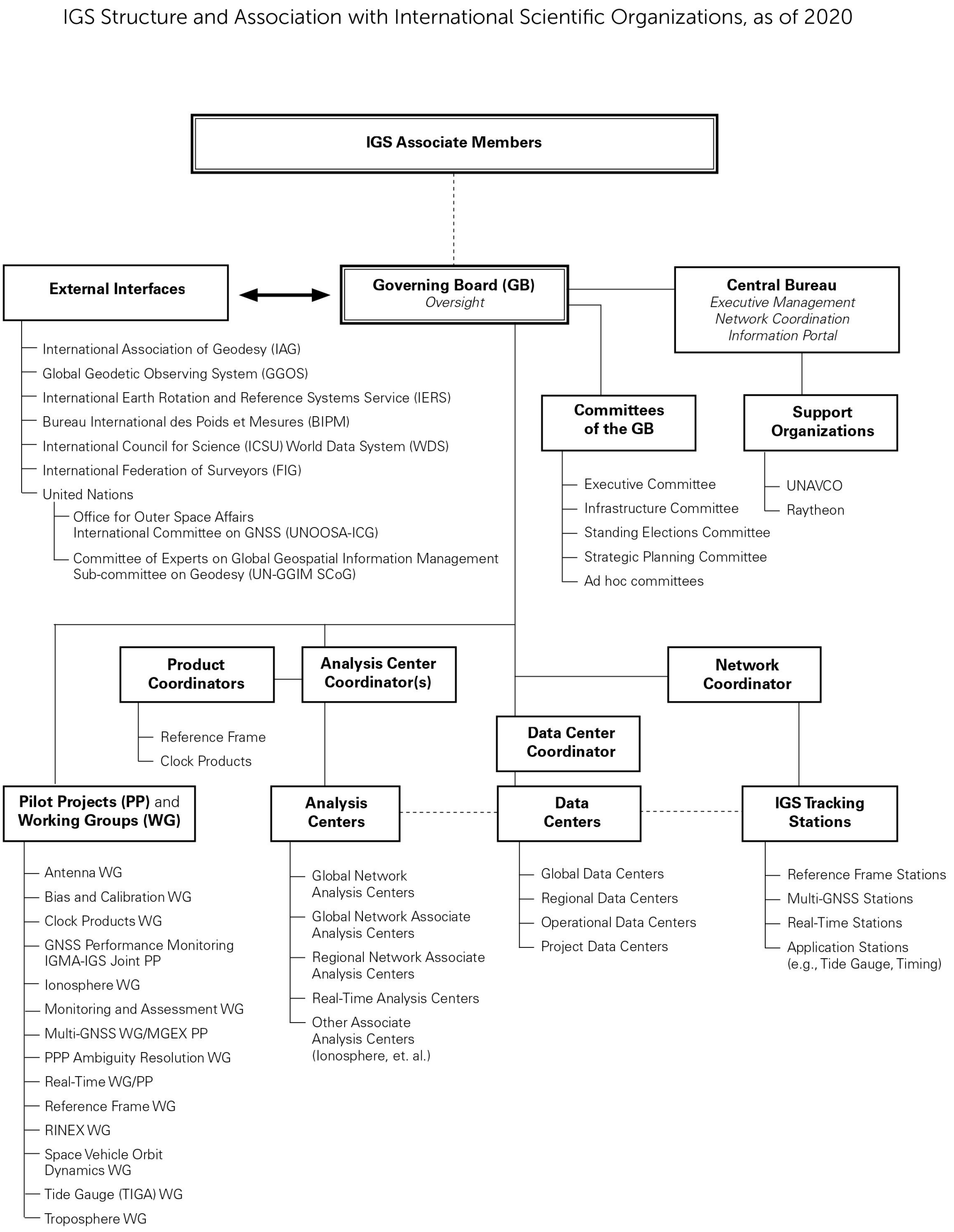

Figure 1: IGS Structure

Table 1: Members of the IGS Governing Board, 2020

Role	First Name Last Name	Affiliation	Country	V	EC
Analysis Center Coordinator	Thomas Herring	Massachusetts Institute of Technology (MIT)	USA	V	EC
Analysis Center Coordinator	Salim Masoumi	Geoscience Australia (GA)	Australia	V	
Analysis Center Representative	Benjamin Männel	Deutsches Geo-ForschungsZentrum (GFZ)	Germany	V	
Analysis Center Representative	Paul Ries	NASA Jet Propulsion Laboratory (JPL)	USA	V	
Analysis Center Representative, IERS Representative	Rolf Dach	Astronomical Institute, University of Bern (AIUB)	Switzerland	V	EC
Antenna Working Group Chair	Arturo Villiger	Astronomical Institute, University of Bern (AIUB)	Switzerland		
Appointed Member	Werner Enderle	ESA/European Space Operations Centre	Germany	V	
Appointed Member	Satoshi Kogure	National Space Policy Secretariat (NSPS), Cabinet Office	Japan	V	
Appointed Member	José Antonio Tarrío - Mosquera	Universidad of Santiago de Chile	Chile	V	
Appointed Member	Qile Zhao	Wuhan University	China	V	
Appointed Member, IERS Representative	Elisabetta D'Anastasio	GNS Science	New Zealand	V	
Bias & Calibration Working Group Chair	Stefan Schaer	Federal Office of Topography - swisstopo	Switzerland		
BIPM/CCTF Representative	Gérard Petit	Bureau International des Poids et Mesures (BIPM)	France		
Board Chair	Felix Perosanz	Centre National d'Etudes Spatiales (CNES)	France	V	EC
Board Vice Chair	VACANT VACANT	VACANT	VACANT	V	EC
Central Bureau Deputy Director & GB Executive Secretary	Mayra Oyola-Merced	NASA Jet Propulsion Laboratory (JPL)	USA		EC
Central Bureau Director	Allison Craddock	NASA Jet Propulsion Laboratory (JPL)	USA	V	EC
Clock Products Coordinator	Michael Coleman	Naval Research Laboratory (NRL)	USA	V	
Data Center Coordinator	Patrick Michael	NASA Goddard Space Flight Center (GSFC)	USA	V	
Data Center Representative	Jianghui Geng	Wuhan University	China	V	
IAG Representative	Zuheir Altamimi	Institut National de l'Information Géographique et Forestière (IGN)	France	V	
IAG Representative	Basara Miyahara	Geospatial Information Authority of Japan (GSI)	Japan	V	

Table 2: Members of the IGS Governing Board, 2020 (continued).

Role	First Name Last Name	Affiliation	Country	V	EC
IERS Representative	Richard Gross	NASA Jet Propulsion Laboratory (JPL)	USA	V	
IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair	Tim Springer	ESA/European Space Operations Center	Germany		
Infrastructure Committee Coordinator	Markus Bradke	Deutsches GeoForschungsZentrum (GFZ)	Germany	V	EC
International Federation of Surveyors (FIG) Representative	Suelynn Choy	Royal Melbourne Institute of Technology (RMIT)	Australia		
Ionosphere Working Group Chair	Andrzej Krankowski	University of Warmia and Mazury in Olsztyn	Poland		
Multi-GNSS Working Group Chair	Oliver Montenbruck	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany		
Network Coordinator	David Maggert	UNAVCO	USA		
Network Representative	Rui Fernandes	University of Beira Interior (UBI); Institute Dom Luiz (IDL); SEGAL (UBI/IDL)	Portugal	V	
Network Representative	Ryan Ruddick	Geoscience Australia (GA)	Australia	V	EC
Network Representative	Wolfgang Söhne	Federal Agency for Cartography and Geodesy (BKG)	Germany	V	
PPP-AR Working Group Chair	Simon Banville	Natural Resources Canada / Ressources naturelles Canada (NRCan)	Canada		
Real-time Analysis Coordinator	Loukis Agrotis	ESA/European Space Operations Centre	Germany	V	
Real-Time Working Group Chair	André Hauschild	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany		
Reference Frame Coordinator	Paul Rebischung	Institut National de l'Information Géographique et Forestière (IGN)	France	V	
RINEX-RTCM Working Group Chair	Ignacio Romero	ESA/European Space Operations Centre	Germany		
Satellite Vehicle Orbit Dynamics Working Group Chair	Tim Springer	ESA/European Space Operations Center	Germany		
TIGA Working Group Chair	Tilo Schöne	Deutsches GeoForschungsZentrum (GFZ)	Germany		
Troposphere Working Group, Chair	Sharyl Byram	United States Naval Observatory (USNO)	USA		

Table 4: 2021 GB Meeting

Date	Place	Comments
06 January, 2021	GB 57b Meeting Telecon	Fully dedicated to deciding Goals and Objectives for the organization Strategic Plan
07 July, 2021	GB-58 Meeting Telecon	• Approval of the final draft of the IGS Strategic Plan • Analysis Center Capacity Development • Site Log Manager 2.0 • Network Maps • IGS Working Group Pages • GNSS inter-system information/biases and CCTF recommendation • ACC Updates Multi-GNSS Real Time Memberships and Elections Working Group Sustainability and Resilience Tour de l'IGS Upcoming Events
Dec 2021	IGS 4th Open Associate Member Meeting Telecon	• Working Group Updates
Dec 2021	GB-58 Meeting Telecon	• Outcomes and items for discussion identified at the open Associate Member and Working Group meeting •IGS Policy for Geographical Description Standardizations and Usage Guidelines •RINEX 4.0 • ACC Highlights and Key Issues • Clock Products WG statement on GNSS Timescales • GDPR Implementation Policy for SLM and IGS Network • Newly published "Guidelines for IGS Real-Time Broadcasters and Stations" • Year-end elections• IGS Committee on Sustainable Working Group Governance • Analysis Center Capacity Development: Update on Japan-led Analysis Center Capacity Development Efforts • Introducing the *new* Network Station Individual Pages • Progress on Site Log Manager Refresh "SLM 2.0"• IGS Branding Toolkit and IGS Communications • IGS Community Workshop in Boulder • Tour de l'IGS update • 2022 Proposal to host 2024 IGS Community Workshop in Bern

3 IGS Governing Board Meetings in 2021

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 4, summarizes the 2021 GB meetings.

GB 57a (December 2020):

- Successful
- Decision 57a-01: The Infrastructure WG Chair position changed to the Infrastructure Coordinator with Governing Board voting privileges
- Decision 57a-02: RINEX 3.05 Format was approved by GB
- Decision 57a-03: New RINEX WG Charter was approved by GB
- Decision 57a-04: New WG Charters were approved by GB

- Decision 57a-05: Salim Masoumi approved as new co-ACC.
- Decision 57a-06: GB postponed the IGS workshop to 2022 to an in-person event
- Decision 57a-07: GB approved Elisabetta D'Anastasio as an appointed member of the GB (2021-2023) and IERS representative.
- Decision 57a-08: GB approved José Antonio Tarrío Mosquera as an appointed member of the GB (2021-2023)
- Decision 57a-09: GB elected and approves of Dr. Patrick Michael as the new DCC.

GB57b (January 2021):

- GB Approved of Goals and Objectives for the new IGS Strategic Plan as well as accompanying text

GB 58 (June 2021):

- Successful
- Decision 58-01: The 2021 IGS Strategic Plan was provisionally approved, provided CB completed the required modifications noted by the GB during the consultation period.

GB 59 (December 2021):

- Decision 59-02: The IGS GB agreed to replace the term "Country" with "Country/Region" on the IGS website, IGS site-log, RINEX 4.0 files, clock products, or any other instance in which the word "Country" is used per community request.
- Decision 59-03: GB approve of the use of three character country code, however opposed to the removal of any references to ISO-3166 (or any other International standards0 from website or documentation.
- Decision 59-04: The IGS GB approved of RINEX 4.0 for public distribution and use
- Decision 59-05: The GB approved an updated statement on GNSS Timescales redacted by M. Coleman and the Clock WG
- Decision 59-06: The GB approved the new Guidelines for IGS Real-Time Broadcasters and Stations
- Decision 59-07: The GB approved of Rui Fernandes as the new Network Representative as elected by the AM.
- Decision 59-08: The GB approved of Paul Ries as the new Analysis Center Representative as elected by the AM.
- Decision 59-09: The GB approved of Jianghui Geng as the new Data Center Representative as elected by the AM.

- Decision 59-10: The GB approved on the extension/renewals of Z. Altamimi (IAG Representative) S. Byram (Troposphere Working Group Chair) , W. Enderle (Appointed Member), T. Herring (Co-ACC), David Maggert (Network Coordinator), G. Pettit (BIPM/CCTF Representative) to the GB.
- Decision 59-11: The GB approved the Astronomical Institute of the University of Bern (AIUB) proposal to host the IGS Community Workshop in 2024.

4 IGS Operational Activities

4.1 Network Growth

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. 2) 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. With the assistance of the CB Network Coordinator and the Infrastructure Committee, the IGS CB coordinates the monitoring of station logs and RINEX metadata and evaluates new IGS station proposals on a regular basis. As a result, the IGS network added 7 new stations and identified 5 stations for decommissioning in 2021, bringing the total from 507 to 509 stations. The number of muti-GNSS stations increased from 326 to 353, while the number of real-time stations increased from 259 to 292. Additionally, 25 changes to the rcvr_ant.tab files were implemented with collaboration of the Antenna WG. At the end of the year, support for the SLM included 662 site log updates (60 per month) and 9 antenna changes (2 of them at IGS14 core stations).

The CB real time caster has been manned by the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado since January 2021. The CB Network Coordinator also responded to over 130 inquiries about data, products, or general IGS information. Currently, the IGS is encouraging station operators to use generic agency contacts instead of person specific contact information for EU GDPR compliance as well as providing multi-GNSS data with RINEX3.

4.2 Product Generation and Performance

At the end of 2020, Salim Masoumi of Geoscience Australia, succeeded Michael Moore as the IGS Co-ACC. Joint management of the IGS ACC by Salim Masoumi and Tom Herring of the Massachusetts Institute of Technology (MIT) 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

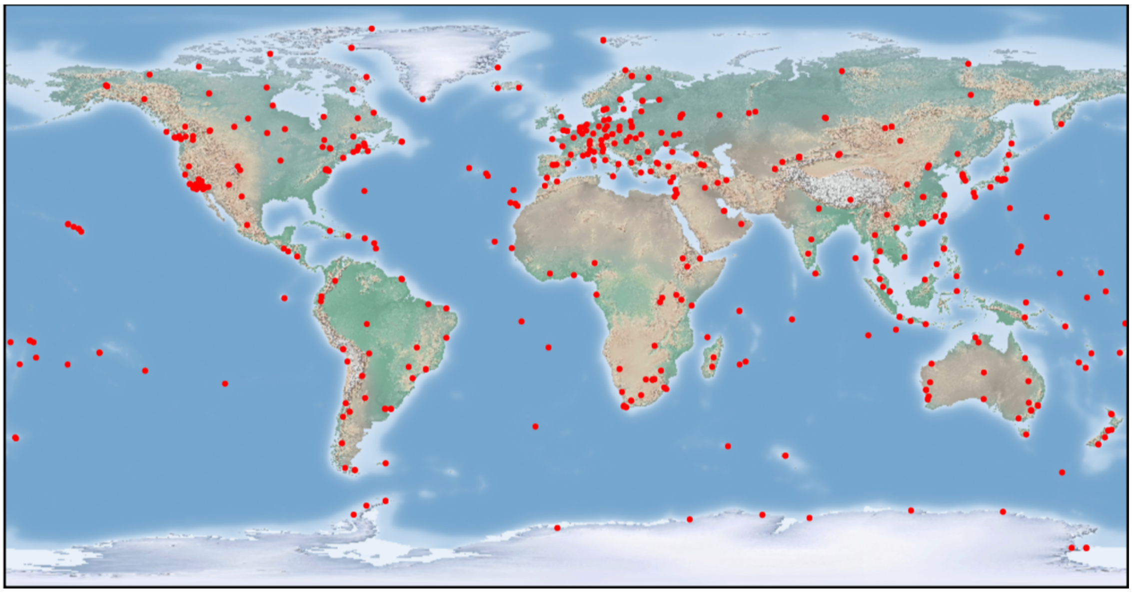

Figure 2: The 509 IGS stations as of January 31, 2021. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

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.

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 were released by the extended IERS deadline (10 April 2021). At this point, 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:

Table 6: 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	2013-12-21
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

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 full 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

5 IGS Strategic Plan

The 2021+ Strategic plan was developed by the IGS Governing Board with the help and support of the Central Bureau, and guided by extensive community feedback and discussions. It presents a forward-looking strategy addressing the role of IGS as facilitator, incubator, coordinator, and advocate working towards three major goals in service to our community and beyond. The plan focuses on how the IGS maintains and enhances its leadership role within the broader GNSS community, as societal demands for GNSS products and services continues to grow. Central to the goals and objectives are the complementary roles of the IGS as a collaborative research program, as well as an operational service. The plan seeks to maintain appropriate balance of the two roles to ensure ongoing support from associate members and collaborating organizations.

The IGS 2021+ Strategic Plan has been balanced to address both internal and external factors driving IGS organizational growth towards multi-GNSS technical excellence. By setting our first goal to "achieve multi-GNSS technical excellence" we strive to increase organizational capability by identifying barriers to multi-GNSS success throughout the IGS, supporting solutions to key challenges, and reinforcing the importance of continuous technical evolution. Our second goal is to "strengthen outreach and engagement." Objectives of this goal will guide advocacy for open access geodetic and GNSS data and products that facilitate collaborations, standardization, and inclusivity. Looking forward, implementation of this plan will include our third goal of ensuring sustainable and resilient contributions to the IGS community and its work, as it is the diversity of contributors to the IGS as well as their high levels of commitment that have ensured the high level of performance and reliability of product generation and delivery thus far.

The plan continues in the spirit of previous strategic plans in that it is intended to guide our service to the community, and is not intended to be restrictive. It is our hope that the guidance in this plan will ensure the best possible IGS for the ever-growing community of users relying upon its openly available high-quality GNSS data and products. To view and download the 2021+ Strategic Plan, go to the IGS 2021+ Strategic Plan page on igs.org.

6 Tour de l'IGS

The Tour de l'IGS is a series of virtual workshops on relevant topics to the IGS membership, stakeholders and GNSS community in general. These events (dubbed as "Tour Stops") started during 2021 with the intention to compensate for the delay in the IGS Workshop due to the restrictions imposed by COVID-19. The current intention is to continue to host these events several times a year covering a wide range of topics including space-borne and ground-based instrumentation, technology development, scientific and societal applications. At the moment of this writing two virtual workshops have taken place. The topics covered IGS reprocessing activities (1ST Stop), IGS Infrastructure (2nd Stop) with the third "Stop" dedicated to GNSS Processing to be held in February 2022. For more information on these events and/or to access the recorded presentations, please visit: https://igs.org/tour-de-ligs.

7 IGS Workshop

The IGS Workshop (originally scheduled for 2020) was delayed on multiple occasions given the travel restrictions imposed by the novel coronavirus. Despite attempts to host an in person workshop in 2022, the IGS had to move the event to a fully virtual format due to circumstances beyond our control. However, this change of circumstances helped the Service to refocus the IGS Workshop back to being just a community workshop taking place in June 2022. The workshop will take place on a compressed schedule to try to be inclusive to as many time zones as possible, and with a condensed program to aspects that are the most critical to the function of our Service. The emphasis will be on bringing our community together to discuss key issues and brainstorm the next steps toward a multi-GNSS IGS in service to our global community.

8 Communications Development and Guidance

During 2021, the Service launched Constellations: The Newsletter of the International GNSS Service. At the moment of this writing two issues had been completed with a third one under production. The newsletter will be published on a quarterly basis. This format will allow the IGS to approach relevant news and other interesting articles pertaining to our community members. The first issue included a "behind-the-scenes" the Service's oldest (BAKO) and newest (CYNE) IGS Stations, thoughts from the Governing Board Chair, a feature of the new Infrastructure Committee Coordinator, highlights on recent publications, and an overview of upcoming events. The second issue featured was dedicated to the newly released IGS Strategic Plan and its components, feature our newest Governing Board Members, Elisabetta D'Anastasio and José Antonio Tarrío Mosquera.

Besides the Newsletter, 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/ and https://twitter.com/IGSorg/.

9 IGS Advocacy and External Engagement

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

9.2 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).

9.3 International Association of Geodesy

9.3.1 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).

10 Outlook 2022 and beyond:

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 2021

A. Craddock, M. Oyola, A. Santiago and R. Khachikyan

NASA Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA

1 Introduction

The International GNSS Service (IGS, where GNSS stands for Global Navigation Satellite Systems) is the world's largest GNSS organization, with an over twenty-five years of history of advocating for and providing freely and openly available high precision GNSS data and products.

As of early 2021, the IGS consists of over 300 Associate Members (AM), representing over 45 countries/regions and over 200 contributing organizations. The 36-member IGS Governing Board (GB) guides the coordination of over 142 contributing organizations participating within the IGS, including 108 operators of GNSS network tracking stations, 6 global Data Centers, 13 Analysis Centers, and 4 product coordinators, 21 Associate Analysis Centers, 23 regional/ project Data Centers, 14 technical Working Groups and two active pilot projects (i.e., Multi-GNSS and Real-time). It is the Central Bureau's (CB), responsibility to act as the linchpin that holds all of the components of the IGS together by providing continuous management and technology in order to sustain the multifaceted efforts of the IGS in perpetuity. The CB supports the IGS strategic goals of achieving multi-GNSS technical excellence, strengthening outreach and engagement, and building sustainability and resilience by functioning as the executive office of the Service, responding to the directives and decisions of the IGS GB and also representing the outward face of IGS to a diverse global user community, as well as the general public.

The IGS CB is funded by the US National Aeronautics and Space Administration (NASA) and hosted at the Jet Propulsion Laboratory in Pasadena, California, USA. This office is led by Director, Ms. Allison Craddock and Deputy Director, Dr. 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, USA). Additionally, the CB manages the primary IGS information system (CBIS), the principal information portal where the IGS web, data and mail services are

Table 1: Central Bureau Staff (as of January, 2022)

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 User Interface Specialist
David Stowers	NASA Jet Propulsion Laboratory	CBIS Advisor

hosted. These tasks are led by Mr. Robert Khachikyan and Ms. Ashley Santiago (both Raytheon, USA).

2 Summary of Accomplishments during the COVID-19 Pandemic

The following report highlights progress made by the IGS CB in 2021.

The global IGS community continues to face the impacts of COVID-19, particularly with the newly introduced changes in work environment and travel limitations. The IGS CB has continued to hold 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 CBIS, 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 and with limited on-lab access. Despite the constraints and restrictions, the CB has achieved the following:

1. Supported data and products timely delivery and maintained the IGS stations operations with no interruptions
2. Initiated upgrades to the current Site-log Manager (SLM)
3. Completed and released the new IGS 2021 Strategic Plan
4. Oversaw the development of the Committee of Working Group Sustainability
5. Successfully planned and conducted 3 around-the-world clock virtual Governing Board Meetings
6. Successfully planned and executed the year-end virtual open Associate Member Meeting with 150+ participants
7. Supported the 2022 IGS Associate Member elections
8. Developed a new IGS Branding and Branding Toolkit available to all Governing

Board Members

9. Released the first and second issues of Constellations: an IGS Newsletter
10. Supported repro3 related activities
11. Continued support of website and updates to include improvements to the network maps, user interfaces and Working Group pages
12. Submitted the IAG Travaux Report on behalf of the Service
13. Continued to support the development of IGS compliance with the European Union General Data Protection Regulation (EU GDPR)
14. Organized the Tour de l'IGS, a series of virtual mini-workshops on relevant topics to the IGS membership, stakeholders and GNSS community in general and hosted two of these events
15. Organized and executed monthly Executive Committee (EC) meetings
16. Led the recent update of Working Group Charters and Contributing Organizations
17. Supported the dissemination of newly developed IGS Products to include RINEX4.0, new Guidelines for IGS Real Time Broadcasters and Stations, etc.
18. Introduced new social media and communication pieces to include: Quarterly Highlighted Publications, Station Operator Highlights, and celebrations of relevant international days and weeks currently observed by the United Nations.
19. Continued 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 System (WDS), 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.

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 January, July and December 2021. The EC met additionally 5 times by teleconference. The CB also hosted two virtual workshops (Tour de l'IGS), two Standing Election Committee meetings and two Committee of Sustainability and Working Group Governance meetings. Staff of the CB, as part of its work program carrying out the business needs of the IGS, implemented actions defined by the

Table 2: CB led and/or coordinated virtual meetings during 2021.

Date	Place	Comments
06 January, 2021 1800–1900 UTC	GB 57b Meeting	Telecon Fully dedicated to deciding Goals and Objectives for the organization Strategic Plan
17 February, 202 20:00-21:00 UTC	EC -Telecon	The ex-officio role of the ACC on the IGS Executive Committee and ACC succession · Potential new members to fill EC vacancies · An update on the Real-Time concerns/issues · New 2022 Workshop dates 57a/b and 58 Governing Board Meetings · Repro 3 Status · IGS Communications · Website latest update
15 April, 2020 11:00-12:30 UTC	EC-Telecon	Update on the Real-Time concerns/issues · Repro3 activities status · WG Sustainability - Chair/Vice-Chair Position Renewals and Recruitment · Next GB Meeting · Post-COVID travel, conference representation/Sessions (AGU and beyond) · Tech Report Status, Future of Tech Report request · Central Bureau Reporting
02 June, 2021 1100–1300 UTC	Tour de l'IGS: First Stop	Mini workshop with nearly 300 participants on repro3
22 June, 2020 1900–2000 UTC	EC-Telecon	Strategic Plan · Associate Member application and approval process · GB-58 (July) Meeting Agenda approval and review · Reflections on the first Stop on Le Tour de l'IGS · Communications Update
29 June, 2021 0600–0700 UTC	Standing Election Committee Meeting	2021 Associate Member Election
07 July, 2021 2000–2230 UTC	GB-58 Meeting Telecon	Approval of the final draft of the IGS Strategic Plan · Analysis Center Capacity Development · Site Log Manager 2.0 · Network Maps · IGS Working Group Pages · GNSS inter-system information/biases and CCTF recommendation · ACC Updates Multi-GNSS Real Time Memberships and Elections Working Group Sustainability and Resilience Tour de l'IGS Upcoming Events
11 August, 2021 2000–2100 UTC	First Meeting of the Committee of Sustainability and Working Group Governance (CSWG2)	Close door meeting
01 September, 2021 2000–2100 UTC	Tour de l'IGS: Second Stop	Dedicated to IGS Infrastructure. Nearly 200 people participated virtually
07 October, 2021 0400–0500 UTC	Standing Election Committee Meeting Telecon	2021 Associate Member Election

Table 2: CB led and/or coordinated virtual meetings during 2021 (continued).

Date	Place	Comments
12 October, 2021 0400–0500 UTC	EC-Telecon	· GB December Agenda · Strategic Plan Implementation · Working Group Engagement · Elections Update · RTWG/IC Guidelines · Creative Commons Licensing
03 Nov, 2021 2100–2300 UTC	Second Meeting of the Committee of Sustainability and Working Group Governance (CSWG2)	Close door meeting
09 Nov, 2021 2100–2300 UTC	EC-Telecon	· ISO Name Policy issues · SEC Outcomes and Elections · Analysis Center Capacity Development Project · Tour de l'IGS Stop Proposal, Capacity Development and community outreach theme · Reviving preparations for IGS Boulder Workshop
Dec 2021 1900–2000 UTC	IGS 4th Open Associate Member Meeting Telecon	· Working Group Updates

GB throughout the year. A list of these activities is included in Table 2.

4 Network Coordination and User Community Support

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. With the assistance of the CB Network Coordinator and the Infrastructure Committee, the IGS CB coordinates the monitoring of station logs and RINEX metadata and evaluates new IGS station proposals on a regular basis. As a result, the IGS network added 7 new stations and identified 5 stations for decommissioning in 2021, bringing the total from 507 to 509 stations. The number of muti-GNSS stations increased from 326 to 353, while the number of real-time stations increased from 259 to 292. Additionally, 25 changes to the rcvr_ant.tab files were implemented with collaboration of the Antenna WG. At the end of the year, support for the SLM included 662 site log updates (60 per month) and 9 antenna changes (2 of them at IGS14 core stations).

The CB real time caster has been manned by the University Corporation for Atmospheric

Research (UCAR) in Boulder, Colorado since January 2021. The CB Network Coordinator also responded to over 130 inquiries about data, products, or general IGS information. Currently, the IGS is encouraging station operators to use generic agency contacts instead of person specific contact information for EU GDPR compliance as well as providing multi-GNSS data with RINEX3.

For additional statistics and information about the IGS Network, please refer to the Infrastructure and Governing Board chapters of this report.

5 New IGS Website and http services

Following the launch of the new IGS website in December in 2020 and the transition from ftp to https services, the CB has been able to better monitor website traffic and engagement through Google Analytics. A total of 87,199 users visited igs.org and 53,574 visited files.igs.org. Most users were desktop users and visited the website between 08:00-16:00 UTC Monday through Friday. About half of the users arrived to the website via organic search engines. Additionally, social media referral doubled when compared with previous years. Table 3 summarizes the most visited pages and where the visits were coming from:

With the recent upgrade to RINEX 3, many stations were missing RINEX3 streams' latest

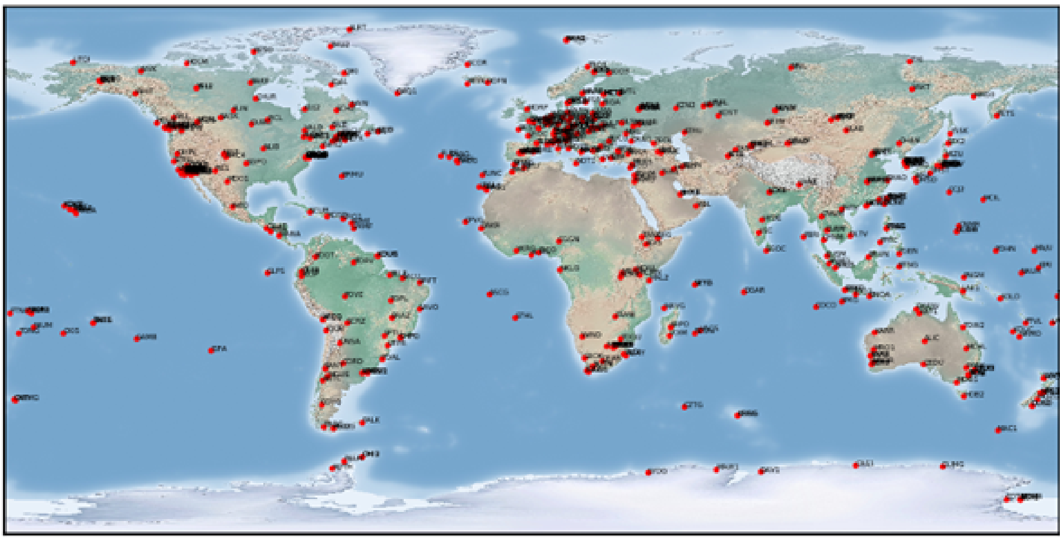

Figure 1: The 509 IGS stations as of January 31, 2021. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

Table 3: Summary of the most visited pages and where the visits were coming from.

Top 10 Pages Visited	Top Countries/Regions Visitors
1. Home	1. China
2. Network	2. United States
3. Products	3. India
4. Data	4. Turkey
5. Access to Products	5. Russia
6. Data Access	6. Germany
7. Formats and Standards	7. Brazil
8. Network	8. France
9. MGEX Data + Products	9. Japan
10. RINEX	10. United Kingdom

data on the IGS network page. The IGS CB refreshed these station pages to include this additional data for each station as well as position time series data and data from multiple constellations. The layout was also reorganized and consolidated to make it easier to see station information and data graphs.

The website has been useful in supporting IGS virtual events, to include the entire series of the Tour de l'IGS (`https://igs.org/tour-de-ligs/`). Besides supporting the advertisement and pre-event registration, the page also serves as an online catalogue of recorded presentations and other resources to the community after an event has been completed (`https://igs.org/tour-de-ligs-presentations`). Similarly, the meeting agendas and presentations for the IGS 4th Annual Associate Members and Open Working Group Meeting were made available on a dedicated Associate Members meeting page (`https://igs.org/am-meetings/`).

6 Site-log Manager

The IGS Site Log Manager (SLM, referred to as SLM 1.0) currently still in use by IGS ground station operators, has become increasingly outdated in both its software and design, functioning on a series of patches since its initial development. Considering the vital

Figure 2: Tour de l'IGS landing page on igs.org.

role that the SLM holds for the IGS in regards to the global GNSS community, the need to develop an updated metadata management system to replace the current SLM has arisen.

The SLM 2.0 will bring the system back to its core functionality while providing a base for future improvements. An eventual desired feature is related to the adoption of a standardized encoding language for site log data, known as GeodesyML. The incorporation of this tool will play a vital role in increasing the efficiency of geodetic metadata management as it allows for synchronization across multiple regional systems.

The start of the project involved in depth research into the SLM 1.0 and other site log management systems such as Metadata Management and distribution system for Multiple GNSS Networks (Royal Observatory of Belgium) and GNSS Site Manager (Geoscience Australia). The Central Bureau identified current functionality issues as a result of the PHP upgrade and identified possible solutions from other systems. To gain additional feedback from the IGS Community, the Central Bureau conducted several interviews with station operators to learn about their experience using the SLM 1.0 and what they feel can be improved. Additionally, different types of frameworks and coding languages were looked into to ensure the new version is using the latest, secure technology.

After research on SLM 1.0's user experience and possible new frameworks, the Central Bureau began the SLM 2.0 beta development. The decision was to use a new coding language, Python, and a python-based web framework called Django. Using the initial Django framework files, login functionalities were developed and the system was connected with the previous SLM database to create placeholder SLM metadata forms. On the front-end, wireframes were designed to give an early static visual of the new SLM layout. This helped in the development of front-end templates, starting with the login, home, and station section edit forms.

It is expected that the SLM 2.0 will be unveiled at the 2022 IGS Community Workshop.

7 2022 Strategic Planning

Figure 3: IGS 2021+ Strategic Plan Goals.

This Strategic Plan, built upon the feedback of many IGS community members, outlines key points of the IGS goals and the anticipated path to meet its objectives within the next decade and its strives to serving the community with facilitation, coordination, incubation, and advocacy in three strategic goals: The strategic plan, covering the period 2021 and beyond, was created over a two-year period. The following activities took place in an over-arching and multi-modal community engagement and plan development process:

- Convening a Strategic Planning Task Force working session to co-plan and oversee the planning process
- Series of dedicated Central Bureau working sessions
- Open meetings at various conferences with Associate Members and stakeholders
- Facilitated dedicated workshop with Governing Board Members to address key issues faced by the IGS, the GNSS community, the membership, and considered history, current
- vironment, and future opportunities in developing the future direction
- Research, analysis, and updating of our understanding of economic, social, and cultural external environmental changes
- Creation of a Vision 2021+ document to serve as a launching pad
- Development of an environmental scan and analysis of strengths, weaknesses, opportunities, and threats
- Online membership survey with nearly 100 completed surveys

- Review of internal organizational documents, including the 2017 Strategic Plan, organizational structure information, conference materials, and other organizational materials
- Development of a framework of organizational goals, strategies, and recommendations
- Preparation of an implementation plan for the strategic plan
- Board review, approval, and adoption of the full strategic plan

For information on the strategic plan contents including strategic goals, objectives and future implementation, please visit the Governing Board Chapter of this document or access the 2021+ Strategic Plan.

8 Tour de l'IGS and IGS Community Workshop 2022

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 has been delayed multiple times, with the Local Organizing Committee (LOC) and CB identifying a date and confirmed the availability of the UCAR Center Green Conference Facility and NCAR MESA Lab, in Boulder Colorado (United States) for a 26 June-01 July 2022 Workshop. For more information on the 2022 and the preparations for the 2024 Workshops, please refer to the GB Chapter of this Report.

The IGS CB introduced a series of virtual technical mini-workshops dubbed as "Tour de l'IGS" focused on topics of interest to the IGS membership, stakeholders and GNSS community in general. While initially, these events were organized in order to alleviate the impact of the 2020 Community Workshop delay, the GB and CB concluded that it will be a good practice to host these events several times a year. Each individual event within the Tour de l'IGS series is dubbed as a "Stop", each one of them covering a wide range of topics including space-borne and ground-based instrumentation, technology development, scientific and societal applications.

The first "Stop" was a session fully dedicated to discuss the process and initial results of the IGS Third Reprocessing Campaign (Repro3), which supports the development of the International Reference Frame 2020. It was held on 02 June, 2021.

The Second Tour de l'IGS is focused on IGS Infrastructure. This includes topics related to network stations and their configurations (instrumentation, monumentation, communications, etc), data flow, and other considerations involved in the collection and distribution of GNSS observational data and information. The Second stop was held on 01 September, 2021.

At the end of 2021, a third stop had already been organized for February 2022 with the intention of providing GNSS users (even without a geodetic background) an overview on the value by applying IGS products for their activities. This "Stop" is co-hosted by the University of Bern.

9 Standing Election Committee

Elections for the Governing Board positions of Analysis Center, Data Center and Network Representatives, took place in December 2021. 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.

10 Communications and Coordination

During 2021, the CB has worked to implement a new communication plan bridging the gap between Working Groups, Associate Members and the community in general in order to introduce a better and more diversified portfolio. Besides increasing direct interaction with the community via the "Tour de l'IGS", enhanced social network interactions, a regular circulation of our new quarterly newsletter (Constellations), enhancing our transdisciplinary collaborations, 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 (UNDRR) and UN Sustainable Development Goals (via contributions to the UNDRR Global Assessment Report -see Oyola et al. 2022). Additionally, the CB will engage in an implantation strategy for the 2021 Strategic Plan.

Social media has been regularly maintained by CB staff and continued to grow in followers in 2021, 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 2022. IGS Social Media accounts and follower statistics are as follows:

- Slack (For GB use)
- Twitter (2000 followers): https://twitter.com/igsorg
- LinkedIn Page (920 followes): https://www.linkedin.com/company/igsorg/

- YouTube (221 subscribers, 8121 views):http://www.youtube.com/igsorg

11 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.

12 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 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 (M. Oyola) represents the IGS in the new IAG Inter-Commission Committee on Geodesy for Climate Research (ICCC), as both IGS and GGOS representative and as member of the Scientific Committee of the International Science Council of the World Data System. 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), who retired from his role representing the IAG at PNT Advisory Board meetings at the end of 2021. 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.

13 Publications

- IGS 2020 Technical Report, IGS Chapter
- Oyola et al. 2022: Transdisciplinary Application of Global Navigation Satellite System Radio Occultation (GNSS-RO) to Characterize Atmospheric Hazards and Model Systemic Risk, in production.

14 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

15 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 2021

S. Masoumi[1], T. Herring[2]

[1] Geoscience Australia, Canberra, ACT, Australia
E-mail: salim.masoumi@ga.gov.au

[2] Massachusetts Institute of Technology, Cambridge, MA, USA

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 ACC also has the overall responsibility for coordinating the changes, developments and improvements within the contributing analysis centers to produce the IGS products using the latest models and standards. The IGS products continue to perform at a consistent level, and in general the solutions submitted by the analysis centers maintain a consistent level of performing.

In 2021, the developments required for multi-GNSS combination of the products and the processing of the data related to the third IGS reprocessing effort (Repro3) continued. The multi-GNSS combination of the orbits from the contributing analysis centers were completed by the new multi-GNSS combination software developed by the ACC at Geoscience Australia. The multi-GNSS bias and clock combinations of the IGS Repro3 are also being performed by Wuhan University, with the combinations expected to be completed in 2022. A full suite of the IGS Repro3 orbit, bias and clock products as well as results of PPP solutions using the Repro3 products is going to be publicly released in 2022. Also in 2022, the new orbit and clock software used for the Repro3 will be integrated into a new multi-GNSS combination platform to be used for combining the operational products of the IGS.

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.

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 (NRCan)	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

2 Product Quality and Reliability

In 2021, with a few exceptions, the delivery of the ultra-rapid, rapid and final products were well within the expected latencies. There were a few occasions where rapid and/or ultra-rapid products were delivered with a few hours delay. One occasion happened due to an overflow of the processing server most likely as a result of the occurrence of a runaway process, which needed a reboot of the server to resolve. Two other occasions occurred due to issues in the retrieval of data from the global data centers to the combination server, and were resolved by manual interventions.

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 2021, the IGS was receiving 7 submissions from different ACs for combined IGS ultra-rapid products (see Table 2 for a list of ACs that are currently weighted in the solutions). The combined IGS ultra-rapid orbit can be split into two

Table 2: ACs contributing to the IGS 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. The clock products are only a combination of broadcast clocks.

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

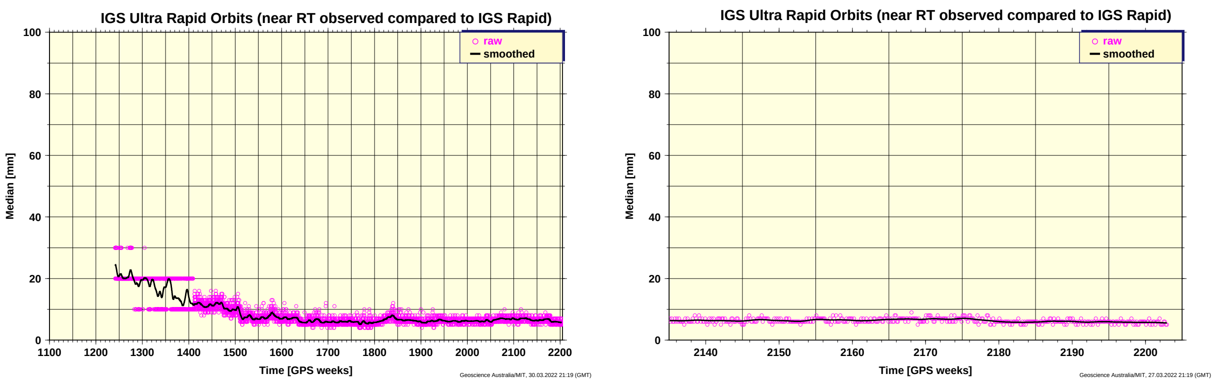

Figure 1: The median difference of the fitted component of the IGS ultra-rapid (IGU) combined orbits with respect to the IGS rapid (IGR) orbits. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

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 a median 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 compared to the IGS rapid orbits (see Figure 2) hovering around a median of 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 IGS rapid products (see Table 3). The rapid orbit products from the different analysis centers weighted in the

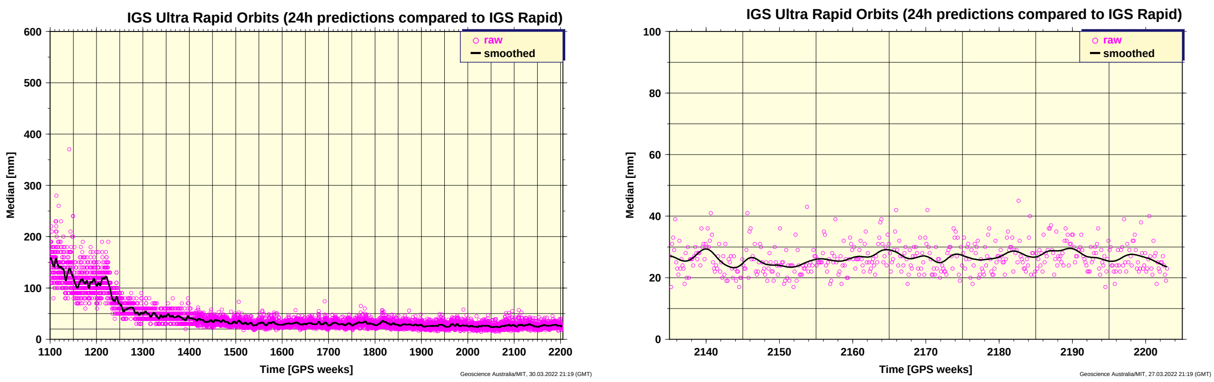

Figure 2: Median of IGU combined predicted orbits compared to IGR. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

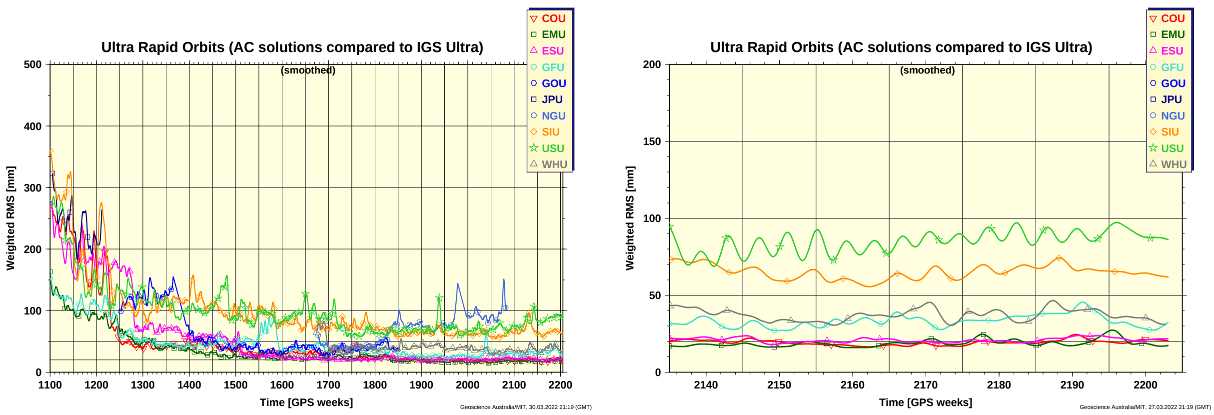

Figure 3: Weighted RMS of AC Ultra-rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

Table 3: ACs contributing to the IGS Rapid products, *W* signifies a weighted contribution, *C* is comparison only. The USN ERP solutions are not weighted in the combination, with the exception of the length of day estimate, which is weighted. Wuhan clocks have been weighted in the rapid clock combinations since 26 January 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	W

combination remained at a consistency level of up to 15 mm (Figure 4), and the difference between the combined IGS rapid orbits and the combined IGS final orbits was consistently below 5 mm (see Figure 6). The standard deviation of the rapid satellite and station clock solutions remained below 20 ps for the weighted centers (Figure 5). In early 2022, The clock RMS values were poorly performing for most of the analysis centers from GPS week 2194 to GPS week 2198. The reason for this increased RMS was identified to be a sudden switch in the GPS satellite PRN 22 allocation from SVN 47, which was decommissioned on 18 January, to SVN 41, which resumed transmitting L-band on 20 January. This switch in PRN was reflected as a new PRN 72 (22+50) in the CODE monthly differential code bias (DCB) files. The centers relying on CODE DCB and not accounting for this change were using the wrong P1-C1 bias for the SVN 41 until the old PRN22 fell out of the 30-day window. This wrong P1-C1 bias information showed up in the clock solutions as high RMS; however, the standard deviations were not impacted, and the PPP solutions relying on the IGS clocks were not impacted. Using the new BIAS SINEX format (Schaer, 2016) in the GNSS processing helps avoid such confusions with PRN allocations.

2.3 Final

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

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 7). GFZ clocks suffered from high RMS with respect to the combined clocks between the GPS weeks 2160 and 2162, which resulted in the GFZ clocks being excluded from the final solutions during this period. This issue was resolved starting from GPS

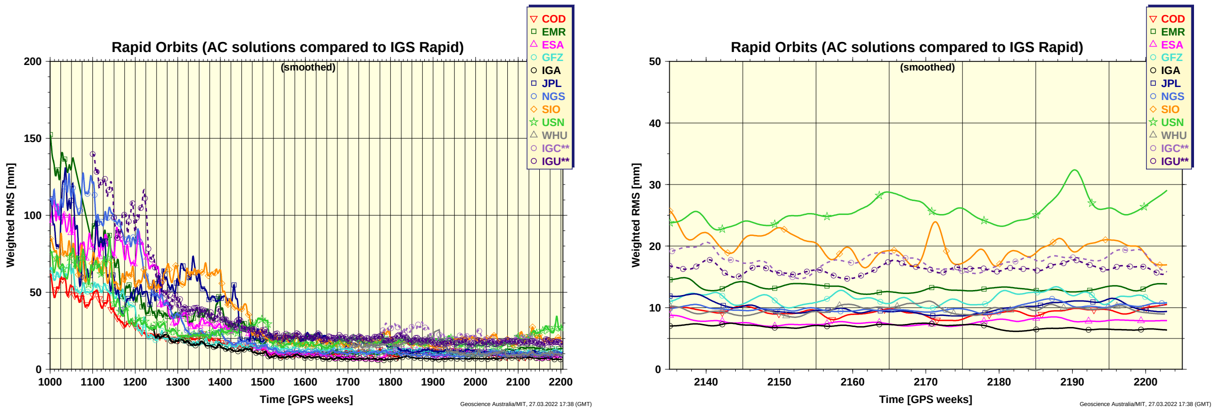

Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time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

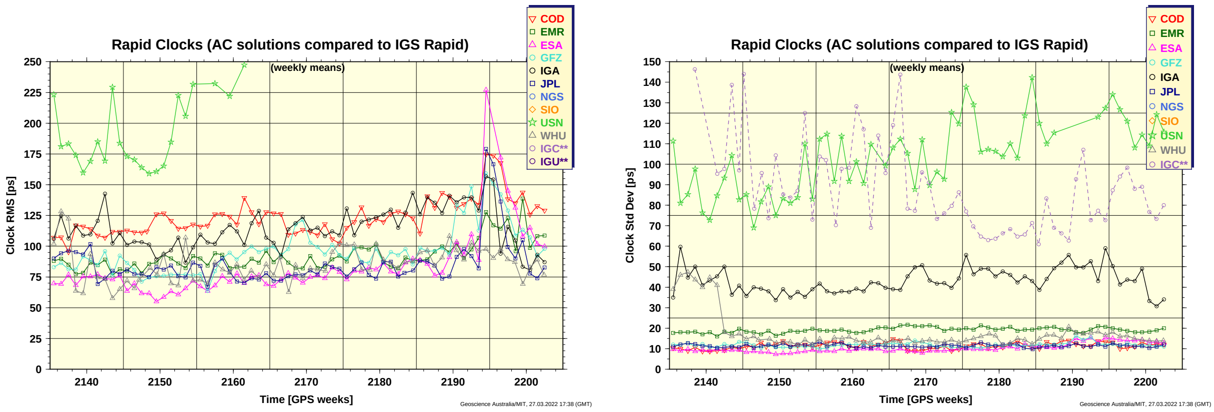

Figure 5: Weighted RMS (left) and standard deviation (right) of ACs Rapid clock submissions (smoothed). IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time stream. IGU** consists of four separate comparisons to IGR done each day over the first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

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 2160 to GPS week 2162.

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

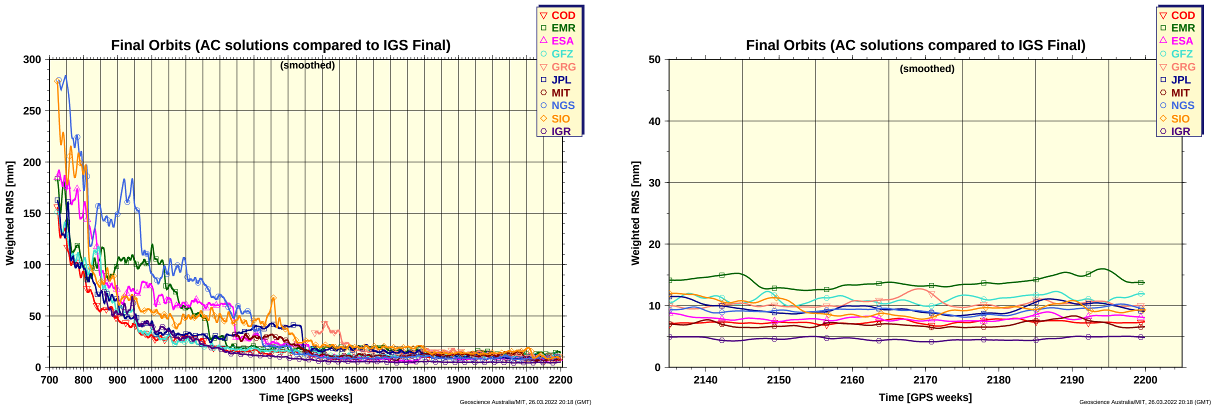

Figure 6: Weighted RMS of IGS Final orbits (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

week 2163, and hence their clock solutions were included back in the final combinations.

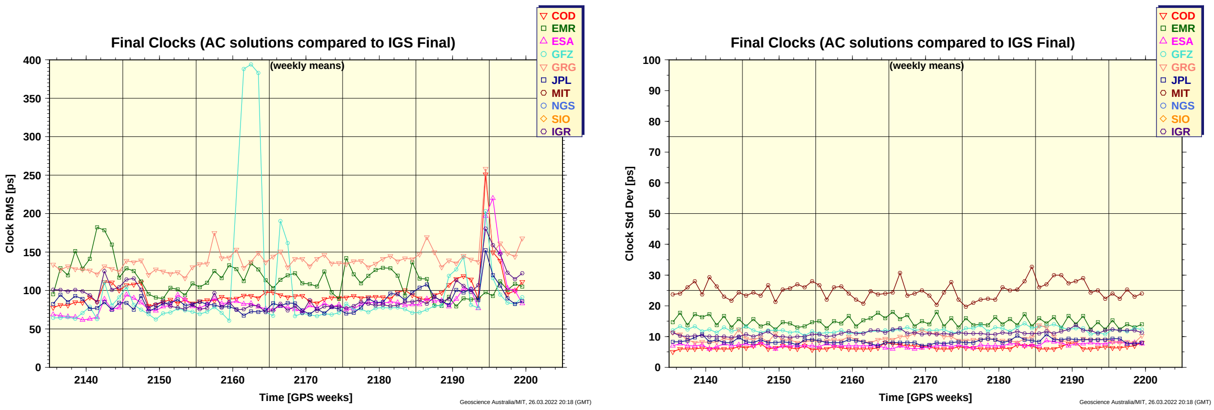

Figure 7: Weighted RMS (left) and standard deviation (right) of IGS Final clocks (smoothed)

The final clocks also suffered from the high RMS between GPS weeks 2194 and 2198 resulting from the same PRN switch issue as the rapid clocks (Section 2.2), which was resolved after GPS week 2198 and did not impact the clock standard deviations.

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 are then combined and submitted as the IGS contribution to the next version of the International Terrestrial Reference Frame, ITRF2020.

In total, eleven analysis centers submitted solutions to be included in the Repro3. These analysis centers and their submitted solutions are listed in Table 5. The combination of the Repro3 orbits using the newly developed version of the orbit combination software was completed in 2021. 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 RMS errors of the different analysis center orbit solutions with respect to the IGS combined Repro3 solutions for the whole period 1994 to 2020 are displayed in Figure 8. The RMS related to the GPS satellites is at levels of around 10 mm for all the analysis centers since around 2014, which is similar to the RMS levels of IGS final orbits (Figure 6). The comparison of the GPS orbits from the multi-GNSS combination to the GPS-only orbits from the legacy software shows a consistent RMS of around 1 mm since about 2004 (with a median of 1.4 mm for the whole period). The RMS for GLONASS is between 20 and 40 mm for different analysis centers after 2012, while the RMS for GALILEO orbits is between 10 and 20 mm for most of the analysis center solutions after 2017. This shows promising consistencies for GALILEO orbits.

Combination of phase bias and clock products from the Repro3 campaign is being performed by the group at Wuhan University, and is expected to be completed in 2022. These new multi-GNSS bias and clock combinations are based on Banville et al. (2020), and allow for precise point positioning solutions with ambiguity resolutions (PPP-AR). In addition, PPP soutions are being performed at the Natural Resources Canada (NRCan) using the Repro3 products to validate the products. Also, Graz University of Technology contributed to the project by performing the calculations of the reference satellite attitudes, which are used for the clock combinations.

The full suite of the IGS Repro3 orbit, bias and clock products, as well as PPP results,

Table 5: ACs contributing to the Repro3 campaign. In addition to the time periods in the table, analysis centers are in the process of producing Repro3 products for 2021 and 2022 until the date the switch to ITRF2020 and Repro3-standard products occurs.

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	2000-2020	✓						
WHU	GPS GLONASS	2008-2020 2010-2020	✓	✓	✓	✓		✓	✓

for the whole period since 1994 will be publicly released in 2022. Also in 2022, the IGS ACC plans to transition the IGS products to the next reference frame ITRF2020, as well as to the Repro3 standards and models. Furthermore, the new multi-GNSS products are planned to become operational in 2022.

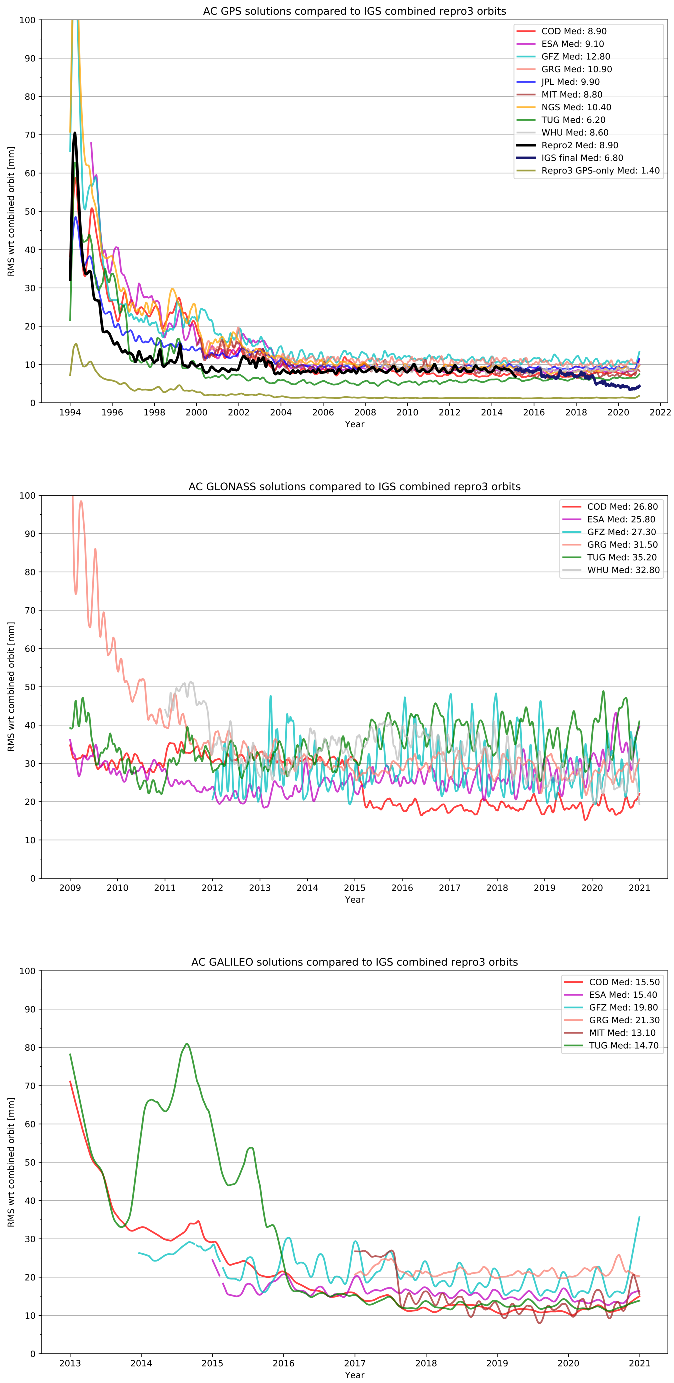

Figure 8: RMS of analysis center orbit solutions (smoothed) compared to the IGS combined orbits for the IGS Repro3 solutions for GPS (top), GLONASS (middle) and GALILEO (bottom).

References

Simon Banville, Jianghui Geng, Sylvain Loyer, Stefan Schaer, Tim Springer, and Sebastian Strasser. On the interoperability of igs products for precise point positioning with ambiguity resolution. *Journal of geodesy*, 94(1):1–15, 2020.

Stefan Schaer. Sinex bias—solution (software/technique) independent exchange format for gnss biases version 1.00. In *IGS workshop on GNSS biases, Bern, Switzerland*, 2016.

Center for Orbit Determination in Europe (CODE) Technical Report 2021

R. Dach[1], S. Schaer[2],

D. Arnold[1], M. Kalarus[1], L. Prange[1], P. Stebler[1], A. Villiger[1], A. Jäggi[1],

E. Brockmann[2], D. Ineichen[2], S. Lutz[2], U. Wild[2], M. Nicodet[2],

D. Thaller[3], L. Lengert[3], J. Dostal[3], W. Söhne[3], J. Bouman[3],

I. Selmke[4], U. Hugentobler[4]

[1] Astronomical Institute, University of Bern, Bern, Switzerland
E–mail: code@aiub.unibe.ch

[2] Federal Office of Topography swisstopo, Wabern, Switzerland

[3] Federal Agency of Cartography and Geodesy, Frankfurt a. M., Germany

[4] Institute for Astronomical and Physical Geodesy, Technical University of Munich, Germany

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://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. (2021). 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 with 5 minutes sampling
COD.ERP_U	CODE ultra-rapid ERPs belonging to the ultra-rapid GNSS 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 Z-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 solution of the day)
CODwwwwd.ERP_U	CODE ultra-rapid ERPs belonging to the above ultra-rapid GNSS 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 with 5 minutes sampling
CODwwwwd.EPH_R	CODE early rapid GNSS orbits with 5 minutes sampling
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 Z-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 the GPS and GLONASS satellites
P1P2_ALL.DCB	CODE sliding 30-day P1−P2 DCB solution, Bernese format, containing the 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 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.OBX.Z	Satellite attitude information in ORBEX format
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 the GPS and GLONASS satellites
yyyy/P1P2yymm_ALL.DCB.Z	CODE monthly P1−P2 DCB solution, Bernese format, containing the 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_v3.CLK.Z	same as above but in clock RINEX version 3.04
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
yyyy/COMwwwwd.OBX.Z	Satellite attitude information in ORBEX 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.obx.Z`	Satellite attitude information in ORBEX format
`codwwwwd.tro.Z`	GNSS 2–hour troposphere delay estimates obtained from the long–arc solution in troposphere SINEX format
`codwwww7.erp.Z`	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COD–ERP solutions of the week in IGS IERS ERP format
`codwwww7.sum`	Analysis summary for 1 week

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

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

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

`CODOMGXFIN_yyyyddd0000_01D_05M_ORB.SP3.gz`
: CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format

`CODOMGXFIN_yyyyddd0000_03D_12H_ERP.ERP.gz`
: CODE MGEX final ERPs belonging to the MGEX final orbits

`CODOMGXFIN_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

`CODOMGXFIN_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

`CODOMGXFIN_yyyyddd0000_01D_15M_ATT.OBX.gz`
: Satellite attitude information in ORBEX format

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

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 .
- Selmke, Inga; Dach, Rolf; Arnold, Daniel; Prange, Lars; Schaer, Stefan; Sidorov, Dmitry; Stebler, Pascal; Villiger, Arturo; 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 .

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. In March 2021, the BeiDou 3 constellation was added to the processing (see Section 3.2). For that reason a jump in the number of processed BeiDou satellites appears in the plot. Since that change, the MGEX solution includes about 115 satellites of five satellite systems.

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

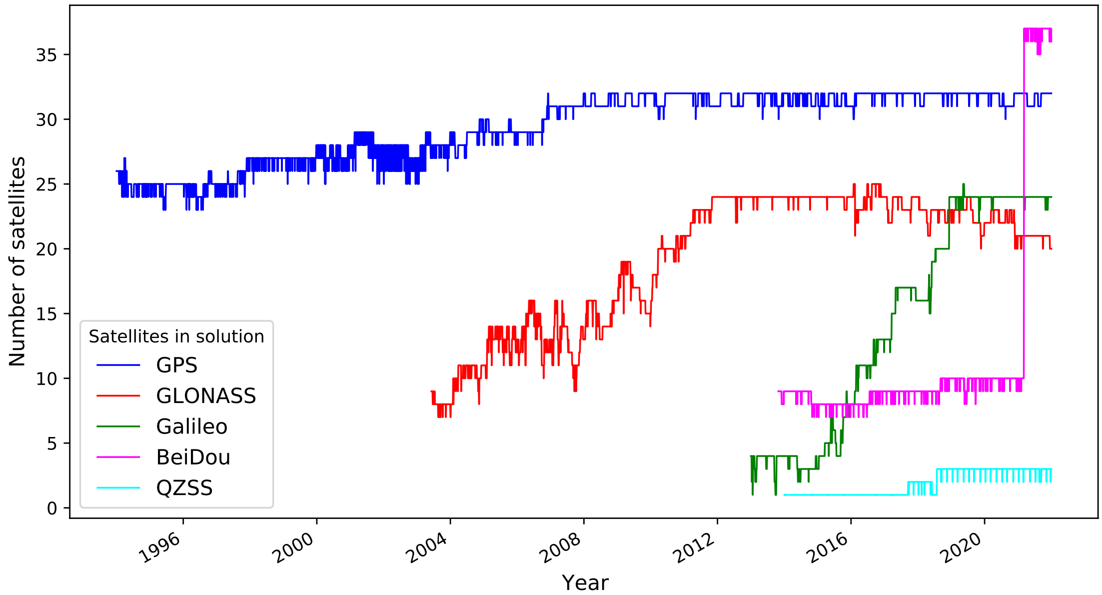

Figure 1: Development of the number of satellites in the CODE orbit products.

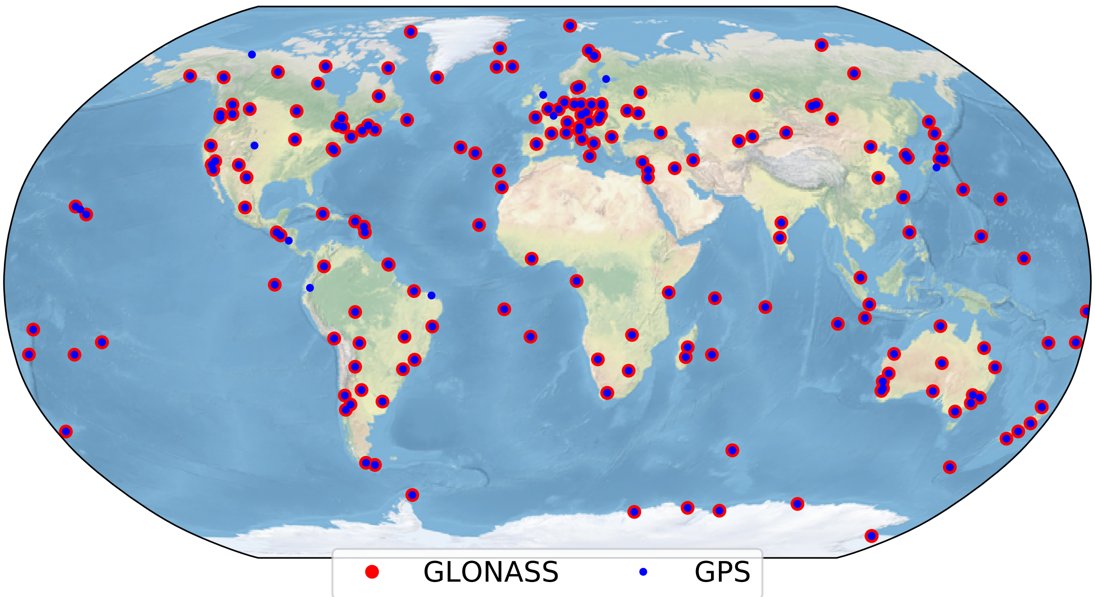

Figure 2: Network used for the final processing at CODE by the end of 2021.

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. (2021).

In Section 3.1 we give an overview of important development steps in the year 2021. More details on adding the BeiDou 3 constellation to the MGEX solution series is provided in Section 3.2 .

3.1 Overview of changes in the processing scheme in 2021

Table 3 gives an overview of the major changes implemented during the year 2021. 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.

3.2 Inclusion of BeiDou 3 constellation into CODE's MGEX solution

After the tracking of the BeiDou 3 constellation has been improved within the IGS network (see Figure 3), CODE extended its MGEX solution by these satellites in March 2021 (visible in Figure 1). Several adaptions in the software were necessary to allow this inclusion. On top of the three MEO and seven IGSO satellites from the BeiDou 2 constellation, the CODE MGEX solution now considers another 24 MEO and 3 IGSO satellites of the BeiDou 3 constellation in addition. Thanks to the additional satellites in MEO orbits the new, extended solution has become interesting for global applications outside from East Asia.

When comparing the SLR residual statistics on the web-page (https://igs.org/mgex/analysis/#bd3-slr-residuals) for the BeiDou 3 satellites with those from the other analysis centers, the CODE solution (label `com`) shows the lowest RMS which might also be explained by the short time series that contains only the last period with the best tracking coverage. Regarding the bias the CODE solution is comparable to the other contributions.

The linear fit of the satellite clock corrections during one day is often used for orbit quality assessment. The median together with the inter quartile range (IQR) is shown for all satellites in CODE's MGEX solution of the year 2021 in Figure 4 . The newly established BeiDou 3 satellites behave in most cases like old GPS satellites (before Block IIF generation). At the same time, there are the BeiDou 3 from the type SECM-A which

Table 3: Selected events and modifications of the CODE processing during 2021.

Date	DoY/Year	Description
13-Jan-2021	013/2021	Improved multi-GNSS ambiguity resolution by improving the screening of the code data for the Melbourne-Wübbena linear combination.
16-Jan-2021	016/2021	Report satellite attitude in ATT-ORBEX format in the final and MGEX solution series; files are submitted to CODE's FTP server and CDDIS
24-Jan-2021	024/2021	Corrected datum definition when computing the code biases.
07-Mar-2021	066/2021	Activation of BeiDou 3 constellation in MGEX solution series
28-Mar-2021	087/2021	Software update with more digits for estimated orbit parameters transferred from the parameter estimation to orbit intergration step.
03-May-2021	123/2021	Update the complete FES2014b ocean tidal loading correction table; changes with tenth of millimeter differences
05-May-2021	125/2021	Relocation of the directory structure on the computing cluster
28-Mar-2021	087/2021	Change non-gravitational force modelling to a slightly different set of formulas
02-May-2021	122/2021	Switch from IGS14 to IGS14R3 antenna model (igsR3.atx + disclosed BeiDou & QZSS satellite antenna pattern); Announcement via IGSMGEX mail
05-Jul-2021	186/2021	Eclipse attitude laws introduced for BeiDou 2 and 3 constellations and QZS-2 satellite; for GPS IIIA the attitude from IIR satellites are preliminary adopted until final model disclosed.
04-Jul-2021	185/2021	Change of tropo model (GMF1 to GPT3/GMF3 in the rapid and ultra-rapid series; VMF1 to VMF3 in the final and MGEX series)
20-Jul-2021	201/2021	Add a consistency check for GNSS orbit solution with emergency stop in case of datum definition problems.
02-Aug-2021	213/2021	Activate a new reference ambigutiy setup in the parameter estimation and ambiguity resolution step (set ambiguity for each iteration individually, also if GLONASS included)
27-Sep-2021	270/2021	Increase the sampling of the satellite positions in SP3 files of the rapid and ultra-rapid solution from 900 to 300 seconds (because of the Galileo satellites on the elliptic orbits).

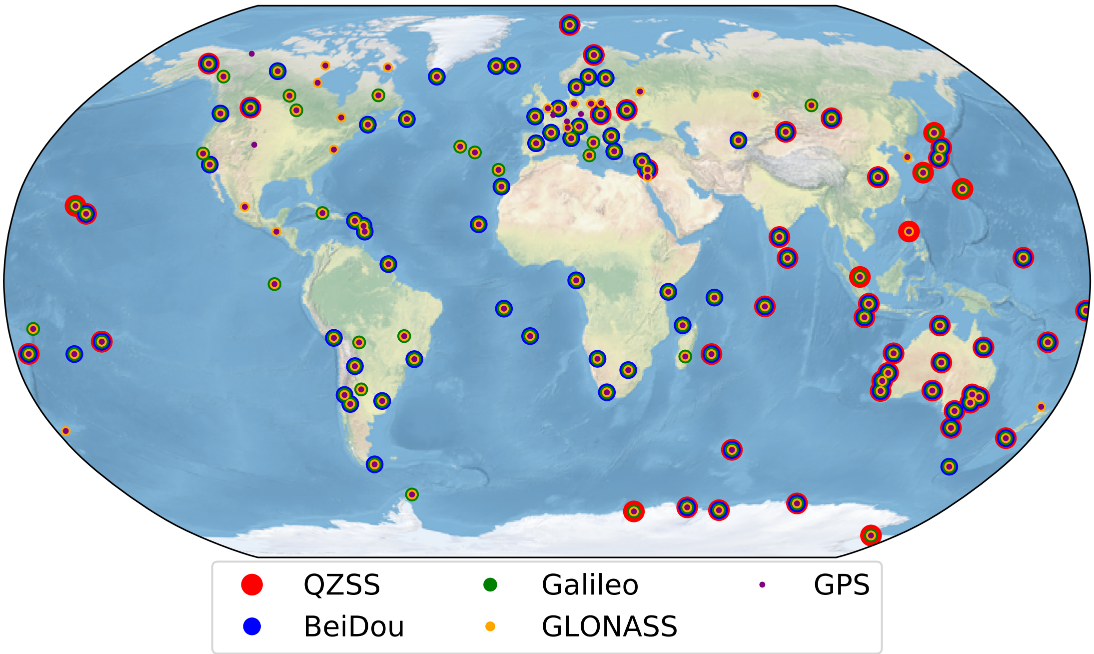

Figure 3: Network used for the MGEX processing at CODE by the end of 2021.

are equipped with passive H-maser clocks as the Galileo space vehicles. The median linear fit is for these satellites 0.109 ns with an IQR of 0.047 ns which is very close to the Galileo satellites with a median of 0.087 ns and IQR of 0.042 ns . The satellites on the IGSO orbits have a performace on the magnitude of the QZSS satellites.

Regarding orbit misclosures and long-arc fit the BeiDou 3 satellites in IGSO orbits are on

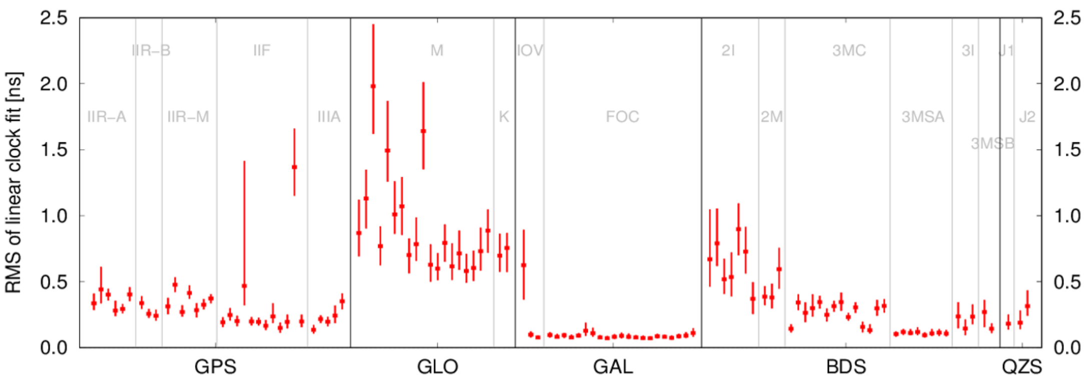

Figure 4: Boxplot from the RMS of a linear fit of the satellite clocks during 24 hours obtained from the MGEX solution of the year 2021.

the level of the QZSS satellites. The satellites in MEO orbits can be better represented by the orbit model than the satellites from the BeiDou 2 generation. They quality parameters indicate that the performance of BeiDou 3 is better than that of GLONASS and BeiDou 2, but not yet as good as that of the GPS and Galileo satellites.

The satellites in GEO are not considered in the solution so far.

4 Contribution to the IGS-Reprocessing

As a global analyis center CODE contributed 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. (2021).

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 were submitted in time to the IGS for combination and made available at the server at AIUB as listed in Table 4. 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.

Together with the clock corrections also the phase biases are provided allowing for a PPP ambiguity resolution according to Schaer et al. (2021).

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/GCC 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

5 Development of a combined ERP product at BKG

The publicly available daily EOP products provided by the IERS (e.g., IERS Bulletin A, IERS 14 C04) are based on the combination of individual space-geodetic technique solutions. Within this approach the different parameter types are combined independently, thus, correlations between the parameters are not taken into account. It represents the least rigorous combination method. Current activities at BKG focus on the development of a more rigorous combination strategy, the main objective of which is to improve the consistency between the space geodetic techniques through common parameters, in particular EOP. The combination is based on normal equations (NEQ) using GNSS and VLBI data covering 7 days. Constraint-free NEQs are stacked into one NEQ system before applying datum constraints and solving for the parameters. The resulting solution, essentially includes EOP, TRF, CRF and other technique-specific parameters. Its estimates are more consistent than those from the combination approach performed on parameter level.

At the moment, the combination process is based on VLBI and GNSS Rapid observation campaigns provided via SINEX files by the BKG IVS Analysis Centre (AC) and CODE

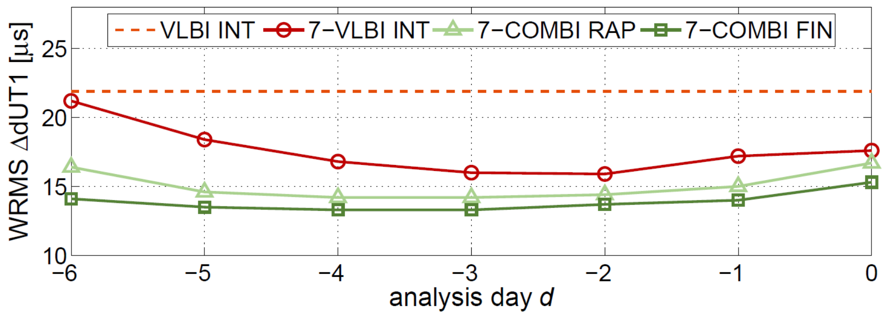

Figure 5: WRMS values of dUT1 estimates resulting from different analysis approaches compared to the IERS Bulletin A series. The analysis epoch is 12 h .

IGS AC, respectively. Two approaches are considered regarding the VLBI contribution: COMBI RAP is the rapid solution using VLBI Intensive Sessions covering 1 hour, which are available within 1-2 days. COMBI FIN is additionally using 24-hours VLBI R1/R4 sessions with a much longer latency of about 2 weeks.

Detailed information about the data processing, the combination strategy, the validation procedure and the different EOP solutions including session-wise single-technique solutions (GNSS, VLBI INT, VLBI R1/R4), multi-day single-technique solutions (n-VLBI INT, n-GNSS) and the two different inter-technique combined solutions (COMBI RAP, COMBI FIN) can be found in Lengert et al. (2021, 2022a,b). The EOP are estimated as 24-h continuous piece-wise linear polygons over the entire solution interval (i.e., up to 7 days).

Figure 5 gives a brief insight into the 7-day dUT1 solution. The WRMS values of the dUT1 estimates w.r.t. the IERS Bulletin A series estimated by the 7-day COMBI RAP and COMBI FIN approaches are shown in Figure 5. The comparison epoch is 12 h. The WRMS values of the single-day and 7-day VLBI Intensives (VLBI INT, 7-VLBI INT) solutions are depicted additionally. The analysis day d ranges from 0 to -6 and represents the day within the 7-day polygon used for the comparison, with $d = 0$ being the rightmost and $d = -6$ the leftmost day on the time axis.

The weekly combination of GNSS and VLBI INT data leads to a significant improvement in the consistency of the dUT1 time series w.r.t. external reference series. As a consequence, the combination of the continuous GNSS LOD information and the high-quality VLBI INT dUT1 information results in a high quality 24h-dUT1 product with a latency of about two days (COMBI RAP). The addition of the VLBI R1/R4 sessions to the VLBI INT and GNSS data has a positive impact on the entire 7-day solution (COMBI FIN), especially stabilizing the dUT1 estimates of the boundary days. The rightmost boundary days (i.e., d=0) is of special interest: as this epoch is the most recent one, the estimated EOP highly influences the prediction, which is crucial for real-time applications, especially satellite navigation.

Based on the improved combination method, BKG is working on the development of a new operational EOP product. Once in place, BKG will be the first institution (according to current knowledge) providing a complete and homogeneously combined EOP product with daily resolution and short latency (1-2 days) with open access for the international community.

References

Dach, R., S. Lutz, P. Walser, and P. Fridez, editors. *Bernese GNSS Software, Version 5.2.* Astronomical Institute, University of Bern, Bern, Switzerland, November 2015. ISBN 978-3-906813-05-9. doi: 10.7892/boris.72297. URL ftp://ftp.aiub.unibe.ch/BERN52/DOCU/DOCU52.pdf. User manual.

Dach, R., S. Schaer, D. Arnold, M. Kalarus, L. Prange, D. Sidorov, P. Stebler, A. Villiger, A. Jäggi, G. Beutler, E. Brockmann, D. Ineichen, S. Lutz, U. Wild, M. Nicodet, J. Dostal, D. Thaller, W. Söhne, J. Bouman, I. Selmke, and U. Hugentobler. CODE Analysis center: IGS Technical Report 2020. In A. Villiger and R. Dach, editors, *International GNSS Service: Technical Report 2020*, pages 49–66. IGS Central Bureau, May 2021. doi: 10.7892/boris.156425.

Dach, R., I. Selmke, A. Villiger, D. Arnold, L. Prange, S. Schaer, D. Sidorov, P. Stebler, A. Jäggi, and U. Hugentobler. Review of Recent GNSS Modelling Improvements Based on CODEs Repro3 Contribution. *Advances in Space Research*, 68(3):1263–1280, 2021. doi: 10.1016/j.asr.2021.04.046.

Lengert L., D. Thaller, C. Flohrer, H. Hellmers, A. Girdiuk. Combination of GNSS and VLBI data for consistent estimation of Earth Rotation Parameters. Proceedings of the 25th European VLBI Group for Geodesy and Astrometry Working Meeting (EVGA 2021). (eds. R. Haas). ISBN: 978-91-88041-41-8, 2021. URL: https://www.oso.chalmers.se/evga/25_EVGA_2021_Cyberspace.pdf.

Lengert L., C. Flohrer, A. Girdiuk, H. Hellmers, D. Thaller. Single- and Multi-day Combination of VLBI and GNSS Data for Consistent Estimation of Low-Latency Earth Rotation Parameters. *Journal of Geodesy*, in praparation, 2022a.

Lengert L, D. Thaller, C. Flohrer, H. Hellmers, A. Girdiuk. On the improvement of combined EOP series by adding 24-hour VLBI sessions to VLBI Intensives and GNSS data. Proceedings of the 2021 IAG Symposium, Beijing, China, in print, 2022b.

Schaer, S, A. Villiger, D. Arnold, R. Dach, L. Prange, A. Jäggi. The CODE ambiguity-fixed clock and phase bias analysis products: generation, properties, and performance. *Journal of Geodesy*, 95(81), 2021. doi: 10.1007/s00190-021-01521-9.

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 2021

S. Banville, P. Collins, B. Donahue, S. Elson, R. Ghoddousi-Fard, M. A. Goudarzi, O. Kamali, Y. Mireault, T. Nikolaidou, C. M. I. Robin

Canadian Geodetic Survey, Natural Resources Canada
588, Booth Street, Ottawa ON, Canada K1A 0Y7
E-mail: Reza.Ghoddousi-Fard@NRCan-RNCan.gc.ca

1 Introduction

This report covers the major activities conducted at the NRCan Analysis Center (NRCan-AC) and product changes during the year 2021 (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 2021, with no major changes to the processing strategy. The GNSS Rapid and Ultra-Rapid products continued to be generated using the Bernese software version 5.2 (Dach et al., 2015). The Final GLONASS products are taken from a separate GNSS Final run coming from the Bernese software version 5.2.

The products available from the NRCan-AC are summarized in Table 1 The Final and Rapid products are available from the following anonymous ftp sites:

ftp://cacsa.nrcan.gc.ca/gps/products
ftp://cacsb.nrcan.gc.ca/gps/products

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. High-rate Galileo phase rate measurements from Canadian stations are being monitored in a development platform to enhance studies on ionospheric irregularities.

4 Real-time correction service

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 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 36 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 36 stations NRCan contributes to the IGS network, a further 31 GNSS stations are submitted to IGS data centers. Several upgrades/changes to NRCan's IGS stations were completed in 2021 and these are listed in Table 2. Figure 1 shows a map of the NRCan GNSS network as of January 2022. 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://cacsa.nrcan.gc.ca/gps
ftp://cacsb.nrcan.gc.ca/gps

6 Acknowledgement

NRCan Contribution number / Numéro de contribution de RNCan : 20210586

References

Dach R., S. Lutz, P. Walser and P. Fridez. (2015). Bernese GNSS Software Version 5.2 AIUB, Astronomical Institute, University of Bern.

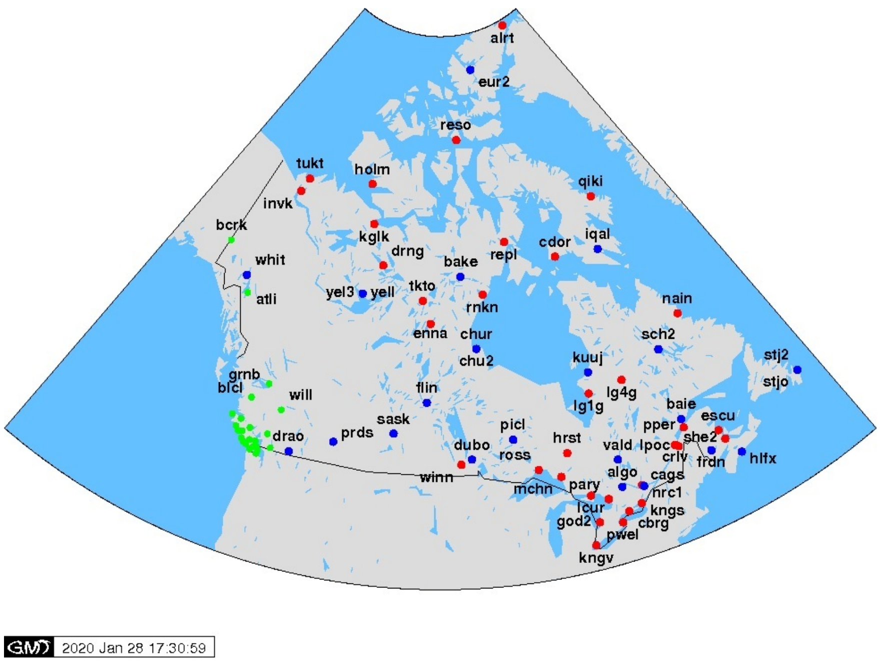

Figure 1: NRCan Public GNSS Stations (CGS-CACS in blue, CGS-RACS in red and CHIS-WCDA in green).

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

Repro3:	

`EMR0R03FIN_`
`yyyydoy0000_`
`01D_01D_OSB.BIA`
`EMR0R03FIN_`
`yyyydoy0000_`
`01D_30S_CLK.CLK`
`EMR0R03FIN_`
`yyyydoy0000_`
`01D_30S_ATT.OBX`
	GPS only
	• Time Span 1996-Jan-01 to 2020-Dec-31
	• In-house software (SPARKNet)
	• 30-sec clocks
	• Based on NGS repro3 solution (ERP, SP3 and SNX)
	• Submission for IGS repro3 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, hourly 30-sec GLONASS clocks produced (used to be every 3h) in addition to orbits and ERP with a delay of less than one hour.
Real-Time:	

	GPS only
	• Since 2011-11-10 until 2018-05-07
	• In-house software (HPGPS.C)
	• RTCM messages:
	  – orbits and clocks:1060
	    positions at Antenna Reference Point
	    float ambiguity clocks
	  – pseudorange biases: 1059
	  – phase biases: 1265
	• 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

Table 2: NRCan-IGS Station upgrades in 2021.

Station	Date	Remarks
drao	2021-09-02	Antenna replaced
whit	2021-06-22	Station receiver upgraded to SEPT POLARX5

GFZ Analysis Center Technical Report 2021

B. Männel, Z. Deng, P. Sakic, A. Brack, T. Nischan, A. Brandt, M. Bradke, M. Ramatschi

Deutsches GeoForschungsZentrum (GFZ)
Department 1: Geodesy, Section 1.1: Space Geodetic Techniques
Telegrafenberg A 17, 14473 Potsdam, Germany
E-mail: benjamin.maennel@gfz-potsdam.de

1 Summary

During 2021, 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. With respect to user needs we added Galileo in our ultra-rapid and rapid products starting from 2021/138 (May 18). The multi-GNSS processing was continued routinely during 2021 including GPS, GLONASS, BeiDou, Galileo, and QZSS. In the past year we finalized the GFZ contribution to the IGS repro3 campaign including GPS, GLONASS, and Galileo and derived combined orbits using a weighting scheme based on variance component estimation.

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 240, 120, and 65 sites are used, respectively. The slight reduction of processed stations in ultra-rapid and rapid lines is associated with the inclusion of a third constellation. Since May

Table 1: List of products provided by GFZ AC to IGS and MGEX; YD = YYYYDDD0000

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, Galileo since week 2159)	
gfzWWWWD.sp3	Daily orbits for GPS, GLONASS, Galileo satellites
gfzWWWWD.clk	5-min clocks for stations and GPS, GLONASS, Galileo 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, Galileo since week 2159)	
gfuWWWWD_HH.sp3	Adjusted and predicted orbits for GPS, GLONASS, Galileo satellites
gfzWWWWD_HH.erp	Earth rotation parameters
gfzWWWWD_HH.sum	Summary file
MGEX Rapid containing GPS/GLONASS/Galileo/BeiDou/QZSS	
GBM0MGXRAP_YD_01D_01D_ORB.SP3	Daily satellite orbits
GBM0MGXRAP_YD_01D_30S_CLK.CLK	30 sec receiver and satellite clocks
GBM0MGXRAP_YD_01D_01D_ERP.ERP	Daily Earth rotation parameters
GBM0MGXRAP_YD_01D_01D_OSB.BIA	Bias file: observable-specific signal bias
GBM0MGXRAP_YD_01D_01D_REP.BIA	Bias file inter-system biases
GBM0MGXRAP_YD_01D_01D_ATT.OBX	Attitude quaternions

Table 2: Recent processing changes

Date	IGS	IGR/IGU	Change
2021-03-21	w2150		revised station selection for final processing
2021-05-18		w2159	Galileo added and station selection adjusted in IGR and IGU
2021-08-15	w2171		switch to GFZ TEC maps

2021, we provide orbit and clock corrections also for Galileo. To avoid inconsistencies in the station coordinate time series Galileo data are not considered in the final products. We updated our final station selection in March 2021 by adding several IGS stations which were without any operational solution in the combined products. Recent changes in the processing strategy are listed in Table 2. Minor changes have been applied for the observation modeling to keep the consistency concerning the repro-2 processing strategy. Since week 2171 (August 2021) we use the GFZ TEC maps in our final processing (see Sect. 5 for more details). 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
- Männel, B., Brandt, A., Nischan, T., Brack, A., Sakic, P., Bradke, M. (2020): GFZ rapid product series for the International GNSS Service (IGS). GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2020.003
- Männel, B., Brandt, A., Nischan, T., Brack, A., Sakic, P., Bradke, M. (2020): GFZ ultra-rapid product series for the International GNSS Service (IGS). GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2020.004

4 Multi-GNSS data processing

The rapid multi-GNSS product GBM was continued in 2021. Starting from day 2021/167 and announced in IGS-Mail 8068, the GBM products provide satellite orbit and clock estimated with un-difference ambiguity resolution using daily wide/narrow-lane un-calibrated-phase-delay (UPD) method. The GBM products naming follows the IGS long-name definition and include bias as well as attitude products. All GBM products are available at ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

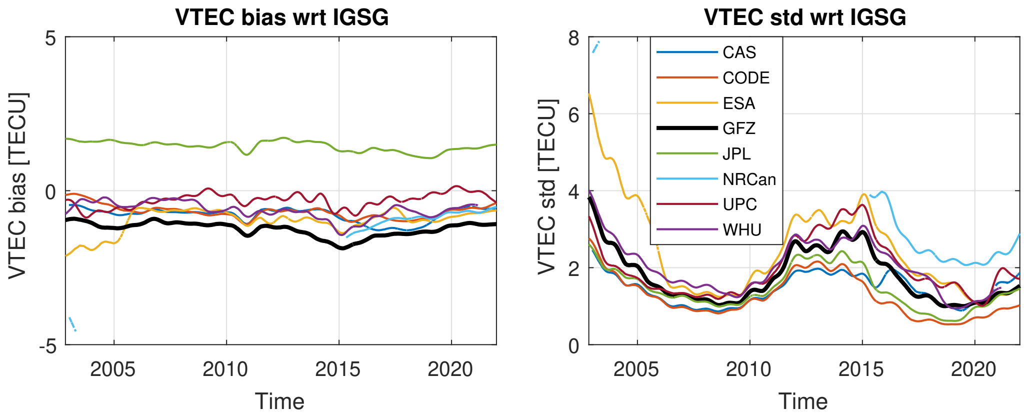

Figure 1: Smoothed time series of daily biases and standard deviations between the final IGS solution IGSG and the final solutions of the ACs.

5 Operational ionosphere products

The GFZ EPOS.P8 processing software was extended for the capability to estimate the total electron content (TEC) of the Earth's ionosphere. Rapid and final global VTEC maps with a temporal resolution of two hours are computed from GPS, GLONASS, and Galileo observation data from around 250 IGS tracking stations. The final solutions contain the middle day of a combination of three consecutive daily solutions on the normal equation level. The processing is based on a rigorous least-squares approach using uncombined code and phase observations, and does not entail leveling techniques. A single-layer ionospheric model with a spherical harmonic VTEC representation is applied. For a detailed description see Brack et al. (2021). A comparison with the final combined IGSG solution is shown in Figure 1.

The products are provided via `https://isdc.gfz-potsdam.de/gnss-products` since week 2171 (August 2021) as daily IONEX files following the IGS long-name definition. Reprocessed solutions are available since the beginning of 2000. The products are referenced under the DOI:

- Brack, A.; Männel, B.; Bradke, M.; Brandt, A.; Nischan, T. (2021): GFZ Global Ionosphere Maps. GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2021.006

6 Reprocessing and combination activities

The GFZ Analysis Center contributed to the IGS repro3 campaign. The processing details are provided under the associated DOI:

- 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

The final submission (solution indicated as GFZ2) is available via the ISDC (`https://isdc.gfz-potsdam.de/gnss-products/`). We extended the solution on a quarterly basis to provide products for 2021.

During 2021, we pursued our efforts into the elaboration of an orbit and clock combination strategy compatible with a multi-GNSS environment. Our investigations focused on 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 radial, along and cross components 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 1cm level for GPS and up to a few centimeters for the other constellations. The agreement is slightly better with the AC and constellation weighting. Our method shows a sub-centimeter level consistency with the official legacy IGS combination. Then, we applied this new combination strategy to the recently provided Repro3 products, which includes not only GPS and GLONASS but also the Galileo constellation. For this study, we adopted the so-called AC+constellation strategy. The combination results show an agreement between the different AC's input orbits around 10 mm for GPS, 30 mm for GLONASS. The combination also highlights the improvement of the Galileo orbit determination over the past decade, the internal precision decreasing from around 35 mm to 16 mm for the most recent weeks. We used Satellite Laser Ranging (SLR) observations for external validation. The combined orbit has one of the best RMS agreements with respect to the SLR measurements (9.1 mm for GLONASS, and 8.3 mm over the last five years of the processed period). More details are available in Sakic et al. (2022).

Our current work focus is on the clock offset combination where we apply a Variance Component Estimated weighting scheme similar to the orbits. The first studies show that the ISBs estimated by each AC needed to be taken into account in a multi-GNSS clock combination, in order to deal with this issue we apply two different clock alignments, one using a reference satellite and the other an AC as reference. First results analysis showed that both strategies have identical weights for the ACs, varying around 2%, as well as the most stable constellations, are GPS and Galileo.

Based on the GFZ repro3 contribution we participate in the current TIGA reprocessing. To determine vertical land motion we processed 101 TIGA stations, 153 stations co-located to tide gauges, and the 66 stations of the simplified IGS14 core network. The processing was performed as network solution with fixed orbit and clock products. Preliminary results are presented in Männel et al. (2022). Using a conventional time series analysis we estimated mean coordinate repeatabilities of 2.9, 3.3, and 5.6 mm for north, east, and up directions, respectively. The derived velocities are in good agreement to comparable solutions (e.g., the mean difference to the ULR6a solutions is -0.1 mm yr^{-1}). We determined finally a geocentric sea level trend of 2.3±0.1 mm yr^{-1} by correcting tide gauge records available via the Permanent Service for Mean Sea Level for the individual vertical station velocity including eventually velocity changes.

7 Operational GFZ Stations

The global GNSS station network operated by GFZ comprised 24 GNSS stations contributing to the IGS tracking network in 20201. Beside regular F/W updates only minor hardware changes were necessary in 2021. In MIZU (Mizusawa/Japan) we changed the receiver from SEPT ASTERX4 to SEPT POLARX5, in OUS2 (Dunedin/New Zealand) it was necessary to replace a faulty SEPT POLARX5 receiver and in LPGS (La Plata / Argentina) we had to change the JAVRINGANT_G5T to a JAV_RINGANT_G3T NONE due to malfunctioning of the antenna. Negotiations for a new station in Kigali, Ruanda are still ongoing.

Additional information and quality indicators (e.g., data availability, latency, completeness) can be accessed through our new GNSS portal gnss.gfz-potsdam.de. This portal serves also as the landing page for our RINEX toolbox **gfzrnx** which was updated to fully support the new RINEX4 formats.

8 References

A. Brack, B. Männel, J. Wickert, and H. Schuh. Operational Multi-GNSS Global Ionosphere Maps at GFZ Derived from Uncombined Code and Phase Observations. *Radio Science*, 56(10):e2021RS007337, 2021. doi: 10.1029/2021RS007337.

B. Männel, T. Schöne, M. Bradke, and H. Schuh. Vertical Land Motion at Tide Gauges Observed by GNSS: A New GFZ-TIGA Solution. *International Association of Geodesy Symposia*, 2022. doi: https://doi.org/10.1007/1345_2022_150.

G. Mansur, P. Sakic, B. Männel, and H. Schuh. Multi-constellation GNSS orbit combination based on MGEX products. *Advances in Geosciences*, 50:57–64, 2020. doi: 10.5194/adgeo-50-57-2020.

G. Mansur, P. Sakic, A. Brack, B. Männel, and H. Schuh. Combination of GNSS orbits using variance component estimation. *Journal of Geodesy*, 2021. under review, preprint available on EarthArXiv California Digital Library (CDL) https://doi.org/10.31223/x5mk64.

G. Petit and B. Luzum, editors. *IERS Conventions (2010)*. Number 36. Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, Germany, 2010. ISBN 3-89888-989-6. IERS Technical Note No. 36.

P. Sakic, G. Mansur, B. Männel, A. Brack, and H. Schuh. An experimental combination of IGS repro3 campaignś orbit products using a variance component estimation strategy. *International Association of Geodesy Symposia*, 2022. under review, preprint available on EarthArXiv California Digital Library (CDL). https://doi.org/10.31223/x5k614.

Graz University of Technology (TUG) Analysis Center Technical Report 2021

S. Strasser, T. Mayer-Gürr

Institute of Geodesy, Graz University of Technology
Steyrergasse 30/III, 8010 Graz, Austria
Email: sebastian.strasser@tugraz.at, mayer-guerr@tugraz.at

1 Introduction

In 2020, Graz University of Technology (TUG) contributed to the International GNSS Service (IGS) for the first time as an Analysis Center by providing solutions for the third reprocessing campaign (repro3). This reprocessing effort was finished in early 2021 and the final products are now available. In addition, TUG has contributed to the repro3 combination effort by providing the IGS repro3 reference satellite attitude data.

2 Reprocessing campaign

Our contribution to repro3 was computed using our open-source software GROOPS (Mayer-Gürr et al., 2020), which is available on GitHub[1]. We apply an uncombined and undifferenced (raw) observation approach in our GNSS processing (Strasser et al., 2019). The contribution 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).

Our repro3 products are listed in Tab. 1. They are available at the IGS data centers and in our data repository (Strasser and Mayer-Gürr, 2021). More information about the products and our processing settings can be found on our website[2] and in the corresponding

[1] https://github.com/groops-devs/groops
[2] https://www.tugraz.at/institute/ifg/downloads/gnss-reprocessing-products/

Table 1: TUG's repro3 products

Product	Filename	DOI
Satellite orbits	TUG0R03FIN_*_01D_05M.ORB.SP3.gz	10.3217/dataset-7012-6314-1426
Clock errors	TUG0R03FIN_*_01D_30S.CLK.CLK.gz	10.3217/dataset-0745-4712-0218
Satellite attitude	TUG0R03FIN_*_01D_30S.ATT.OBX.gz	10.3217/dataset-4513-3418-4180
Code and phase biases	TUG0R03FIN_*_01D_01D.OSB.BIA.gz	10.3217/dataset-4173-2316-8234
Station coordinates	TUG0R03FIN_*_01D_01D.CRD.SNX.gz	10.3217/dataset-3682-0318-2418
Troposphere estimates	TUG0R03FIN_*_01D_05M.TRO.TRO.gz	10.3217/dataset-2068-4685-3810
Earth rotation param.	TUG0R03FIN_*_01D_01D.ERP.ERP.gz	10.3217/dataset-0712-3278-8016
Normal equations	TUG0R03FIN_*_01D_01D.SOL.SNX.gz	10.3217/dataset-5837-5341-5407

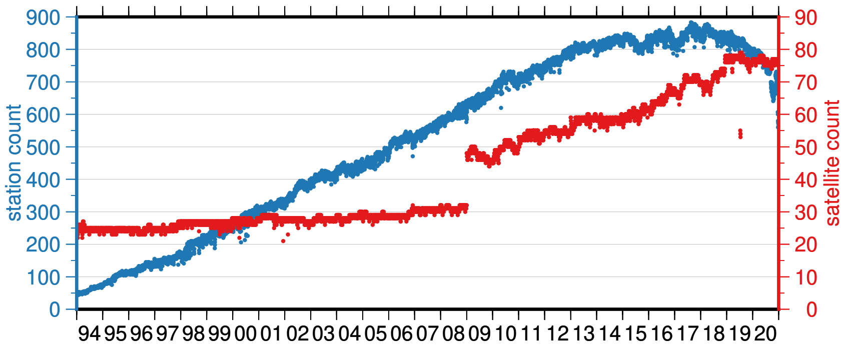

Figure 1: Number of processed stations and satellites per day.

analysis center summary file TUG0R03FIN.acn[3].

[3] https://www.tugraz.at/fileadmin/user_upload/Institute/IFG/satgeo/repro3/TUG0R03FIN.acn

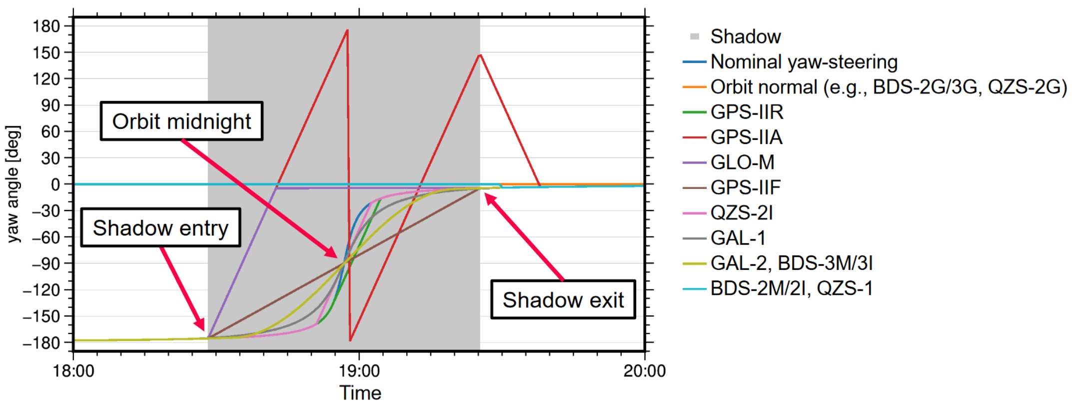

Figure 2: Shadow crossing behavior of various GNSS satellite types.

3 IGS repro3 reference satellite attitude

In 2020, we 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 reimplemented 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. Strasser et al. (2021) provides an overview of the reworked attitude modeling, including model comparisons and example implementations. As an example, Fig. 1 visualizes the attitude behavior during shadow crossings for various GNSS satellite types. As GROOPS is open-source software, the source code and documentation of the attitude model implementations can be found in our GitHub repository.

Considering satellite attitude during the clock combination process results in a more consistent combined product (Loyer et al., 2021). As the attitude products cannot be meaningfully combined, a reference attitude is required during this step. For maximum transparency, these models should be publicly available and well documented. As this is the case for GROOPS, the reference attitude products for the IGS repro3 combination were computed at TUG based on the combined repro3 orbits. These attitude products are going to be publicly available together with the orbit, clock, and bias combination products some time in 2022.

References

S. Loyer, S. Banville, J. Geng, and S. Strasser. Exchanging satellite attitude quaternions for improved GNSS data processing consistency. *Advances in Space Research*, 68(6): 2441–2452 2021. DOI: 10.1016/j.asr.2021.04.049

T. Mayer-Gürr, S. Behzadpour, A. Eicker, M. Ellmer, B. Koch, S. Krauss, C. Pock, D. Rieser, S. Strasser, B. Suesser-Rechberger, N. Zehentner, A. Kvas. GROOPS: A software toolkit for gravity field recovery and GNSS processing. *Computers & Geosciences*, 155:104864, 2021. DOI: 10.1016/j.cageo.2021.104864

S. Strasser, T. Mayer-Gürr, and N. Zehentner. Processing of GNSS constellations and ground station networks using the raw observation approach. *Journal of Geodesy*, 93: 1045–1057, 2019. DOI: 10.1007/s00190-018-1223-2

S. Strasser S. Banville, A. Kvas, S. Loyer, and T. Mayer-Gürr. Efficient multi-GNSS processing based on raw observations from large global station networks. *EGU General Assembly 2021*, Online, 19–30 April 2021, EGU21-7825, 2021. DOI: 10.5194/egusphere-egu21-7825

S. Strasser and T. Mayer-Gürr. IGS repro3 products by Graz University of Technology (TUG). Data set (version 1), 2021. DOI: 10.3217/dataset-4528-0723-0867

CNES-CLS
Technical Report 2021

F. Perosanz[1,3], S. Loyer[2], F. Mercier[1,3], A. Banos Garcia[2], A. Mezerette[2], G. Katsigianni[2], E. Saquet[2], A. Santamaria Gomez[3] J.C. Marty[1,3]

[1] Centre National d'Etudes Spatiales,18 av. Edouard Belin
31400 Toulouse, France

[2] Collecte Localisation Satellite, 8-10 rue Hermès
31520 Ramonville, France

[3] Geoscience Environnement Toulouse, 14 av. Edouard Belin
31400 Toulouse, France

E-Mail: igs-ac@cls.fr

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 in 2021 are summarized in table 1. Daily available MGEX products are listed in table 2.

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

2 GNSS satellite attitude information (ORBEX files)

The provision of attitude information used to generate the products in a dedicated format called ORBEX, initiated by our group several years ago, became a reality this year within the different ACs. As illustrated on the following figure 1, in the case of GPS satellites, because of the various implementations in the different software used by the

Table 1: Main processing changes

Date	GPS week	Change
2021/01/24	2142	Pole tide model correction SP3 sampling 300 s (900s before) Start delivering satellite attitude quaternions files (OBX files)
2021/01/24	2142	Pole tide model correction SP3 sampling 300 s (900s before) Start delivering satellite attitude quaternions files (OBX files)
2021/05/16	2158	Start delivering of Observable Specific Biases (OBS files)

Table 2: CNES-CLS MGEX products (new products in 2021 in bold)

File	Type	Sampling
`GRG0MGXFIN_yyyyddd0000_01D_000_SOL.SNX.gz`	SINEX solution (satellite/ station/ERP/satellite PCO)	1/day
`GRG0MGXFIN_yyyyddd0000_01D_30S_ATT.OBX.gz`	ORBEX Satellite attitude	30 seconds
`GRG0MGXFIN_yyyyddd0000_01D_01D_OSB.BIA.gz`	OSB solution	1 set/day
`GRG0MGXFIN_yyyyddd0000_01D_05M_ORB.SP3.gz`	SP3 Satellite orbit	5 minutes
`GRG0MGXFIN_yyyyddd0000_01D_30S_CLK.CLK.gz`	CLK satellite clock	30 seconds

Analysis Centers, the attitude differences computed from these ORBEX files can reach up to 180°. Providing this information will benefit to the users of the products and to clock combination as expressed by PPP-AR working group for the future IGS-REPRO3 combined clocks products.

3 Observable Specific Biases

To facilitate interoperability between GRG/GRM products and others similar products available within the IGS (Banville et al., 2020), we start delivering Observable Specific Biases (OSB) in 2021. These OSB are computed from the three following combinations: Differential code-bias (DCBs), Wide Lane Satellite biases(WSB), and iono-free clocks code-phase bias.

Our OSB may differ from other ACs determinations (as explained in Banville et al. (2020)) since our clock products are referenced to phase measurements ("phase clocks"). Differential code biases have been validated by comparisons with other solutions as shown in Figure 2.

Following SINEX bias definition and convention, these biases can be used to correct the RINEX observations (Schaer, 2016):

$$\text{Observation(true)} = \text{Measurement(RINEX)} - \text{bias}$$

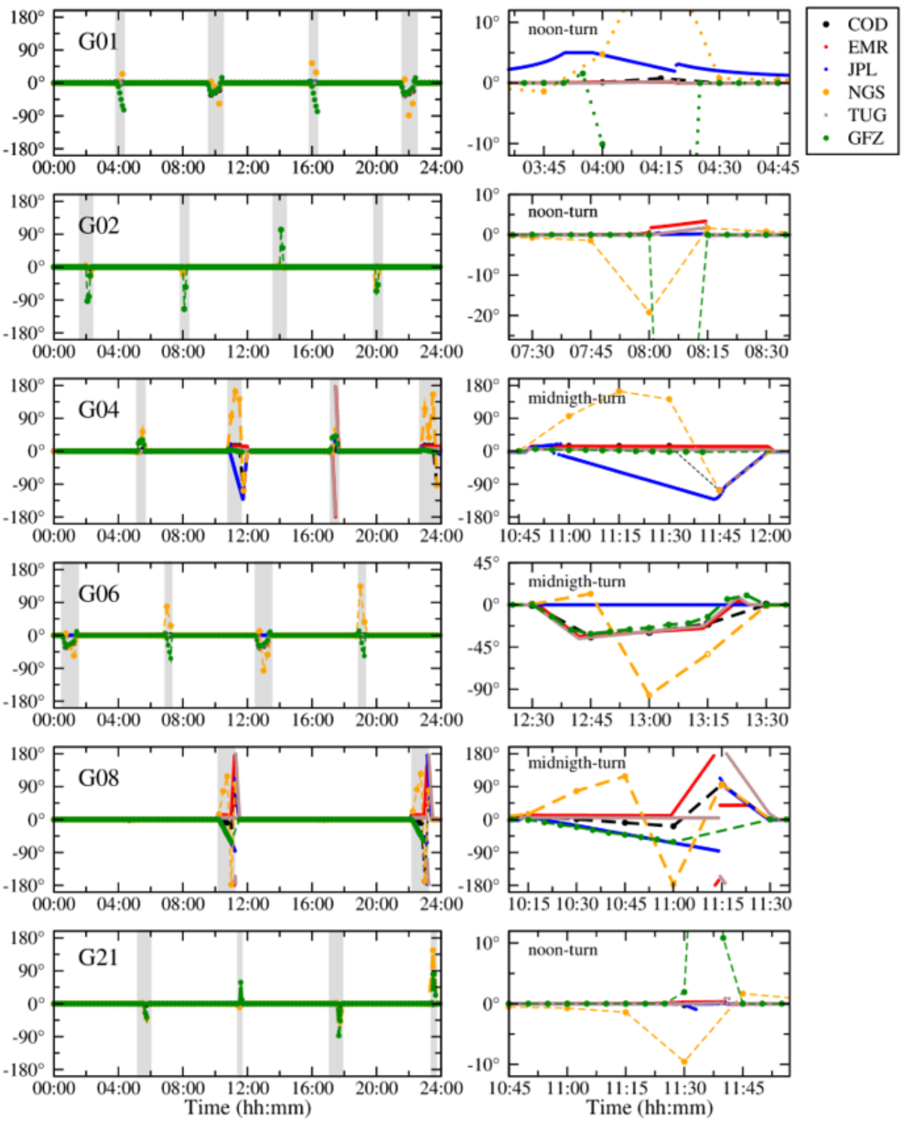

Figure 1: Attitude differences for eclipsing GPS satellites with respect to the GRG solution (20 August 2014). The right column emphasizes some events seen on the left (from Loyer et al. (2021))

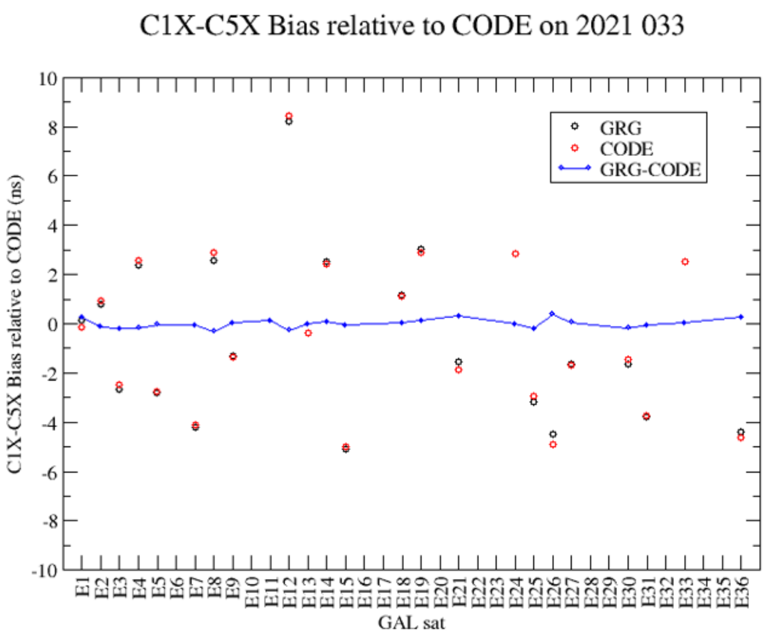

Figure 2: Differential code biases comparisons between GRG and CODE for doy 033/2021.

If used with GRG products, there is no more need for additional DCB corrections such as P1C1, WSB (Wide-Lane Satellite biases) since they are already contained in individual OSB biases.

Note that the WSB and Inter Frequency Differential code biases are computed today without applying antenna PCOs. This can be an issue if PCOs are not equals for each frequencies so this will be modified in the future to follow IGS standards evolution on this point. The OSB files contain individual values related to GPS(G) and GALILEO(E) constellations.

4 References

Banville S., J. Geng, S. Loyer, et al. On the interoperability of IGS products for precise point positioning with ambiguity resolution. J Geod 94, 10 (2020). https://doi.org/10.1007/s00190-019-01335-w

Loyer S., H. Capdeville, A. Mezerette, G. Katsigianni, E Saquet, and A. Banos-Garcia. Exploitation de localisation géodésique. Rapport de juin 2021, CLS-GEO-NT-21-0207

Loyer S., H. Capdeville, A. Mezerette, G. Katsigianni, E Saquet, and A. Banos-Garcia.

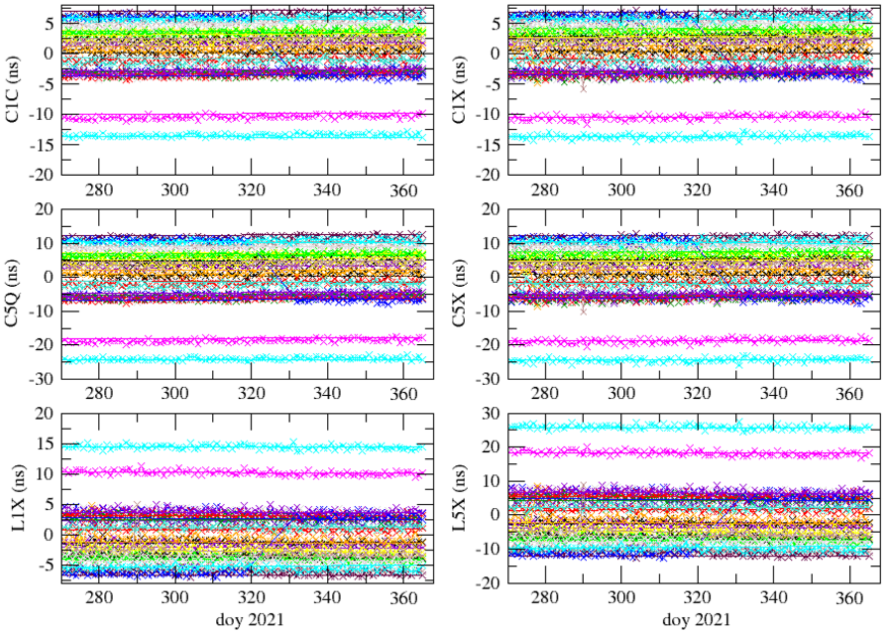

Figure 3: Observed Galileo OSB for the last part of 2021

Exploitation de localisation géodésique. Rapport de décembre 2021, CLS-GEO-NT-21-0546

Loyer S., S. Banville, J. Geng, and S. Strasser Exchanging satellite attitude quaternions for improved GNSS data processing consistency. Advances in Space Research, 2021, ISSN 0273-1177, https://doi.org/10.1016/j.asr.2021.04.049.

Schaer S. SINEX BIAS—Solution (Software/technique) INdependent EXchange Format for GNSS Biases Version 1.00", 2016, sinex_bias_100_dec07.pdf.

JPL IGS Analysis Center||Technical Report, 2021

D. Murphy, W. Bertiger, D. Hemberger,
A. Komanduru, R. Meyer, A. Peidou, P. Ries, A. Sibthorpe

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, M/S 238-600
Pasadena, CA 91001, U.S.A.
(dwm@jpl.caltech.edu, +1-818-354-0845)

1 Introduction

In 2021, 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 2021.

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.

- IGS Repro 3 campaign: We contributed to this campaign by conducting a complete re-analysis of GPS observations from 1994-2020. This set of solutions were delivered in February 2021 in support of the future International Terrestrial Reference Frame, ITRF2020. The reprocessed solutions benefit from the latest updates to the IERS Conventions recommended models including linear mean pole convention and high-frequency Earth Rotation Parameter models along with Earth's libration model. As part of this campaign, JPL also revisited its strategy for ground network selection to deliver a more consistent set of stations and troposphere modeling (using the VMF1 model and mapping function instead of the GPT2 model) to deliver station positions more consistent with physical models. JPL's GipsyX software is ITRF2020-ready, and JPL provided early evaluation and feedback regarding seasonal models in the preliminary ITRF2020P. However, ITRF2020 standards will not be adopted for JPL Final submissions for some time, pending a complete internal reprocessing in ITRF2020.

- Multi-GNSS: Efforts included substantial code refinement, all based around our GipsyX software. In October of 2021, we began production of operational low-rate (5-minute) GPS+GALILEO rapid products:

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

  Remaining development efforts are focused on continuing to ensure that our code-base is robust, capable of producing operational high-rate multi-GNSS Rapid and 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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References

Bertiger, W., Y. Bar-Sever, A. Dorsey, B. Haines, N. Harvey, D. Hemberger, M. Heflin, W. Lu, M. Miller, A. W. Moore, D. Murphy, P. Ries, L. Romans, A. Sibois, A. Sibthorpe, B. Szilagyi, M. Vallisneri, P. Willis (2020), GipsyX/RTGx, a new tool set for space geodetic operations and research, *Advances in Space Research*,Volume 66, Issue 3,469-489,doi:10.1016/j.asr.2020.04.015

Garcia Fernandez, M., S. D. Desai, M. D. Butala, and A. Komjathy (2013), Evaluation of different approaches to modeling the second-order ionosphere delay on GPS measurements, *J. Geophys. Res.*, 118 (12), 7864-7873, doi:10.1002/2013JA019356.

Lagler, K., M. Schindelegger, J. Bohm, H. Krasna, and T. Nilsson (2013), GPT2: Empirical slant delay model for radio space geodetic techniques, *Geophys. Res. Lett.*, 40 (6), 1069-1073, doi:10.1002/grl.50288.

Lyard, F., F. Lefevre, T. Letellier, and O. Francis, Modeling the global ocean tides: Insights from FES2004 (2006), *Ocean Dyn.*, (56), 394-415, doi:10.1007/s10236-006-0086-x.

Ray, R. D., Precise comparisons of bottom-pressure and altimetric ocean tides (2013), *J. Geophys. Res.*, 118, 4570-4584, doi:10.1002/jgrc.20336.

Sibois, A., C. Selle, S. Desai, A. Sibthorpe, and J. Weiss (2014), An update empirical model for solar radiation pressure forces acting on GPS satellites, 2014 IGS Workshop, Pasadena, CA, June 23-27.

Sibthorpe, A., W. Bertiger, S. D. Desai, B. Haines, N. Harvey, and J. P. Weiss (2011), An evaluation of solar radiation pressure strategies for the GPS constellations, *J. Geodesy*, 85 (8), 505-517, doi:10.1007/s00190-011-0450-6.

Weiss, J. P., W. Bertiger, S. D. Desai, B. J. Haines, and C. M. Lane (2010), Near real time GPS orbit determination: Strategies, performance, and applications to OSTM/Jason-2, *Adv. Astronaut. Sci.*, 137, 439-452.

MIT Analysis Center Technical Report 2021

T. Herring

Massachusetts Institute of Technology, Cambridge, MA, USA
E–mail: tah@mit.edu
Phone: +1 617 253 5941

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 processing methods remain unchanged from those discussed in the 2020 MIT Analysis center report (see Villiger and Dach (2021)).

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 2021 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

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)

three topocentric coordinates after the removal of linear trends from the time series. The median WRMS scatters of the 413 sites, measured more than five times, included in the statistics are 1.6, 1.5 mm in North and East and 5.5 mm in height. No annual signals were removed. The station selection in 2021 was based on third reprocessing campaign (Repro3) station selection list. This list was based on the priority order list for Repro3. (http://acc.igs.org/repro3/repro3_station_priority_list.pdf)

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

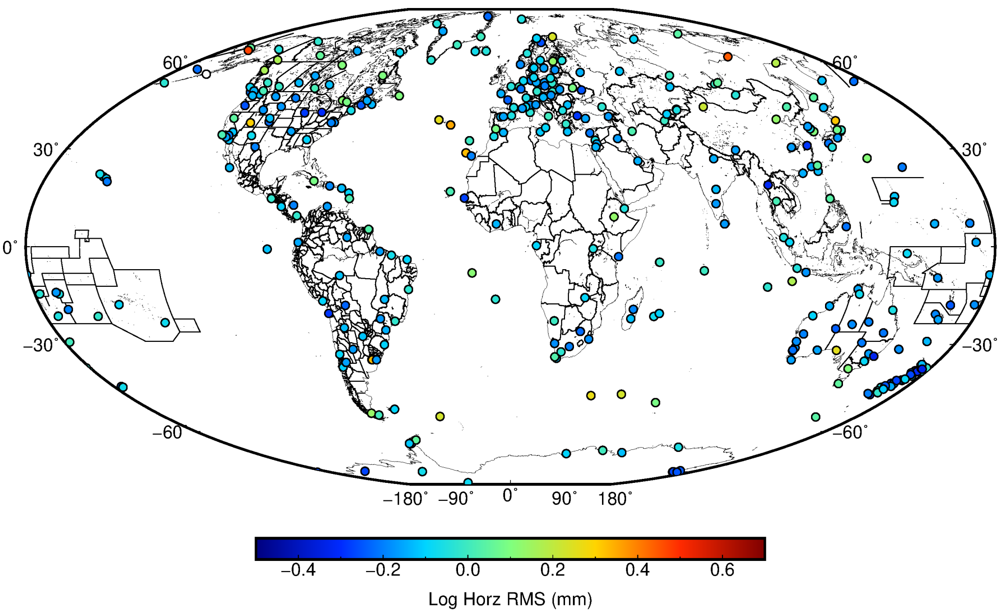


Figure 1: Log (base10) of the RMS scatter of the horizontal position estimates from the network of 412 stations processed more than 5 times by MIT in 2021. Each daily network has 350 station and the networks evolve with time depending on data availability and geometry. The cooler colors are all less 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, mm) are MAG0 (4.08), MIZU (4.23), CEDU (4.26), FLRS (4.35), USUD (4.40), SEY2 (4.42), TONG (4.45), CZTG (4.65), LPAL (4.69), VARS (4.91), NVSK (5.01), PDEL (5.23), P009 (5.62), LPGS (5.71), KEPA (5.82), URUM (5.94), AB11 (7.13), MARN (8.47), YAKT (8.54), and AB07 (13.75) mm. The sites with the largest height RMS scatters (mm) are FTNA (9.55), HIKB (9.70), OHI2 (9.71), BOAV (9.75), WILL (9.88), KRTV (9.94), OHI3 (9.98), NVSK (10.20), ACP1 (10.22), HORN (10.93), AB11 (11.07), URUM (11.99), SEY2 (12.14), MARN (12.18), SOFI (12.36), FLIN (15.28), TNML (16.35), FLRS (17.05), PDEL (18.06) and FUNC (20.35) mm.

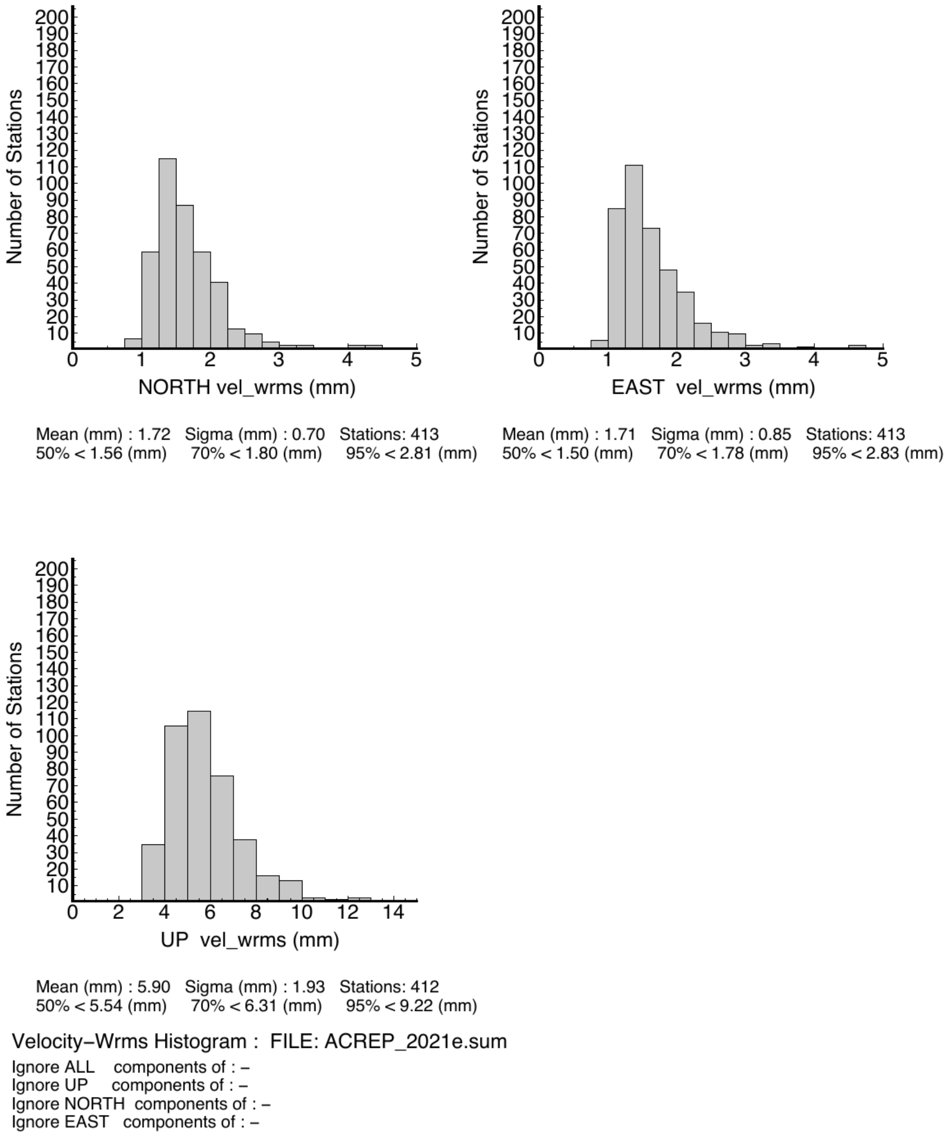


Figure 2: Histogram of the weighted root-mean-square (WRMS) scatter of daily position estimates of site used more than 5 times for 2021 after removal linear trends and elimination of gross outliers (5 times WRMS scatter). The median scatters are similar to last year with 1.6, 1.5 mm horizontal and 5.5 mm vertical.

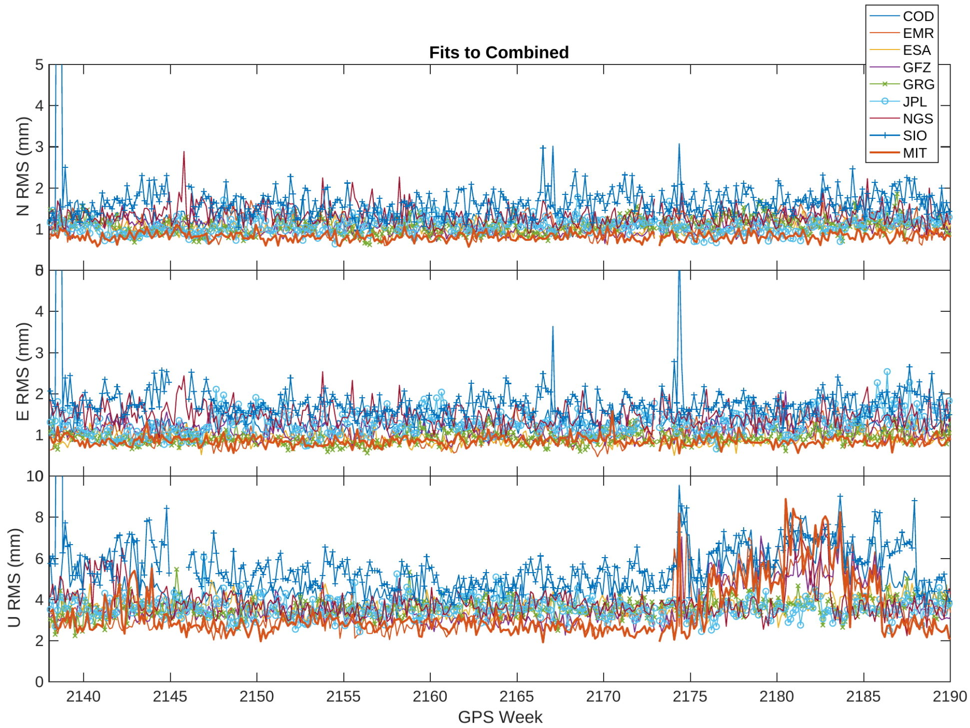


Figure 3: RMS scatters of the fits of the different IGS ACs to the MIG combined solution for 2021. The increase in scatter between wees 2175 and 2186 is due to due -180 mm height errors at DRAO in the NGS AC results after the change from an TRM59800.00 antenna to an TWIVC6050 antenna at DRAO on 2021/09/03. After week 2186, the NGS DRAO result was removed from the combination.

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

4 Third Reprocessing Campaign

MIT contributed to the IGS third reprocessing campaign (Repro3). The models and analysis methods ae the same as our operational processing except (1) we lowered the elevation cutoff angle to 5o from 10o (impact is relatively small because of elevation angle dependent data weighting); (2) the linear pole tide model was used and (3) we used the Repor3 antex file for ground and satellite phase center calibrations. The products sub-

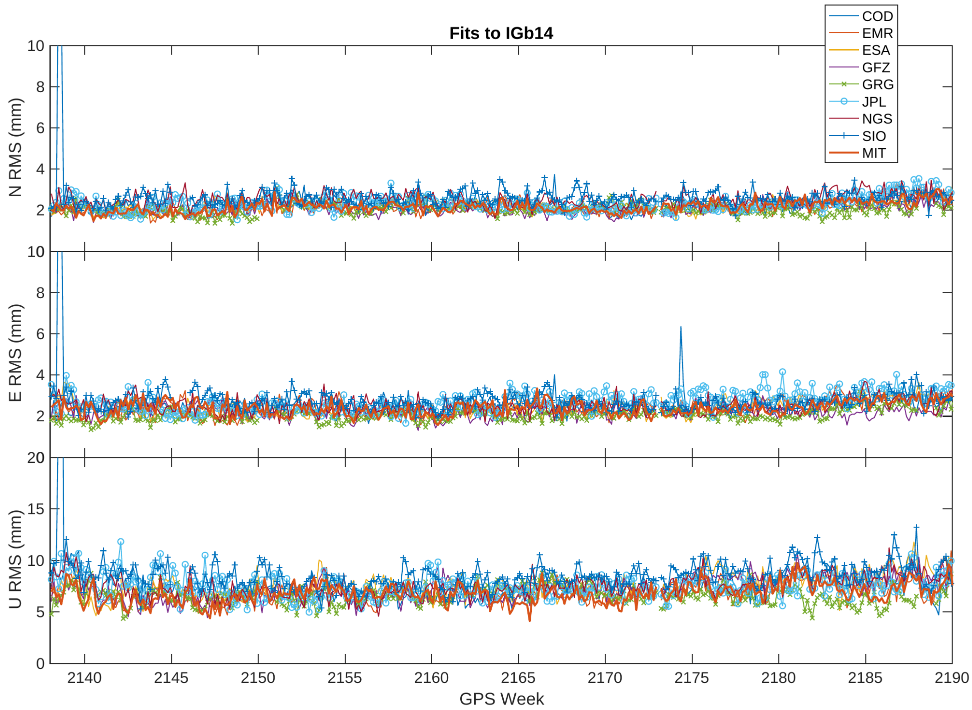


Figure 4: RMS scatters of the fits to IGS14, prior to GPS week 2106 (May 17, 2020), and IGb14 this week and after for the analyses in 2020.

Table 3: Comparison of the fits to the IGb14 reference frame (RF) and daily combined solutions for RF sites in the MIT and other AC daily final SINEX files. Typically, 48 sites are used in the comparison to IGb14.

Center	IGb14			Combined		
	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
MIT	2.16	2.39	6.77	0.82	0.85	3.34
COD	2.23	2.47	7.41	1.33	1.32	4.80
EMR	2.17	2.43	6.86	1.07	1.00	3.50
ESA	2.18	2.44	7.60	1.04	0.92	3.68
GFZ	2.06	2.25	7.16	1.03	1.09	3.69
GRG	2.04	2.06	6.56	1.07	0.94	3.59
JPL	2.34	2.72	7.51	1.08	1.29	3.57
NGS	2.53	2.50	7.46	1.34	1.48	3.90
SIO	2.64	2.78	8.67	1.72	1.82	5.78

mitted were: (1) MIT0R03xxx_yyyyddd0000_01D_01D_SOL.SNX.gz with xxx G– GPS only E– Galileo only GE- GPS+Galileo; (2) MIT0R03xxx-_yyyyddd0000_07D_01D_ERP.ERP.gz and (3) MIT0R03xxx_yyyyddd0000_01D_05m_ORB.SP3.gz. We also submitted clock files MIT0R03xxx_yyyyddd0000_01D_05m_CLK.CLK.gz but these are not fully consistent with the orbit and station positions. (The MIT clock products have not been accurate for some time and for Repro3 we decided to concentrate on position and orbits and not to devote resources the generating accuracy clock estimates.) Results for 2000-2020 for GPS (G–) were submitted. Galileo (E–) and combined GPS and Galileo (GE-) results were submitted for 2017-2020. Time series, aligned to the Repro3 apriori coordinate file with IGS14 hierarchal list of reference frame sites were used for comparison with ITRF2020P. This comparison is given below.

5 MIT Comparisons to ITRF2020P

Our preliminary analysis focuses on the comparison of the MIT GPS position time series from our Repro3 processing and comparing these time series values with the ITRF2020P model predictions. Our times series are rotated and translated to align with the Repro3 apriori coordinates including post-seismic deformation terms. We present three sets of results below. They are generated from analyses which re-align the MIT repro3 time series to ITRF2020P using the hierarchical reference frame site list from IGS14. With this list, typically 48 stations are used each day to align to the reference frame. Since the Repro3 time series are aligned to a linear plus post-seismic motion model, applying the periodic terms in ITRF2020P generates periodic signals in the rotation and translation parameters which is expected. The MIT time series alignment did not include scale changes and therefore applying the periodic terms in ITRF2020P would be expected to reduce the periodic variations in scale estimates in the alignment or the mean of the height residuals at the reference frame sites. Since we down-weight heights in estimating the frame alignment parameters, these two approaches generate almost exactly the same result when scale changes are converted to equivalent height on a 6371km radius sphere. Figure 5, shows the scale differences between the MIT time series and ITRF2020P with and with periodic terms applied.

The estimate of scale rate in Figure 5 is much less than that seen for IGb14. For the same type of analysis with IGb14, the scale offset and rate are 6.0 mm and 0.20 mm/yr. The rate is 7.5 times larger when aligning to IGb14. The periodic terms are similar to the values obtained when no periodic signals are applied to ITRF2020P.

The second comparison is the translation parameter estimates. These results are shown in Figures 6-8 for the X, Y and Z translation estimates. Again these analyses are based on re-aligning the MIT position time series to ITRF2020P and for comparison IGb14 and the Repro3 apriori coordinates. The IGS14 hierarchical reference station list is used. The time series are generated by alignment to Repro3 and we should expect the Repro3 values

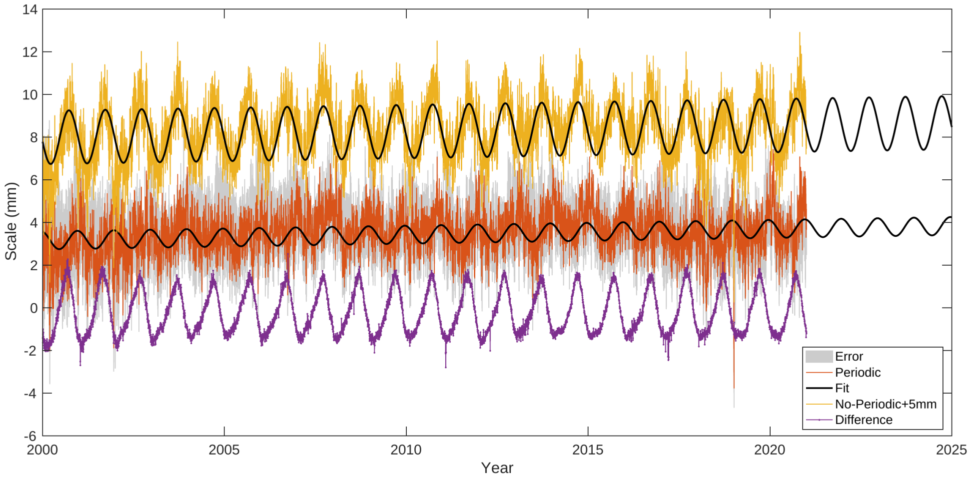


Figure 5: Estimates of scale differences between the MIT Repro3 timeseries and ITRF2020P with periodic terms applied (brown with gray shading showing 1-sigma error estimates) and with no periodic terms (yellow and offset by 5 mm for clarity). The purple curve shows the difference. The black lines are fits to a linear model with annual cosine and sine terms. The estimates of the offset (@2010.0) and rate from two results are 3.4 mm and 0.03 mm/yr. The scale rate looks small compared to the IGS result presented at the AC meeting.

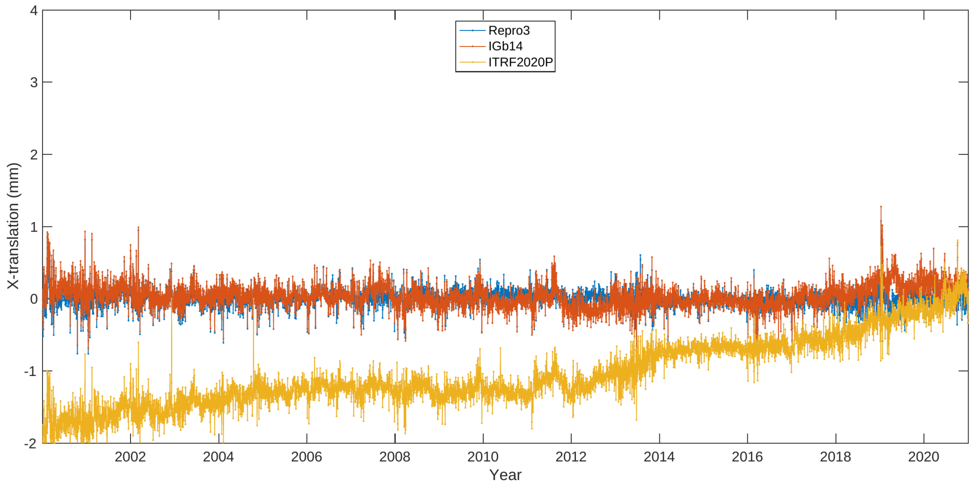


Figure 6: X translation estimates in aligning the MIT position time series to Repro3 (blue), IGb14 (brown) and ITRF2020P (dark yellow). The rates for the three reference frames are -0.00, 0.00 and 0.07 mm/yr, respectively, with zero rate with respect to Repro3 expected.

(blue line in each plot) to be near zero which they are. (The original alignment uses full variance covariance matrices which is slightly different to the time series method here where no inter-site correlations are used).

The figures show that there is a translation rate between ITRF2020P and the Repro3 reference frame. These rates in X, Y and Z are 0.07, -0.08 and 0.15 mm/yr. The Z-rate is larger than the GGOS 0.1 mm/yr reference stability requirement. Using a larger number of reference frame sites for ITRF2020P does not substantially change the result. The IGS14 hierarchical list averages 48 sites over the 20-years. The larger list averaged 327 sites with nearly all 350 sites in the MIT solution used after 2010 and as few as 250 in 2000. Sites were removed based on 4-sigma outlier condition while fitting the reference frame. With the larger number of sites, the X, Y, and Z rates were 0.06, -0.07 and 0.15 mm/yr which are little changed from the values above. The implication is the rates are intrinsic to the reference frame and not the choice of reference frame stations.

The final comparison was the weighted-root-mean-square fits to the reference frame sites from the different reference frames shown in Table 4. With no-scale changes estimated (just translation and rotation to align the frames), the smallest WRMS differences are for ITRF2020P with periodic terms applied. With no periodic terms, the fit to ITRF2020P is smaller than the Repro3 or IGb14 reference frames. (The fit IGb14 degrades after 2015). Estimating scale, reduces the height WRMS scatter but does not affect the N and E WRMS scatters (heights are downweighed in the frame alignment which is why N and

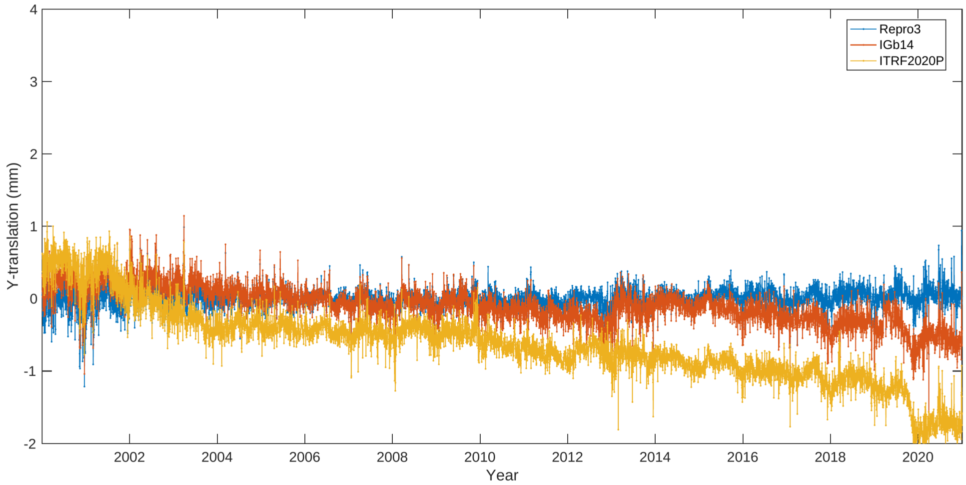


Figure 7: Similar to Figure 2 but for the Y-component. The Repro3, IGb14 and ITRF2020P rates are -0.00, -0.03 and -0.08 mm/yr, respectively.

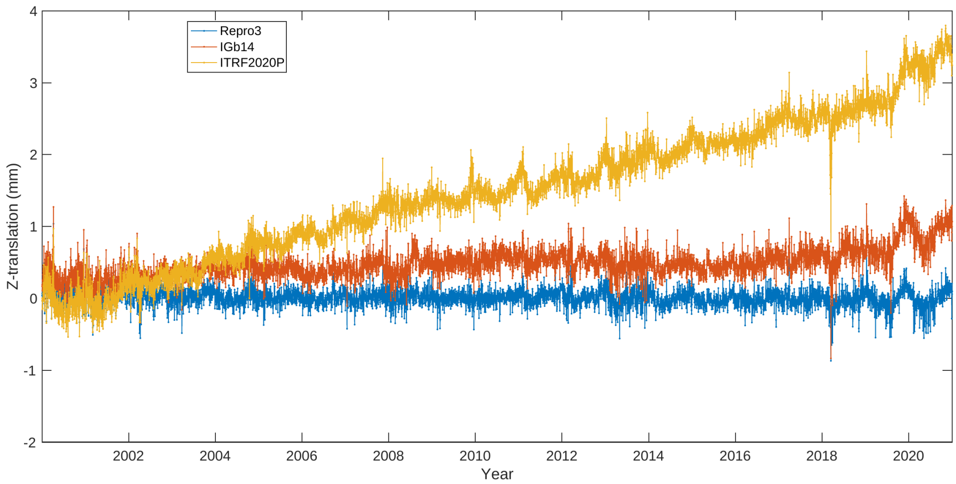


Figure 8: Similar to Figure 2 but for the Z-component. The Repro3, IGb14 and ITRF2020P rates are -0.00, 0.02 and 0.15 mm/yr, respectively.

Table 4: WRMS scatter about fits to 48 IGS14 reference frames sites for different realizations of the reference frame. For ITRF2020P, the frame can be realized with or without periodic terms (no Periodic). For ITRF2020P, we also show results with and without scale estimated.

Analysis	N (mm)	E (mm)	U (mm)
IGB14	1.97	2.17	10.25
Repro3	1.88	2.07	7.50
ITRF202P Periodic, no scale	1.69	1.79	7.29
ITRF202P no Periodic, no scale	1.79	1.87	7.73
ITRF202P Periodic, scale	1.69	1.79	6.29
ITRF202P no Periodic, scale	1.79	1.87	6.81

E scatters are not affected by estimating scale..

References

Herring, T.A., R.W. King, and M.A. Floyd. GAMIT/GLOBK version 10.71. Massachusetts Institute of Technology, 2019 http://www-gpsg.mit.edu/~simon/gtgk/Intro_GG.pdf

Villiger, A. and R. Dach (eds.) International GNSS Service Technical Report 2020 (IGS Annual Report). IGS Central Bureau and University of Bern; Bern Open Publishing DOI 10.48350/156425.

USNO Analysis Center Technical Report 2021

S. Byram, J. Crefton, J. Rohde

United States Naval Observatory
3450 Massachusetts Avenue Northwest
Washington DC 20392 USA
sharyl.m.byram.civ@us.navy.mil

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 Crefton, 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 Precise Point Positioning (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 https://cddis.nasa.gov/archive/gnss/products/troposphere/zpd/.

2 Product Performance, 2021

Figures 1-4 show the 2021 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 24 mm with respect to (wrt) the IGS rapid combined orbits. The USNO Ultra-rapid orbits had median WRMSs of 28 mm (24-h post-processed segment) and 47 mm (6-h predict) wrt the IGS rapid combined orbits. USNO rapid (post-processed) and Ultra-rapid 6-h predicted clocks had median 297 ps and 936 ps RMSs wrt IGS combined rapid clocks.

USNO rapid polar motion estimates had (x, y) 25 and 27 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 419 and 248 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 521 and 371 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 2021, seven-parameter Helmert transformations computed between USNO and IGS Ultra-rapid GPS+GLONASS orbits had median RMSs of 72 and 107 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 1168 and 406 microarcsec, respectively. USNO GPS+GLONASS Ultra-rapid 24-h predicted polar motion x and y values differed from the IGR values, RMS, by 1262 and 517 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 2021.

References

Byram S., and C. Hackman GNSS-Based Processing at the USNO: Incorporation of GLONASS Observations. 2012 IGS Workshop, Olstzyn, Poland, 2012a.

Byram S., and C. Hackman High-Precision GNSS Orbit, Clock and EOP Estimation at the United States Naval Observatory. Proc. 2012 IEEE/ION Position Location and Navigation Symposium, 659-63, 2012b.

Dach, R., S. Lutz, P. Walser, and P. Fridez. (eds.) Bernese GNSS Software Version 5.2. (user manual) Astronomical Institute of University of Bern, Bern, Switzerland, 2015.

Webb F.H. and J.F. Zumberge (eds.) An Introduction to GIPSY/OASIS-II: Precision Software for the Analysis of Data from the Global Positioning System. JPL internal publication D-11088, Jet Propulsion Laboratory, Pasadena, California, 1997.

Zumberge J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb. Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks. *J. Geophys. Res.*, 102 (B3), 5005-17, 1997.

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 past 24 h	ultra–rapid 6-h predict	rapid x	rapid y	ultra–rapid past 24 4 x	ultra–rapid past 24 4 y	ultra–rapid 24-h predict x	ultra–rapid 24-h predict y	rapid past 24 h	ultra–rapid 6-h predict
1/1/2021–12/31/2021	24	28	47	25	27	419	248	521	371	297	936

Table 2: Precision of USNO Ultra-Rapid GPS+GLONASS Test Products, 2021. Orbit statistics computed with respect to IGV Combined Ultra-Rapid GPS+GLONASS Products. Polar motion statistics computed with respect to IGS Rapid combined values.

USNO GLONASS satellite orbits			USNO GPS+GLONASS polar motion estimates	
Median RMS of 7-parameter Helmert transformation units: mm			RMS difference units: 10^{-6} arc sec	
dates	past 24 h	6-h predict	past 24 h	pred 6 h
1/1/2021–12/31/2021	72	107	x:1168 y: 406	x:1262 y: 517

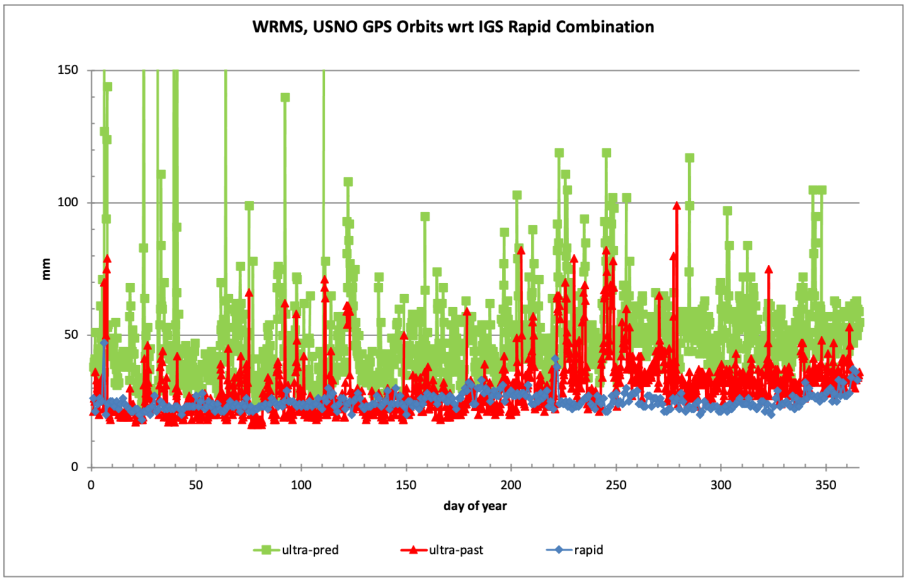


Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2021. "Ultra-past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra-pred" refers to first six hours of Ultra-rapid orbit prediction.

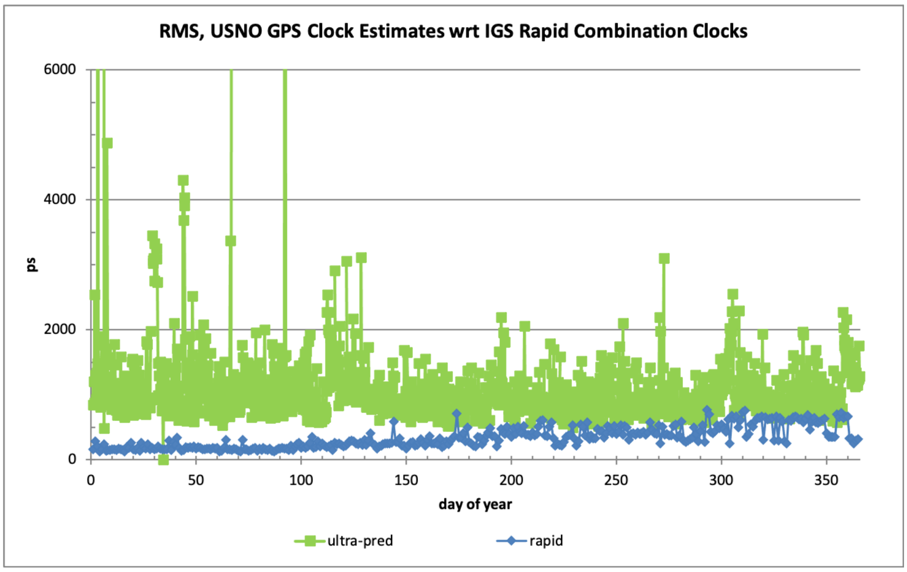


Figure 2: RMS of USNO GPS rapid clock estimates and Ultra-rapid clock predictions with respect to IGS Rapid Combination, 2021.

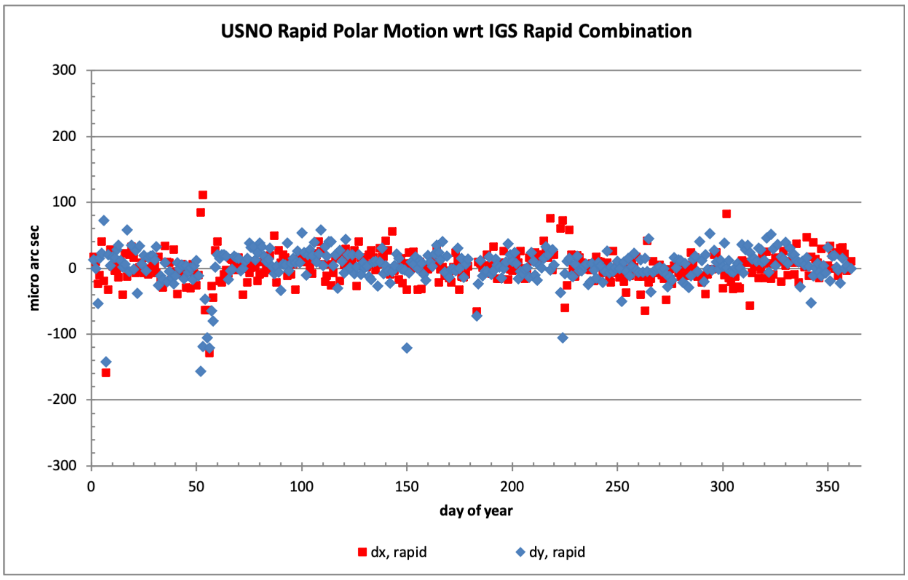


Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2021.

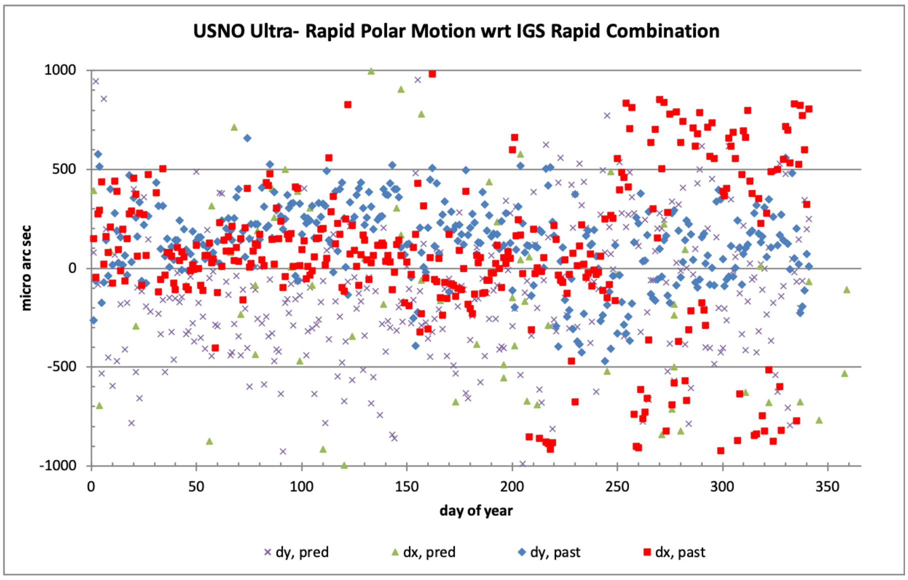


Figure 4: USNO Ultra-rapid polar motion estimates minus IGS Rapid Combination values, 2021.

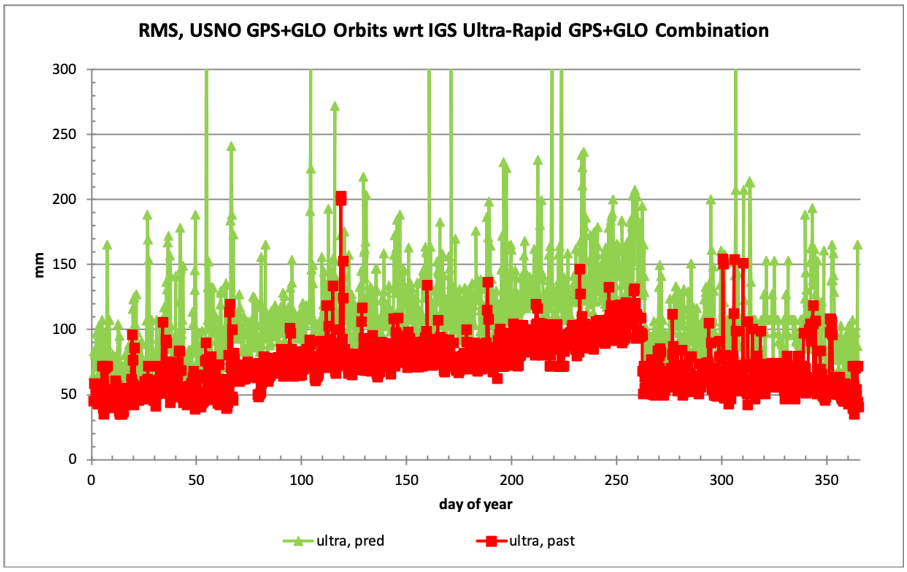


Figure 5: RMS of USNO Ultra-rapid GLONASS orbit estimates with respect to IGS Combined Ultra-rapid GLONASS orbits, 2021. "Ultra, past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra, pred" refers to first six hours of Ultra-rapid orbit prediction.

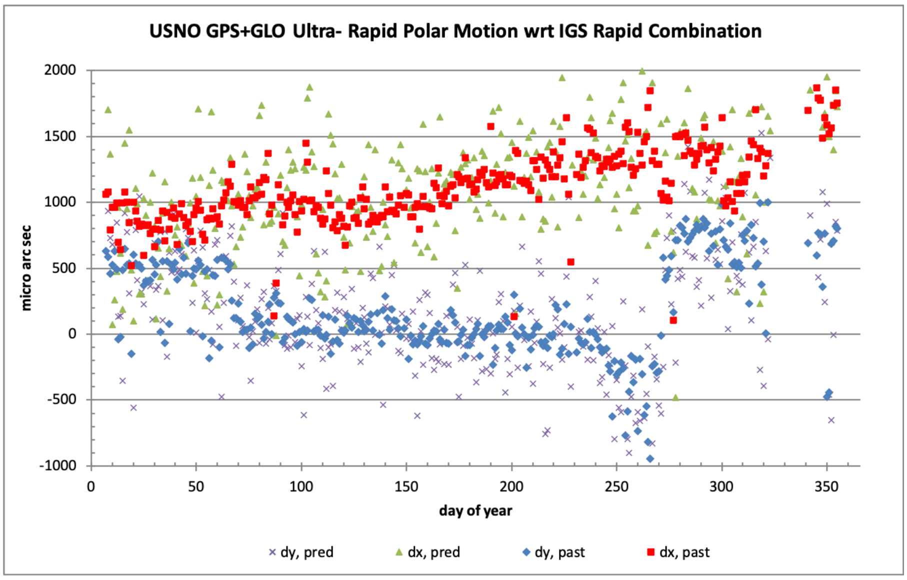


Figure 6: USNO Ultra-rapid GPS+GLONASS polar motion estimates with respect to the IGS "IGR" GPS-only rapid solution, 2021.

WHU Analysis Center Technical Report 2021

C. Shi[1,2], M. Li[1], Q. Zhao[1], J. Geng[1], Q. Zhang[1]

[1] GNSS Research Center, Wuhan University, Wuhan, China
[2] Beihang University, Beijing, China
E–mail: shi@whu.edu.cn

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 2021, WHU participated in the 3rd IGS Reprocessing campaign, updated the real-time global ionosphere modeling method and published the improved WHU RT GIM products, and started to provide multi-GNSS rapid phase bias products.

2 WHU Analysis Products

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

3 Ionosphere Activities

Wuhan University (WHU) was recognized as a new member of the IGS Ionosphere Associate Analysis Centers (IAACs) in February 2016. Since 21 June 2018, the new software named GNSS Ionosphere Monitoring and Analysis Software (GIMAS) (Zhang and Zhao, 2018) has been adopted to generate the daily rapid and final GIM products. At the end of 2020, WHU published the initial RT GIM products. During 2021, WHU published

Table 1: List of products provided by WHU.

WHU rapid GNSS products	
`whuWWWD.sp3`	Orbits for GPS/GLONASS/Galileo satellites
`whuWWWD.clk`	5-min clocks for stations and GPS/GLONASS/Galileo satellites
`whuWWWD.erp`	ERPs
WHU ultra-rapid GNSS products	
`whuWWWD_HH.sp3`	Orbits for GPS/GLONASS/Galileo 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
	Rapid OSB with 1-d multi-GNSS observations
`YYYYDDD0000`	
`IONO00WHU0`	Real time GIM with 5-min GPS observations

the improved RT GIM products, which can be accessed via Wuhan Real Time Data Center (`http://ntrip.gnsslab.cn`) with Mountpoint `IONO00WHU0` and Wuhan Data Center (`ftp://igs.gnsswhu.cn/pub/whu/MGEX/realtime-ionex`) in IONEX format.

Regarding the RT GIM, WHU uses the Spherical Harmonic Expansion (SHE) model with a maximum degree and order 15 to map the global ionosphere in a solar-geomagnetic reference frame. Currently, only the GPS real-time data streams from about 120 globally distributed IGS stations are used. To overcome the limited real-time data coverage and the uneven distribution, the 2-day predicted GIM is used as background information. The real-time SHE coefficients are estimated using both the real-time data and the 2-day predicted SHE coefficients. The weighting between the real-time data and the background information is important for both the RT-GIM precision and the root mean square (RMS) map (Zhang and Zhao, 2019). To avoid the influence of satellite and receiver DCB on ionospheric parameters estimation, we directly use the previous estimated DCB from WHU rapid GIM product. The WHU RT GIM is updated every 5 minutes and broadcasted every 1 minute.

4 WUM Rapid Phase Bias Products

We have started to provide multi-GNSS rapid phase bias products in the bias-SINEX format along with self-consistent orbit, phase clock, code biases and attitude quaternion products since September 2021, and the products are traced back to the beginning of

2020 (ftp://igs.gnsswhu.cn/pub/whu/phasebias/). Five GNSS are included in our products: GPS, GLONASS, Galileo, BDS-2 and BDS-3, but GLONASS and BDS GEO carrier-phase OSBs are not provided. Strategies of precise orbit determination are close to those of WUM final products, and further PPP processing is conducted to extract undifferenced phase biases in the form of OSBs (Geng et al., 2022).

Figs. 1,2,3 shows the phase OSBs for all GPS, Galileo and BDS satellites since 2020. Particularly, we use the phase clock/bias model proposed by Geng et al. (2019b) to resolve ambiguities, which suggests an update of clocks with obtained phase biases to become integer clocks, but keeping compatibility with IGS legacy clocks. Besides, regular comparison indicates that orbits could be more accurate if updated along with clocks, and thus we practically update both orbits and clocks for GPS and Galileo, but for BDS only clocks are updated. Generally, daily products will be uploaded at approximately 11:00 AM UTC on the next day (i.e., 11 hour latency), and additional private check is followed to ensure the reliability and accuracy.

BDS products comprise BDS-2 and BDS-3 constellations, and GEO satellites are excluded from ambiguity resolution. A five-parameter ECOM model is employed for the IGSO satellites while a nine-parameter ECOM2 model plus an a priori force model is used for MEO satellites. No earth radiation model is adopted presently, and neither the thermal radiation model. Considering the accuracy of our BDS orbits for the time being, ERPs are not estimated using BDS satellites, and properly lower weights are adapted for BDS observations compared with GPS. Before May 5th 2021, satellites with PRN above C37 are not included due to delayed updates of receivers on the majority of tracking stations, and we make efforts to maintain the narrow-lane fixing rate above 70% for BDS-3 constellations each day, while 60 for BDS-2 constellations.

Figure 4 depicts multi-GNSS PPP-AR results with our rapid products, conducted by PRIDE PPP-AR software (Geng et al., 2019a). We picked over 200 globally distributed stations, and the positions determined in daily solutions are compared with IGS weekly coordinates. The RMS of the differences are at a level of 1.3 cm, 1.3 cm and 4.9 cm in the east, north and up directions, respectively, after helmet transformation and five times the sigma for outlier rejection. It is highly recommended to use WUM rapid products with PRIDE PPP-AR software.

References

Liu J. and M. Ge PANDA software and its preliminary result of positioning and orbit determination. Wuhan University *Journal of Natural Sciences*, 8(2):603-609, 2003.

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

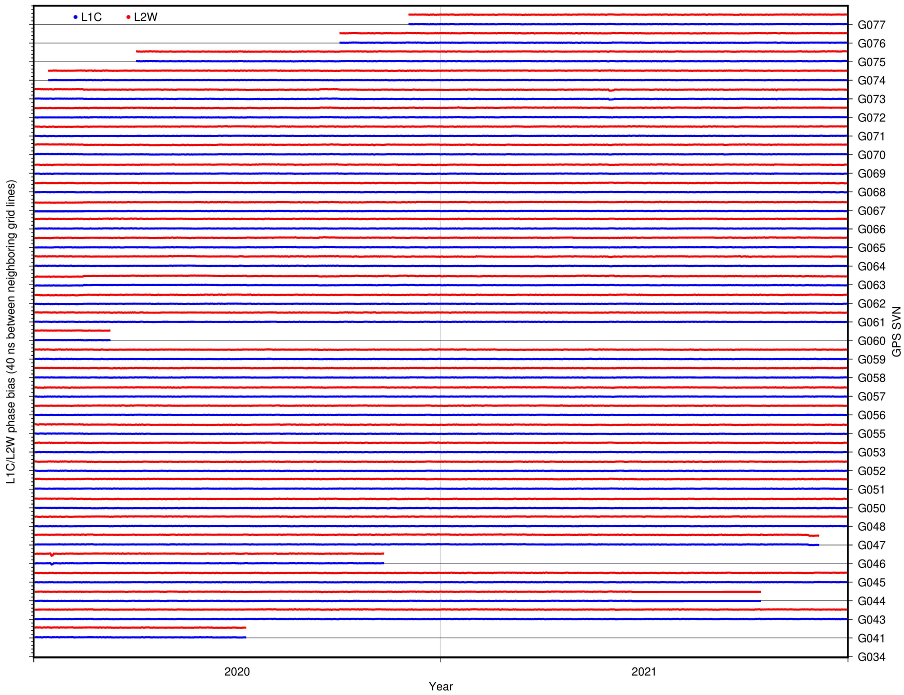


Figure 1: GPS satellite phase biases (ns) for the years of 2020 and 2021.

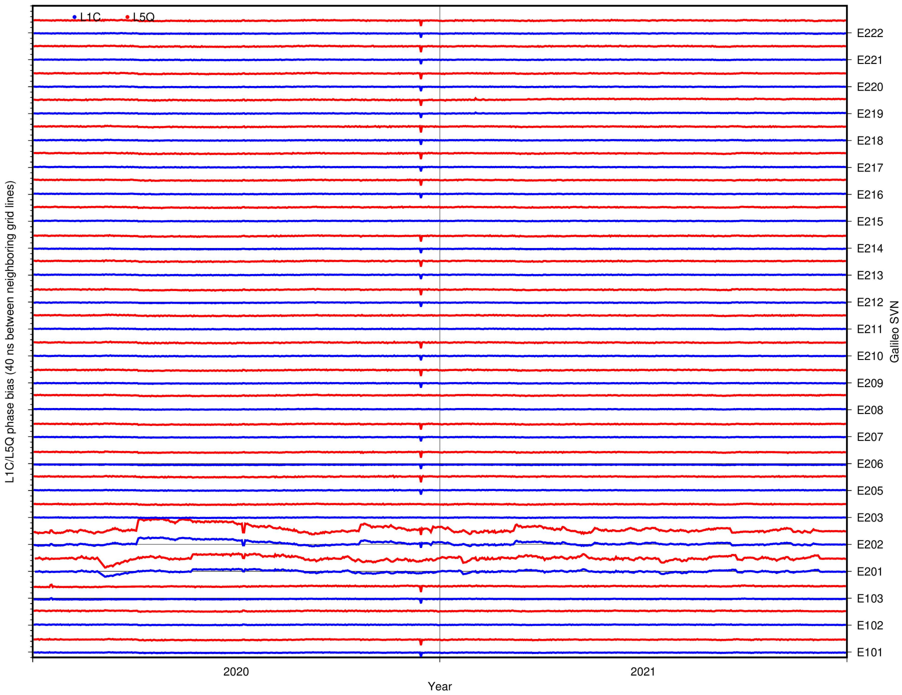


Figure 2: : Galileo satellite phase biases (ns) for the years of 2020 and 2021

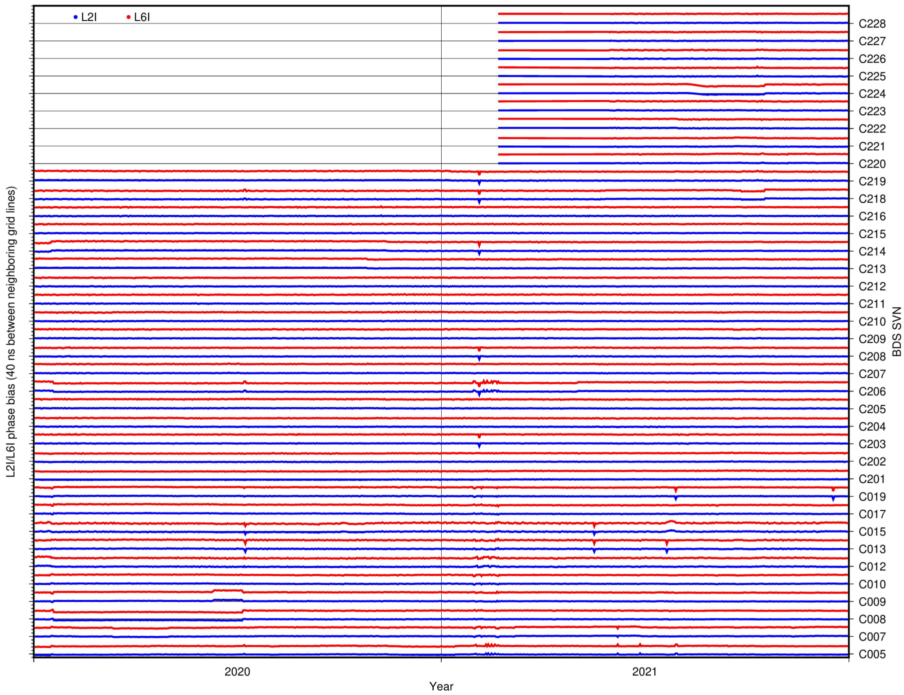


Figure 3: BDS-2 and BDS-3 satellite phase biases (ns) for the years of 2020 and 2021.

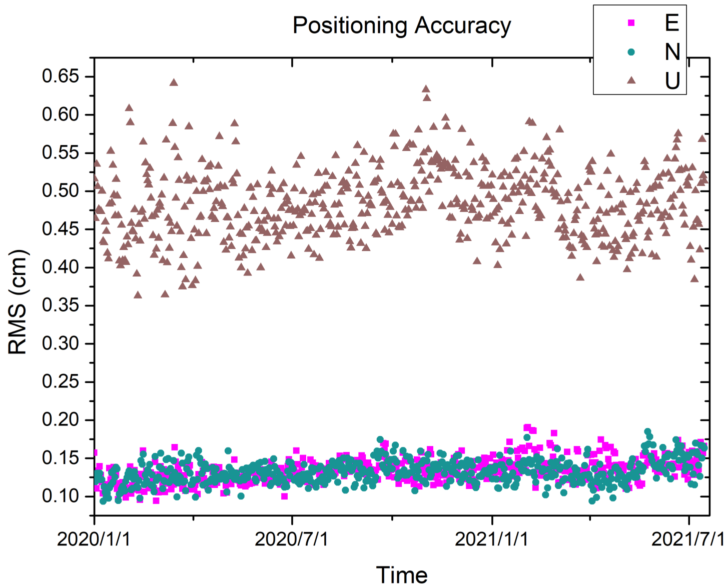


Figure 4: RMS errors (cm) of daily multi-GNSS PPP-AR positions in the east, north and up components at about 200 globally distributed stations against IGS weekly solutions after a Helmert transformation.

Q. Zhang, Q. Zhao Global ionosphere mapping and differential code bias estimation during low and high solar activity periods with GIMAS software. Remote Sensing, 10 (5), 705, 2018.

Q. Zhang, Q. Zhao Q. Analysis of the data processing strategies of spherical harmonic expansion model on global ionosphere mapping for moderate solar activity. Adv Space Res, 63 (3), 1214-1226, 2019.

Geng J, X. Chen Y. Pan, S. Mao, C. Li, J. Zhou, and K. Zhang. PRIDE PPP-AR: an open-source software for GPS PPP ambiguity resolution. GPS Solut 23, 91 doi: 10.1007/s10291-019-0888-1, 2019.

Geng J., X. Chen, Y. Pan, and Q. Zhao A modified phase clock/bias model to improve PPP ambiguity resolution at Wuhan University. J Geod 93(10):2053-2067, 2019.

Geng J., Q. Wen, Q. Zhang, G. Li, and K. Zhang GNSS observable-specific phase biases for all-frequency PPP ambiguity resolution. J Geod, 2022. (accepted)

EUREF Permanent Network Technical Report 2021

C. Bruyninx[1], E. Brockmann[2], A. Kenyeres[3], J. Legrand[1], T. Liwosz[4], R. Pacione[5], W. Söhne[6], C. Völksen[7]

[1] Royal Observatory of Belgium (ROB), Av. Circulaire, B-1180 Brussels, Belgium
E-mail: C.Bruyninx@oma.be
[2] Federal Office of Topography swisstopo, Wabern, Switzerland
[3] LTK Satellite Geodetic Observatory, Budapest, Hungary
[4] Warsaw University of Technology (WUT), Warsaw, Poland
[5] E-GEOS Centro di Geodesia Spaziale (ASI/CGS), Matera, Italy
[6] Federal Agency for Cartography and Geodesy (BKG), Frankfurt am Main, Germany
[7] Bavarian Academy of Sciences and Humanities, Munich, Germany

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 2021.

2 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 2021, the EPN Central Bureau (CB) added 8 new stations to the EPN (indicated in green in Figure 1): one in Germany, three in Denmark, one in Ireland, one in Norway, one in Hungary, and one in Turkey.

During the 2021 EUREF symposium, the EPN CB organized the splinter meeting "Towards FAIR GNSS data" with the goal to raise awareness of EPN station managers and data centres for FAIR data principles, which increase the Findability, Interoperability, Accessibility and Reusability of the GNSS data. As a first step, all EPN station managers have been encouraged to attach in EUREF's GNSS metadata data system M3G (https://gnss-metadata.eu) a data license to their RINEX data. This has been in the meantime been done for 80% of the EPN stations. In addition, the upcoming RINEX 4 observation file format also includes new header lines to insert in a standardized way the data license as well as the Digital Object Identifier (DOI) of the data. Using such a DOI also increases the findability and future tracking of usage of the data.

In 2021, the EPN CB continued to quality check all incoming daily RINEX 2 and RINEX 3 data using the G-Nut/Anubis software (https://gnutsoftware.com/software/anubis/) and provide the results on the EPN CB web site (https://www.epncb.oma.be). In June 2021, G-Nut/Anubis was upgraded from v2.3 to v3.1.

In order to comply with EU General Data Protection Regulation (GDPR), the EPN CB has removed the EUREF mail, EUREF IP mail, and EUREF LAC mail archives from its public-facing ftp and web portals.

Encouraged by Resolution No 2 of the 2019 EUREF symposium in Tallinn, more than 60% of the EPN stations are sharing their daily RINEX data with the European Plate Observing System (EPOS). These EPN data are made available to EPOS through the ROB-EUREF EPOS data node built on top of the historical EPN data centre managed by the EPN CB.

3 Data Products

3.1 Availability

Likewise the EPN data, the EPN data products should be available from all EPN data centers. Some gaps and the necessary improvement to overcome the deficiencies have been identified and will be installed early 2022.

3.2 Positions

The EPN Analysis Centers (ACs) operationally process GNSS observations collected at EPN stations. In 2021, all 16 ACs (Table 1) were providing final daily coordinate solutions of their subnetworks. Twelve ACs were providing also rapid daily solutions, and four ACs

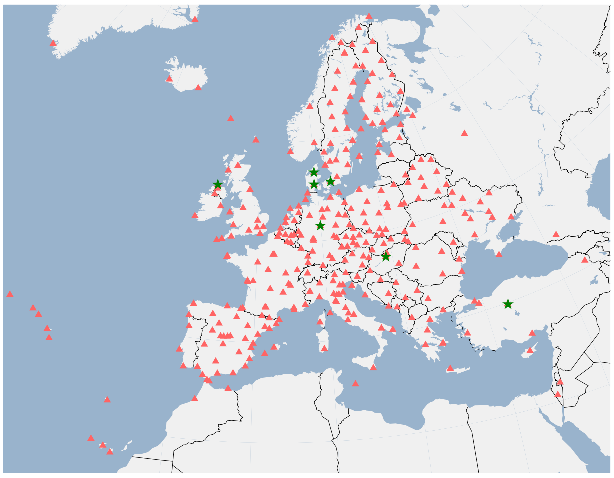


Figure 1: New GNSS stations (in green) integrated in the EPN in 2021. The new Norwegian station is not shown on the map.

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.

In 2021, the main changes concerning AC and combined solutions were as follows. Since April 2021, the SUT (Slovak University of Technology) AC started providing to EUREF ultra-rapid solutions, in addition to final and rapid solutions (Table 1). Previously only three ACs (ASI, BKG and LPT) provided this type of solution to EPN. The AC ultra-rapid solutions are provided to EUREF and combined by ACC every hour. Since January 2021, the ASI (Centro di Geodesia Spaziale G. Colombo, Italy) AC started using new software from the Jet Propulsion Laboratory (JPL), GipsyX (Bertiger et al., 2020) for the generation of its final and rapid products. Previously ASI used the older software from the JPL, GIPSY OASIS. With this change, ASI started processing not only GPS observations, but also GLONASS and Galileo. The new solutions showed better agreement with the combined solution for the north and vertical components, than the solutions computed previously using GIPSY OASIS software. However, for the east component worse agreement was observed for the new solutions (probably due to not fixing ambiguities in these solutions for the moment). Also, in 2021 8 new GNSS stations were added to the EPN and were included in the AC data analysis and combined solutions.

In 2021, the ACC, together with ACs representatives and the EUREF Governing Board members, updated the Guidelines for the EPN ACs. The main changes concerned the

Table 1: 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 (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	79(2/0)	GipsyX 1.6	GRE
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	112(2/0)	BSW 5.2	GRE
BEV	Federal Office of Metrology and Surveying, Austria	WD	132(2/0)	BSW 5.2	GRE
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRU	140(7/0)	BSW 5.2	GRE
COE	Center for Orbit Determination in Europe, Switzerland	WD	40(0/0)	BSW 5.3	GR
IGE	Instituto Geografico Nacional, Spain	WDR	91(1/1)	BSW 5.2	GRE
IGN	Institut Géographique National de L'information Geographique et Forestiére, France	WDR	63(0/1)	BSW 5.2	GR
LPT	Federal Office of Topography swisstopo, Switzerland	WDRU	61(0/0)	BSW 5.3	GRE
MUT	Military University of Technology, Poland	WD	148(0/0)	GG 10.71	GE
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WDR	104(4/0)	BSW 5.2	GRE
RGA	Republic Geodetic Authority, Serbia	WD	55(3/1)	BSW 5.2	GRE
ROB	Royal Observatory of Belgium, Belgium	DR	111(4/1)	BSW 5.2	GRE
SGO	Lechner Knowledge Center, Hungary	WDR	48(1/0)	BSW 5.2	GRE
SUT	Slovak University of Technology, Slovakia	WDRU	58(0/0)	BSW 5.2	GRE
UPA	University of Padova, Italy	WDR	71(0/0)	BSW 5.2	GRE
WUT	Warsaw University of Technology, Poland	WDR	139(1/0)	BSW 5.2	GRE

recommendations on processing Galileo observations with appropriate CODE products, and the modifications of the EPN ground antenna model (with repeated individual calibrations). It was also added in the guidelines that the AC subnetworks of GNSS stations used for the generation of rapid and ultra-rapid AC solutions may be different from the officially assigned AC subnetworks used for the final solutions (e.g., ACs may include more stations in rapid and ultra-rapid solutions to increase redundancy and the number of monitored stations). The new guidelines are available at the EPN Central Bureau website (from https://epncb.oma.be/_documentation/guidelines/guidelines_analysis_centres.pdf).

3.3 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 gradi-ents are delivered with a sampling rate of one hour, on a weekly basis, but in daily files. In 2021, the 8 new GNSS stations added to the EPN have been have successfully included in the tropo-spheric combined products. The EPN combined solution provides ZTD estimates only for sta-tions processed by at least three ACs. Therefore in 2021, the ZTD combined estimates are avail-able, on average, for 355 stations (compared to 341 in 2020).

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.

Starting from GPS week 2139 (January 3rd, 2021), for each combined EPN station, Integrated Water Vapour (IWV) is provided along with ZTD. They are disseminated in SINEX_TRO v2.0 format and are available in the EUREF product directory (https://igs.bkg.bund.de/root_ftp/EUREF/products/) at the BKG data centre. The VMF Data Server at the Technical University of Vienna is acknowledged for providing the necessary auxiliary information, surface air pressure and weighed mean temperature of the atmosphere, used in the conversion.

The EPN multi-year tropospheric solution has been updated up to GPS week 2173 and covers the period 1996-08/2021. For each EPN station, ZTD time series, ZTD monthly mean (period 1996-2020) and inter-technique comparison with radiosonde data (if collocated) plots are available at the EPN CB from http://www.epncb.oma.be/_productsservices/sitezenithpathdelays/. From January 2018 onwards, high-resolution radiosonde data are used. They are provided by EUMETNET in the framework of the MoU in place between EUMETNET and EUREF.

3.4 Reference Frame

To maintain the ETRS89, EUREF releases, each 15 weeks, an update of the multi-year coordinates/velocities of the EPN stations in the latest ITRS/ETRS89 realizations (Legrand and Bruynix, 2019). The Reference Frame Coordinator (RFC) computes these EPN multi-year solutions with the CATREF software (Altamimi et al., 2007). In 2021, four solutions expressed in IGb14 have been released: C2130 (in January 2021, Legrand (2021a)), C2145 (in April 2021, Legrand (2021b)), C2160 (in July 2021, Legrand (2021c)), and C2175 (in December 2021, Legrand (2021d)).

In May 2021, the EUREF Governing Board made a significant update of the "Guidelines for EUREF Densifications" (Legrand et al. , 2021). This update introduces a new station classification. The Reference Frame Product has also evolved. Since solution C2145, the positions and velocities of all the stations with more than 3 years of data are published in the SNX and SSC files. In practice, velocities are now published for much more EPN stations. For the solution C2145, the positions and velocities of 359 EPN stations have been published compared to the 280 class A stations in previous solutions.

In order to evaluate the quality of the EPN stations as reference stations, the "Tool for Reference Station Selection" is available on line and results are updated at each release of the Reference Frame Product: https://epncb.oma.be/_productsservices/ReferenceFrame/ (Legrand and Bruyninx , 2021).

The EPN multi-year product including the SINEX files in IGb14 and ETRF2014, the discontinuity list and the associated residual position time series are available from ftp://epncb.eu/pub/station/coord/EPN/. In addition to the EPN multi-year product, 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.

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 March 2021 (GPS week 1500-2150) 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 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 EPN Densification product portal (https://epnd.sgo-penc.hu).

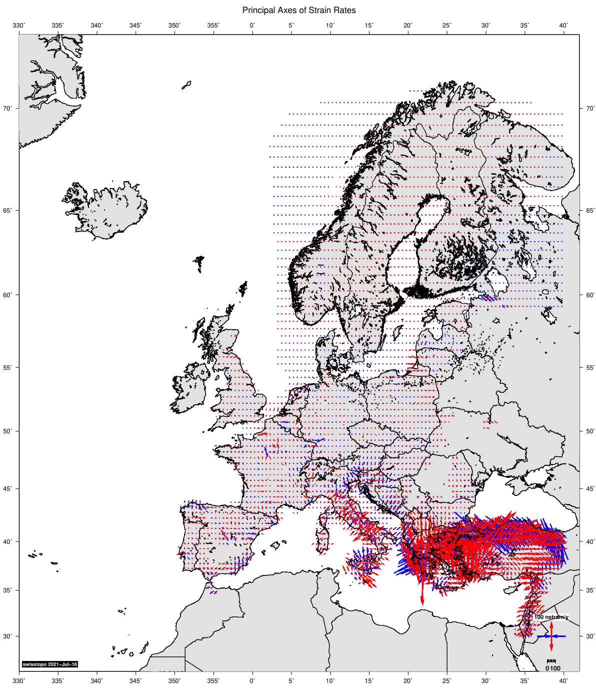


Figure 2: Strain rates derived from the data set of the EU Dense Velocities (using Dionysos Satellite Observatory StrainTool).

4.2 European Dense Velocities

Most of the existing velocity fields in Europe are already included in the data set of the Working Group on Dense Velocities. Totally, more than 7000 individual station velocities are available for Europe. Recently, an automated outlier rejection criterion was implemented to further smooth the data set. Originally, it was planned that this step is not necessary and that the contributor will take care of outlier. We ask the contributors to take some attention on this topic when sending updates. The website of the project, http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html has been extended by "wind animation" visualization as well as strain rate plots.

In parallel, an OGC working group met almost every 2 weeks in 2021 to work on standardizations on a deformation model which will be derived from this data set (see Figure 2).

4.3 Multi-GNSS

Multi-GNSS data processing in operational mode is standard. The majority of ACs are operationally using GPS, GLONASS, and Galileo data. BeiDou, especially BeiDou-3 processing, is not yet possible. The transition for RINEX 2 to RINEX 3 continuously improves, slowly. End of 2021 a new RINEX 4 format version will be released (and confirmed by RTCM beginning 2022). The biggest changes are for the RINEX navigation files. File naming is identical to RINEX 3 and also the content of the observation files includes some minor improvements. Therefore, the version change from 3 to 4 is not comparable with the version change from 2 to 3.

4.4 EPN Reprocessing

A discussion on the implementation of the EPN Repro3 campaign has been initiated within the EPN Analysis Centers group. A large number of ACs are willing to participate. One goal of this campaign will be to generate results largely consistent with the IGS Repro3 campaign. In particular, it will come into play here that almost the same antennae correction models (`igsR3_2077.atx`) will be used as in the IGS Repro3 campaign. Therefore, we are currently discussing whether to dispense the use of individual antenna calibration in the future to increase consistency with IGS results. Furthermore, it must be ensured that the upcoming operational solutions in the IGS20 match the reprocessed solutions.

5 Stream and Product Dissemination

End of 2021, 198 EPN stations (i.e., mount-points) provided real-time data (after 193 end of 2020 and 188 end of 2019) which corresponds to 55 % (after 53 % in 2020 and 54 % in 2019) of the EPN stations. 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 four stations still providing RTCM 2.3. 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. – 8 stations) or MSM5 (message type 1075 etc.), increased to 73 whereas the MSM7 (1077 etc.) was available for 97 (after 83 in 2020) stations. Hence, the stations providing the old "legacy" messages 1004 (GPS) and 1012 (GLONASS) slightly reduced from 27 to 26. 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 the past years, the consistency between the three EPN broadcasters further improved. In particular, the ASI caster successfully continued the implementation of missing stations, so that 96 % (after 95 % in 2020 and 85 % in 2019) of the real-time data is available at all EPN casters. For the remaining 5 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, so-called broadcaster guidelines are going to be published soon, which follow to a large extent the strategy that has been developed in the EPN guidelines and which have been extended also by real-time station guidelines. The IGS is also pushing the development of the specific IGS-SSR format (Hauschild et al., this volume). The long product and broadcast ephemerides mount-point names have been completely introduced within the IGS, and consequently also the EUREF products were adapted: EUREF01 will be replaced by SSRA02IGS0_EUREF and EUREF02 by SSRA03IGS0_EUREF.

References

Altamimi Z., P. Sillard, and C. Boucher CATREF software: Combination and analysis of terrestrial reference frames. LAREG Technical, Institut Géographique National, Paris, France, 2007.

Bertiger W., Y. Bar-Sever, A. Dorsey, B. Haines, N. Harvey, D. Hemberger, M. Heflin, W. Lu, M. Miller, AW. Moore, D. Murphy, P. Ries, L. Romans, A. Sibois, A. Sibthorpe, B. Szilagyi, M. allisneri, P. Willis. GipsyX / RTGx, a new tool set for space geodetic operations and research, Advances in Space Research, vol. 66, iss. 3, pp. 469-489, https://doi.org/10.1016/j.asr.2020.04.015, 2020

Kenyeres A., JG. Bellet, C. Bruyninx, A. Caporali, F. de Doncker, B. Droscak, A. Duret, P. Franke, I. Georgiev, R. Bingley, L. Huisman, L. Jivall, O. Khoda, K. Kollo, AI. Kurt, S. Lahtinen, J. Legrand, B. Magyar, D. Mesmaker, K. Morozova, J. Nagl, S. Ozdemir, X. Papanikolaouo, E. Parseulinas, G. Stangl, OB. Tangen, M. Valdes, M. Ryczywolski, J. Zurutuza, and M. Weber Regional integration of long-term national dense GNSS network solutions. GPS Solutions, 23:122, 2019. https://doi.org/10.1007/s10291-019-0902-7

Legrand J., C. Bruyninx, Z. Altamimi, A. Caporali, A. Kenyeres, and M. Lidberg. Guidelines for EUREF Densifications, Available from Royal Observatory of Belgium, https://doi.org/10.24414/ROB-EUREF-Guidelines-DENS

Legrand J. and C. Bruyninx. Reference Frame Coordination Status Report: EPN Multi-year Position/Velocity Product, Presented at EPN Analysis Center Workshop, Warsaw Poland, October 16-17, 2019

Legrand J. and C. Bruyninx. On-line Reference Station Selection Tool, Presented at Online symposium of the IAG Subcommission for Europe (EUREF), Ljubljana, Slovenia, May 26 – 28

Legrand J. EPN multi-year position and velocity solution C2130, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2130

Legrand J. EPN multi-year position and velocity solution C2145, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2145

Legrand J. EPN multi-year position and velocity solution C2160, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2160

Legrand J. EPN multi-year position and velocity solution C2175, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2175

SIRGAS Regional Network Associate Analysis Centre Technical Report 2021

L. Sánchez

Deutsches Geodätisches Forschungsinstitut
der Technischen Universität München (DGFI-TUM)
Arcisstr. 21, 80333 München, Germany

1 Introduction

The Geodetic Reference System for the Americas (SIRGAS) is presently realised by a network of continuously operating GNSS stations distributed over Latin America (Fig. 1). 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; Sánchez et al. , 2018; Cioce V. et al., 2020; Tarrío et al., 2021)). 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 About SIRGAS and the IGS Regional Network Associate Analysis Centre for SIRGAS

The original acronym of SIRGAS – Geocentric Reference System for South America – changed in 2001 to Geocentric Reference System for the Americas following the recommendation of the seventh United Nations Cartographic Conference for the Americas (New York, January 22 – 27, 2001) to adopt SIRGAS as the reference system in all American

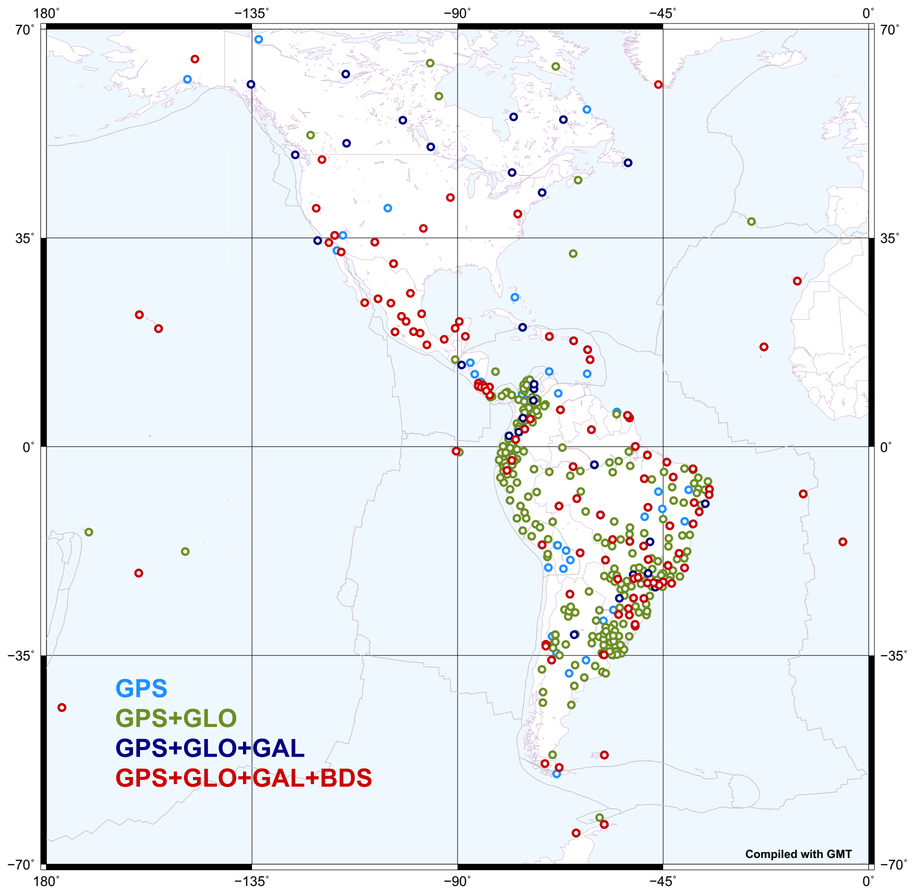


Figure 1: SIRGAS reference frame (as of Dec 2021).

countries. In 2020, the acronym of SIRGAS changed again to Geodetic Reference System for the Americas, as the objectives of SIRGAS were extended to the determination of a unified physical reference system for gravimetry, physical heights and geoid. This change is in agreement with the recommendations arisen from the International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America, held in Buenos Aires, Argentina, in September 2019 (Sánchez and Brunini, 2019).

The Deutsches Geodätisches Forschungsinstitut der Technische Universität München (DGFI-TUM) has been involved in the SIRGAS research activities since the establishment of SIRGAS in 1993 (Sánchez, 2018a). DGFI-TUM coordinated the SIRGAS GPS campaigns of 1995 and 2000 and acted as an analysis centre of both campaigns contributing to the final solutions known as SIRGAS95 (SIRGAS, 1997) and SIRGAS2000 (Drewes et al., 2005). In June 1996, DGFI-TUM established in agreement with the International GNSS Service (IGS) the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS) and assumed the responsibility of processing the SIRGAS continuously operating network in a weekly basis (Seemüller and Drewes, 1998). This responsibility also includes the computation of cumulative (multi-year) solutions and surface velocity models for SIRGAS (known as VEMOS) to monitor the kinematics of the SIRGAS reference frame. Since 2008, with the creation of different SIRGAS processing centres under the responsibility of Latin American agencies, the IGS RNAAC SIRGAS concentrates on the computation of the SIRGAS core network and on the combination of this network with the solutions delivered by the Latin American processing centres for the national SIRGAS densifications. The computation of multi-year solutions and surface deformation models continues being a main contribution of the IGS RNAAC SIRGAS.

DGFI-TUM hosted the SIRGAS portal www.sirgas.org between July 2007 and July 2021, when the SIRGAS Executive Committee decided to move the SIRGAS web site to https://sirgas.ipgh.org/. All official matters related to SIRGAS are available at the new site. The site www.sirgas.org continues providing research results and data products generated by the IGS RNAAC SIRGAS.

3 SIRGAS reference network

The SIRGAS continuously operating network is at present composed of about 450 continuously operating GNSS stations (Fig. 1). 98 of these stations are included in the IGS global network (Johnston et al., 2017) and some of them are used for the datum realisation in the SIRGAS reference frame computation. 86% of the SIRGAS stations track GLONASS, 31% Galileo and 20% Beidou. Compared to previous years, SIRGAS now includes a larger number of IGS stations, especially in North America, in order to support the activities of the Working Group of the Geodetic Reference Framework for the Americas (GRFA) of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM), chapter Americas (see http://www.un-ggim-americas.org/

en/assets/modulos/grupoTrabajo.html?grupo=3). The operational performance of the SIRGAS network is based on the contribution of more than 50 organisations, who 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:

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 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.
- National reference networks (SIRGAS-N) improving the densification of the core network and providing accessibility to the reference frame at national and local levels. Both, the core network and the national networks satisfy the same characteristics and quality; and each station is processed by three analysis centres.

4 SIRGAS processing centres

The SIRGAS-C network is processed by DGFI-TUM as the IGS RNAAC SIRGAS (Sánchez et al. , 2016). 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), see IGAC (2021).
- IGM-Cl: Instituto Geográfico Militar of Chile, see Rozas et al. (2019).

- IGN-Ar: Instituto Geográfico Nacional of Argentina, see Gómez et al. (2018).
- INEGI: Instituto Nacional de Estadística y Geografía (México), see Gasca (2018).
- IGN-Pe: Instituto Geográfico Nacional of Peru (official processing centre since January 2022).
- IGM-Uy: Instituto Geográfico Militar of Uruguay, see Caubarrère (2018).
- USC: Universidad de Santiago de Chile: Centro de Procesamiento y Análisis Geodésico USC (Chile), see Tarrío et al. (2019).

These processing centres deliver loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. The individual solutions are combined by the SIRGAS Combination Centres currently operated by DGFI-TUM (Sánchez et al., 2012) and IBGE (Costa et al., 2012).

In September 2021, a new SIRGAS experimental processing centre was installed at the Instituto Geográfico Nacional of Costa Rica (IGN-CR). 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.

5 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 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).

6 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 Centre for the Neutral Atmosphere generates hourly tropospheric zenith path delays. 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 products are made available by the IGS RNAAC SIRGAS (DGFI-TUM) at `ftp.sirgas.org` (Sánchez et al. , 2018).

7 Reprocessing of the SIRGAS reference frame in ITRF2014

The operational SIRGAS products refer to the IGS reference frame valid at the time when the GNSS data are routinely processed. A first reprocessing campaign of the SIRGAS reference network was performed in 2010 in order to determine SIRGAS coordinates based on absolute corrections for the GPS antenna phase centre variations and referring to the IGS05 reference frame (Seemüller et al., 2010). A reprocessing referring to the

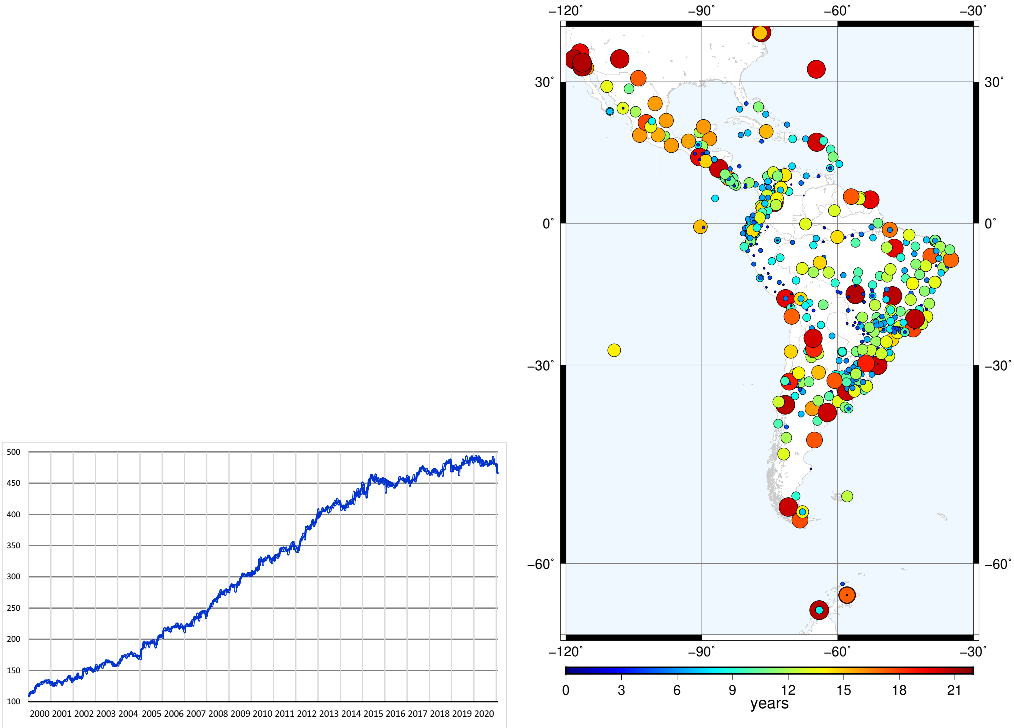


Figure 2: Number of RINEX files processed in each year (left) and number of years processed for each station in the SIRGAS-Repro2.

IGS08/IGb08 frame was not undertaken. In this way, the SIRGAS weekly normal equations presently refer to different reference frames: IGS05 (from January 2000 to April 2011), IGS08/IGb08 (from April 2011 to January 2017). IGS14/IGb14 (since January 2017). In order to evaluate the long-term stability of the SIRGAS reference frame, a new reprocessing of the SIRGAS GNSS historical data from January 2000 to December 2020 based on the ITRF2014 (IGS14/IGb14) was accomplished by the IGS RNAAC SIRGAS, hereinafter referred to as SIRGAS-Repro2 (Sánchez and Kehm, 2021). Figure 2 shows the number of RINEX files processed in each year as well as the number of years processed for each station.

Main products of SIRGAS-Repro2 are weekly station positions referring to the IGb14 reference frame and a cumulative solution including all the SIRGAS stations in operation more than two. Figure 3 depicts the RMS values of the differences between the operational weekly SIRGAS solutions (transformed to IGS14/IGb14) and SIRGAS-Repro2 weekly coordinates with respect to the weekly coordinates of the IGS stations in IGS14/IGb14. Current efforts concentrate on modelling post-seismic effects in SIRGAS stations affected by strong earthquakes (see Fig. 4).

SIRGAS-Repro2 does not include SIRGAS regional stations only, but also a global distri-

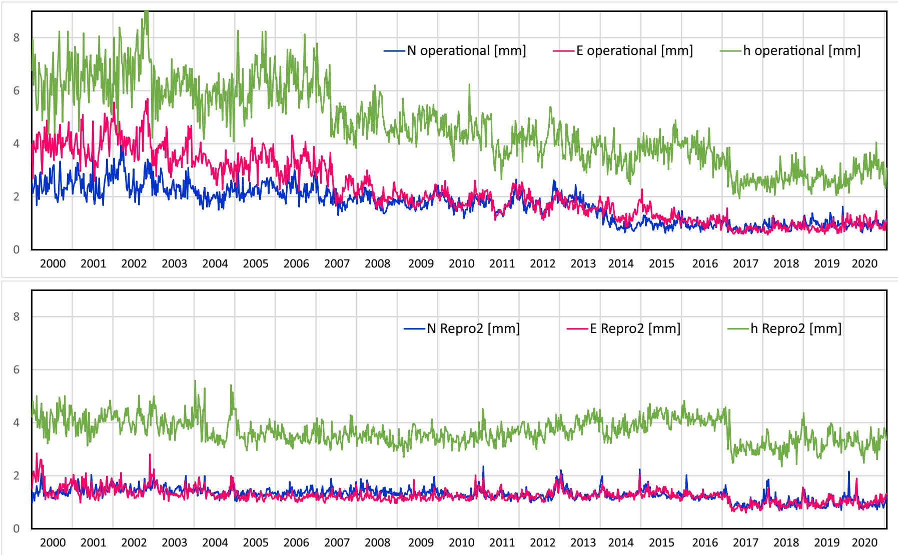


Figure 3: RMS values of the differences between the operational weekly SIRGAS solutions (transformed to IGS14/IGb14) and SIRGAS-Repro2 weekly coordinates with respect to the weekly coordinates of the IGS stations in IGS14/IGb14.

bution of IGS stations co-located with VLBI and SLR (Fig. 5). The main objective is to implement the realisation of 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; Sánchez and Kehm, 2021).

References

Brunini C., L. Sánchez, H. Drewes, S.M.A. Costa, V. Mackern, W. Martinez, W. Seemüller, and A.L. Da Silva Improved analysis strategy and accessibility of the SIRGAS Reference Frame. In: Kenyon S., M.C. Pacino, U. Marti (Eds.), Geodesy for Planet Earth, IAG Symposia 136: 3-10, doi:10.1007/978-3-642-20338-1_1, 2012.

Caubarrère G. Red Geodésica Nacional Activa de Uruguay (REGNA-ROU), Avances del proyecto IHRS, Centro Local de Procesamiento SIRGAS de Uruguay (SGM-Uy), Colaboración en el desarrollo de la Red Geodésica Nacional Activa de la República de Paraguay. Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9-12, 2018.

Cioce V., et al. Actividades del Grupo de Trabajo I (Sistema de Referencia) en el período 2019-2020. Symposium SIRGAS2020, online, 2020.

Costa S., A. Silva, F. Scofano, G. Mantovani, M.A. De Almeida, and N. Moura Ampliación

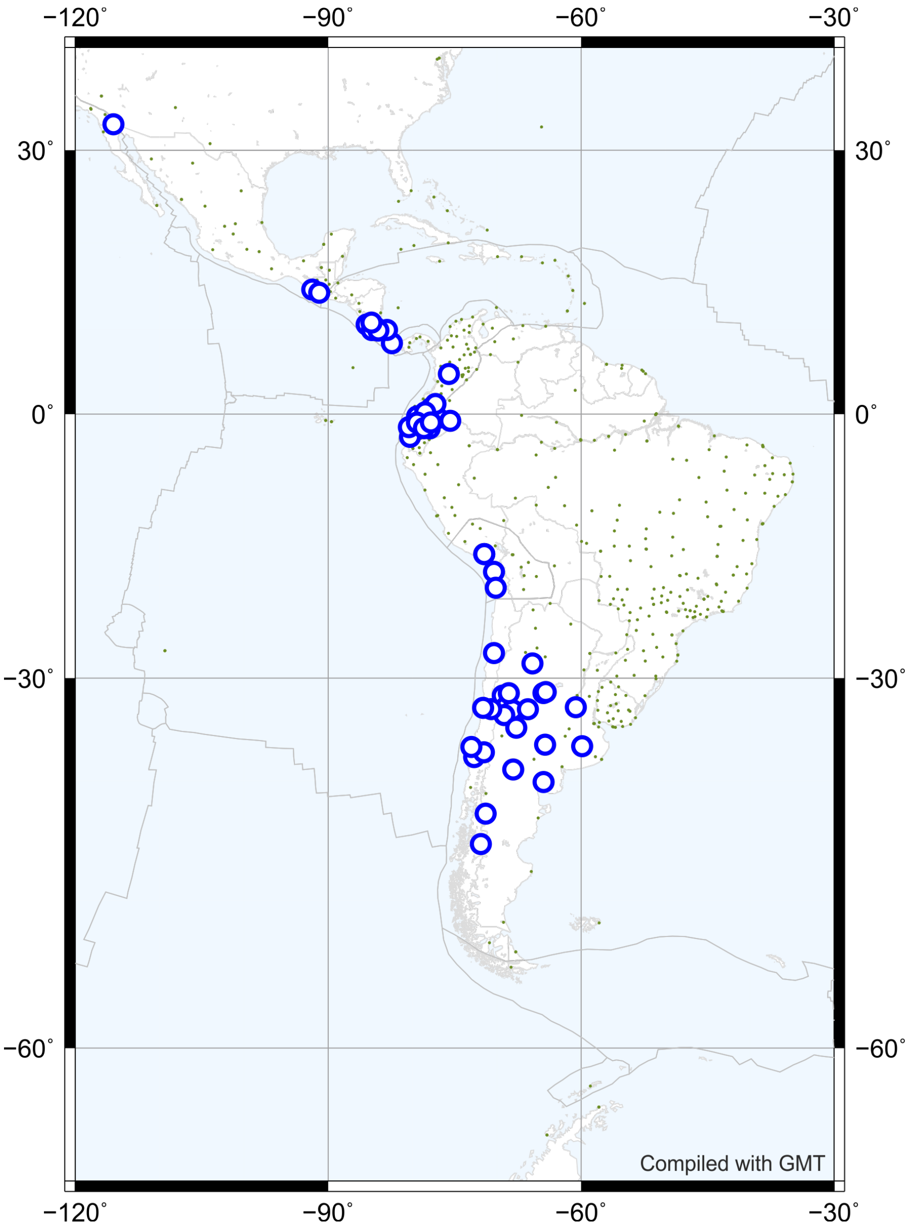


Figure 4: SIRGAS station with post-seismic effects to be modelled.

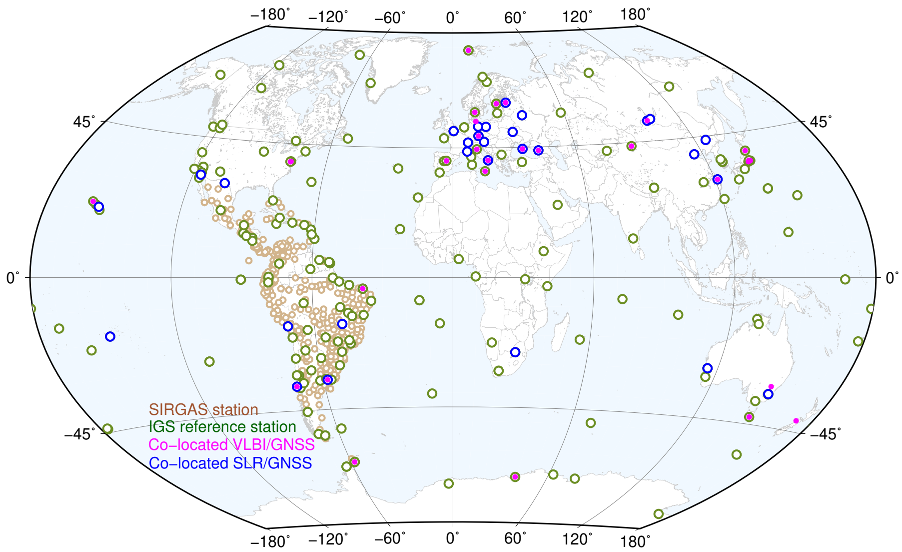


Figure 5: GNSS stations included in SIRGAS-Repro2. VLBI/GNSS (magenta dots) and SLR/GNSS (blue circles) co-located stations are foreseen for the combination of GNSS, SLR and VLBI normal equations. IGS core stations (green circles) are necessary for a high-quality GNSS data processing.

y modernización de la RBMC: Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS. Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9-12, 2018.

Costa S.M.A., A.L. Silva, and J.A. Vaz Processing evaluation of SIRGAS-CON network by IBGE Analysis Center. In: Kenyon S., M.C. Pacino, U. Marti (Eds.), Geodesy for Planet Earth, IAG Symposia, 136:859-868, Springer Berlin Heidelberg, doi:10.1007/978-3-642-20338-1_108, 2012.

Dach R., S. Lutz, P. Walser, and P. Fridez(Eds) Bernese GNSS Software Version 5.2. Astronomical Institute, University of Bern, 2015.

Drewes H., K. Kaniuth, C. Voelksen, S.M. Alves Costa, and L.P. Souto Fortes Results of the SIRGAS campaign 2000 and coordinates variations with respect to the 1995 South American geocentric reference frame. In: A Window on the Future of Geodesy, IAG Symposia, 128: 32-37, doi: 10.1007/3-540-27432-4_6, 2005.

Gasca J.G. : Red Geodésica Nacional Activa en México 1993-2018. Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9-12, 2018.

Gómez D., H. Guagni, D. Piñón, S. Cimbaro, and M. Bevis Nuevo clúster de procesamiento GNSS científico del Instituto Geográfico Nacional. Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9-12, 2018.

Herring T.A., R.W. King R.W., and S.C. McClusky Introduction to GAMIT/GLOBK, Release 10.4, Massachusetts Institue of Technology, 2010.

IGAC La red geodésica nacional: Un servicio continuo y esencial para la planeación y el desarrollo territorial en Colombia, Subdirección de Geografía y Cartografía, Instituto Geográfico Agustín Codazzi - IGAC. Webinar SIRGAS: Actividades Geodésicas en las Americas, July 9, 2021.

Johnston G., A. Riddell, and G. Hausler The International GNSS Service. In Teunissen, Peter J.G., and 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, 2017.

Kehm A., M. Bloßfeld, E. C. Pavlis, F. Seitz Future global SLR network evolution and its impact on the terrestrial reference frame. Journal of Geodesy, 92(6), 625–635, 10.1007/s00190-017-1083-1, 2017

Kehm A., L. Sánchez, M. Bloßfeld, D. Angermann, H. Drewes, and F. Seitz Combination strategies for the realization of an Epoch Reference Frame for South America. European Geosciences Union General Assembly 2019, Vienna, Austria, 2019a

Mackern M.V., M.L Mateo, M.F. Camisay, and P.V. Morichetti Tropospheric products from high-level GNSS processing in Latin America. International Association of Geodesy Symposia Series, Vol 152, open access, doi: 10.1007/1345_2020_121, 2020

Petit G. and B. Luzum (Eds) IERS Conventions 2010. IERS Technical Note 36. Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt a.M., 2010.

Rozas S., I. Parada, C. Reyes, C. Iturriaga Centro Oficial de Procesamiento SIRGAS IGM-CL: Instituto Geográfico Militar de Chile. Symposium SIRGAS2019, Río de Janeiro, Brazil. Nov 6 - 14, 2019.

Sánchez L. 22 years of IGS RNAAC SIRGAS - IGS Regional Network Associate Analysis Centre for SIRGAS. Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9-12, 2018.

Sánchez L. Reprocessing of the SIRGAS reference frame from January 2000 to December 2020. Symposium SIRGAS2021, virtual meeting, 2021.

Sánchez L. and C. Brunini Report on the project Implementation of the United Nations' Resolution on the Global Geodetic Reference Frame (UN-GGRF) for Sustainable Development in Latin America, granted by the International Union of Geodesy and Geophysics (IUGG), 2019, available at http://www.iugg.org/programs/FinalReports_2016-2019/2018-2019_IAG.pdf, accessed on 2022-01-31

Sánchez L. and M. Seitz Recent activities of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR) - Report for the SIRGAS 2011 General Meeting August 8 - 10, 2011. Heredia, Costa Rica. DGFI Report, 87, 48 pp, hdl: 10013/epic.43995.d001, 2011.

Sánchez L., V. Cioce, H. Drewes, C. Brunini, M.A. De Almeida, G. Gaytan, H. Guagni, V. Mackernm, W. Martínez, A. Morillo, J. Moya, H. Parra, O. Rodríguez, N. Suárez, and S. Rudenko Time evolution of the SIRGAS reference frame. International Association of Geodesy Commission 1 Symposium Reference Frames for Applications in Geosciences (REFAG2018), 42nd COSPAR Scientific Assembly. Pasadena, California. July 14-22, 2018.

Sánchez L., H. Drewes, C. Brunini, M.V. Mackern, and W. Martínez-Díaz SIRGAS core network stability. In: Rizos C., Willis P. (Eds.) IAG 150 Years, IAG Symposia 143, 183-190, doi: 10.1007/1345_2015_143, 2016.

Sánchez L. and H. Drewes Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America. Journal of Geodynamics, doi:10.1016/j.jog.2016.06.005, 2016.

Sánchez L. and H. Drewes Geodetic monitoring of the variable surface deformation in Latin America. In: Freymueller J., Sánchez L. (Eds.), IAG Symposia 152, in press, 2020.

Sánchez L. and A. Kehm SIRGAS Regional Network Associate Analysis Centre (IGS RNAAC SIRGAS) Technical Report 2020. International GNSS Service Technical Report 2020, 135-146, doi: 10.48350/156425, 2021.

Sánchez L., W. Seemüller, and M. Seitz Combination of the Weekly Solutions Delivered by the SIRGAS Processing Centres for the SIRGAS-CON Reference Frame. In: Kenyon S., M.C. Pacino, U. Marti (Eds.), Geodesy for Planet Earth, IAG Symposia 136: 845-851, doi:10.1007/978-3-642-20338-1_106, 2012.

Seemueller W. and H. Drewes The IGS regional associate analysis center for South America at DGFI/I. Springer; IAG Symposia; Vol. 118: 211-215, 1998.

Seemüller W., L. Sánchez, M. Seitz, and H. Drewes The position and velocity solution SIR10P01 of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR). DGFI Report No. 86, Munich, 2010.

SIRGAS SIRGAS Final Report; Working Groups I and II IBGE, Rio de Janeiro; 96 p. 1997. Available at http://www.sirgas.org/fileadmin/docs/SIRGAS95RepEng.pdf, accessed on 2022-01-31.

Tarrío Mosquera J.A., M. Caverlotti Silva, J.L. Borcosque, A. Ortega, B. Barraza, R. Quiroga, K. Salinas, G. Lira, J. Inzunza, I. Cepeda, and F. Isla Centro USC de la Universidad de Santiago de Chile: logros, metas y retos. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019.

Tarrío J.A., L. Sánchez, S. Alves, A. Silva, J. Inzunza, G. Caubarrère, A. Martínez, O. Rodríguez, E. Aleuy, H. Guagni, and G. González Recent achievements and current challenges in the maintenance of the geodetic reference frame of the Americas. International Association of Geodesy (IAG) Scientific Assembly 2021, Beijing, China, June 28, 2021.

Part III

Data Centers

Infrastructure Committee Technical Report 2021

M. Bradke[1], D. Maggert[2], R. Ruddick[3], W. Söhne[4]

[1] GFZ Potsdam, Germany
E–mail: markus.bradke@gfz-potsdam.de
[2] UNAVCO, United States
[3] Geoscience Australia, Australia
[4] BKG, Germany

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 Centres, fundamental product coordinators, pilot projects, and working groups.

The IC fulfils this objective by coordinating and overseeing facets of the IGS organisation 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 synchronise 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 mem-

Table 1: List of IGS Infrastructure Committee Members (as of January 1, 2022)

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

bers) and a representative from each of the active global data centres.

Table 1 shows the current membership as of January 1, 2022. Rui Fernandes (UBI/SEGAL) replaced Laura Sanchez (TUM) as IGS Network Representative by IGS Governing Board vote in December 2021.

3 Summary of Activities in 2021

Over 2021 the IC has supported the Network Coordinator on answering questions from IGS product and data users, plus adding 8 Multi-GNSS stations to the network and removing 10 long-standing absent stations from the network as stated in Table 2.

The IC Coordinator (ICC) has participated in several IGS Working Group teleconferences over the year to ensure the coordination in terms of station needs and infrastructure across all the different IGS activities. In addition, the second stop of the "Tour de l'IGS: Infras-

Table 2: List of approved and decommissioned Stations in the IGS Network in 2021

Station	Location	Systems	Real-Time	Agency
Approved Stations (8):				
BAUT00DEU	Bautzen, Germany	GRECS	Yes	BKG
BRMG00DEU	Bremgarten, Germany	GRECS	Yes	BKG
BZR200ITA	Bolzano, Italy	GREC	Yes	STPOS
CYNE00GUF	Cayenne, French Guiana	GRECS	Yes	IGN
JPDR00IND	Jodhpur, India	GREC	Yes	ISRO
MSSA00JPN	Misasa, Japan	GRECJ	Yes	JAXA
NABG00NOR	Ny-Ålesund, Norway	GREC	Yes	NMA
USCL00CHL	Santiago de Chile, Chile	GRECS	Yes	USACH
Decommissioned Stations (10):				
CRAO00UKR	Simeiz, Ukraine	G	No	CRAO
EUSM00MYS	Nibong Tebal, Malaysia	GRECJ	No	JAXA
GMSD00JPN	Nakatane Town, Japan	GRECJ	No	JAXA
GUAO00CHN	Urumqi, China	G	No	UAO
IRKT00RUS	Irkutsk, Russian Federation	G	No	DUT
KSMV00JPN	Kashima, Japan	G	No	NICT
PBRI00IND	Port Blair, India	GRECJSI	No	ISRO
PEN200HUN	Penc, Hungary	GREC	No	SGO
RCMN00KEN	Nairobi, Kenya	GR	No	RCMRD
USNO00USA	Washington DC, United States	G	No	USNO

tructure" has been organised in cooperation with the IGS Central Bureau in September 2021.

The IC worked on the creation and update of infrastructure related guidelines. The "Guidelines for IGS Real-Time Broadcasters and Stations" have been developed in close collaboration with the IGS Real-Time Working Group and accepted by the Governing Board in December 2021. The "Guidelines for IGS Continuously Operating Reference Stations (CORS)" – replacing the "IGS Site Guidelines" (last updated in July 2015) – are currently in preparation and under review by members of the IC. The aim is to publish these Guidelines in the first quarter of 2022. The IC also initiated the creation of guidelines for Analysis Centres and Data Centres.

The Committee established two permanent task teams: "IGS Stations" and "GeodesyML". The first team focuses on the evaluation and assessment of new station proposals. The team consists of the IC Coordinator, the IGS Network Coordinator as well as the three network representatives and selected network representatives from international networks. The task team ensures that new stations are compliant to the newly created "Guidelines for IGS CORS" and the IGS 2021+ Strategic Plan. The team coordinates the integration of such stations to regional GNSS networks (e.g., EPN, APREF, SIRGAS) prior to their acceptance on the IGS level. Furthermore, standardised approval forms for the review of stations were established with the aim to give better feedback to the station operators and to support a better traceability of decisions.

The GeodesyML task team works on the development of new features implemented into the current standard. There are currently features proposed that stem for the need to take into account GNSS data users requests when querying and/or downloading station information (e.g., information on the precise coordinates of the GNSS station) as well as FAIR data principles (e.g., attach data license, include file provenance information, etc.). Related to the metadata handling and exchange, the IC addressed the need for compliance to the GDPR (General Data Protection Regulation, European Union) and similar international data protection policies. The IGS Network Coordinator and Central Bureau reached out to the station operators to use generic email addresses and contact points in the IGS site logs, GNSS data and products.

The IC further initiated that all IGS stations are available in the IGS final products since GPS week 2150. GFZ (as one of the official IGS Analysis Centres) was able to include those stations that haven't being analysed by any of the IGS Analysis Centres.

The Committee initiated the provision of quality check metrics for all IGS stations on the IGS website as well the inclusion of the time series plots formerly hosted by IGN.

4 Current and planned Activities

In 2022, the Committee aims to increase the number of Multi-GNSS and Real-Time stations by active outreach. A special focus will lay on regions that are less represented in the IGS. We are going to provide support to station operators in selected regions (e.g., North African countries, Middle East, Siberia) to build capacity and capability. Currently, 12 Multi-GNSS stations from Mainland US and Alaska are under revision that will support the densification of the IGS network on the North American continent.

Furthermore, we will initiate and support a fast but safe transition to RINEX 4.00 by coordinating the necessary activities in all IGS instances and beyond. The timeline for all steps will be publicly available and communicated to the community as clearly as possible.

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. The new version of the SLM (Site Log Manager) is currently under development by the IGS CB.

Last but not least, the Committee is planning to assemble a comprehensive program for the plenary infrastructure session of the IGS Workshop that will be held in Boulder, Colorado in June 2022.

Acronyms

BKG	Bundesamt für Kartographie und Geodäsie
CDDIS	Crustal Dynamics Data Information System
CRAO	Crimean Astrophysical Observatory
DLR	German Aerospace Center
DUT	Delft University of Technology
ESA	European Space Agency
ESOC	European Space Operations Centre
GA	Geoscience Australia
GFZ	GeoForschungsZentrum Potsdam
GNS	GNS Science New Zealand
GSOC	German Space Operations Center
ICL	Imperial College London
IGN	Institut national de l'information géographique et forestière
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KASI	Korea Astronomy and Space Science Institute
MIT	Massachusetts Institute of Technology
NICT	National Institute of Information and Communications Technology
NMA	Norwegian Mapping Agency
NRCan	Natural Resources Canada
NRL	United States Naval Research Laboratory
RCMRD	Regional Centre for Mapping of Resources for Development
ROB	Royal Observatory of Belgium
SEGAL	Space & Earth Geodetic Analysis Laboratory
SGO	Satellite Geodetic Observatory
SIO	Scripps Institution of Oceanography
STPOS	South Tyrolean Position Service
TUM	Technical University Munich
UAO	Urumqi Astronomical Observatory
UBI	University of Beira Interior
USACH	Universidad de Santiago de Chile
WHU	Wuhan University

GSSC Global Data Center Technical Report 2021

V. Navarro, I. Romero, J. Ventura-Traveset

European Space Agency
Vicente.Navarro@esa.int, Ignacio.Romero@esa.int, Javier.Ventura-Traveset@esa.int

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 2021 Developments

During 2021, GSSC developments have focused on releasing the first public version of the GNSS Science Exploitation Platform "GSSC Now".

Figure 1: GSSC Now - Integration in gssc.esa.int

This platform, released as public beta, provides advanced search and analysis services on top of GSSC's repository (including IGS assets). These services allow users to search IGS data using keywords, worldwide maps and filters.

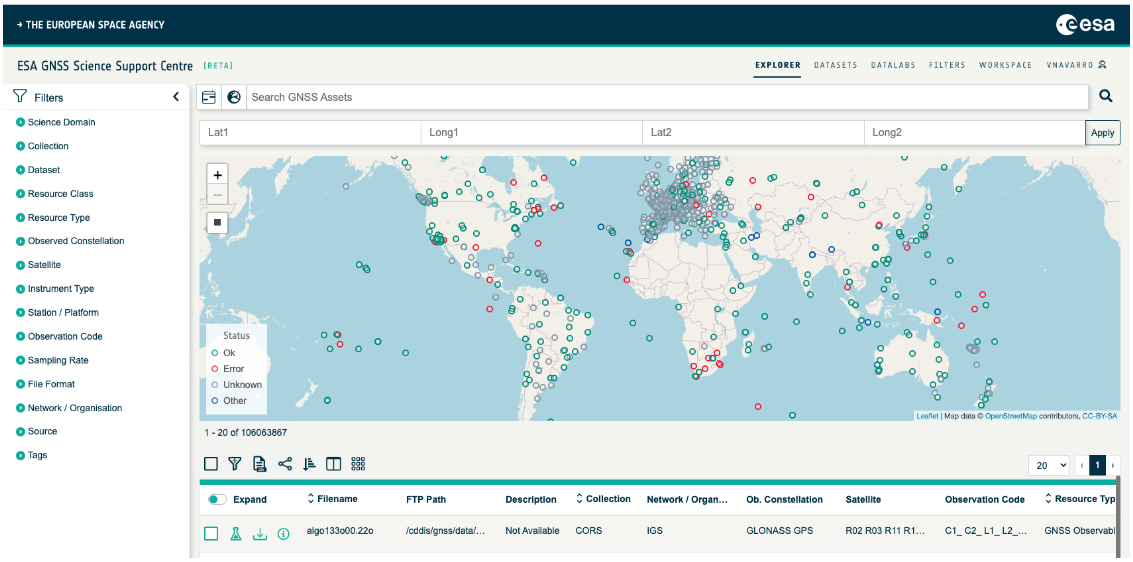


Figure 2: GSSC Now – Explorer View

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 cloud-based analysis using multiple GSSC Datalabs available in an AppStore fashion.

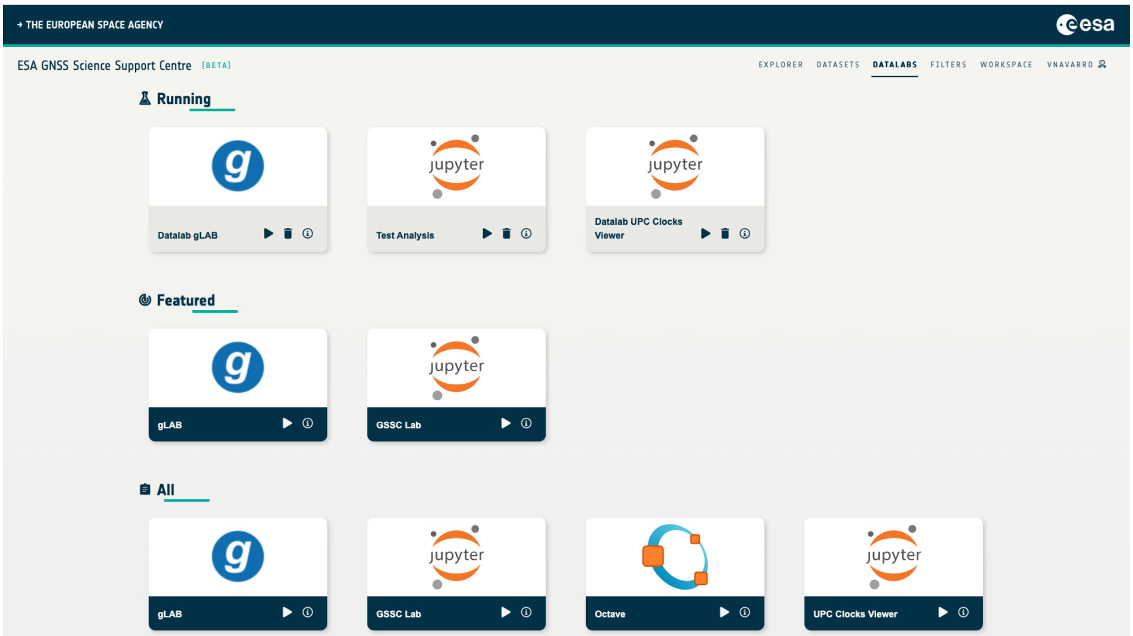


Figure 3: GSSC Now – Datalabs View

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, 2021 has continued with the steady evolution of GSSC (gssc.esa.int) repository and ingestion services supported by following developments:

- GNSS Real-Time data streaming through NTRIP services
- Migration to HTTP ingestion and dissemination services for CDDIS related collections.
- Assessment of additional GNSS collections for integration into the repository extension with new data collections for ESA projects.
- Improved security and monitoring capabilities to support the definition of dashboards with real-time information on alarms and KPIs.
- Improved load balancing capabilities.
- ESA Now user interface improvements

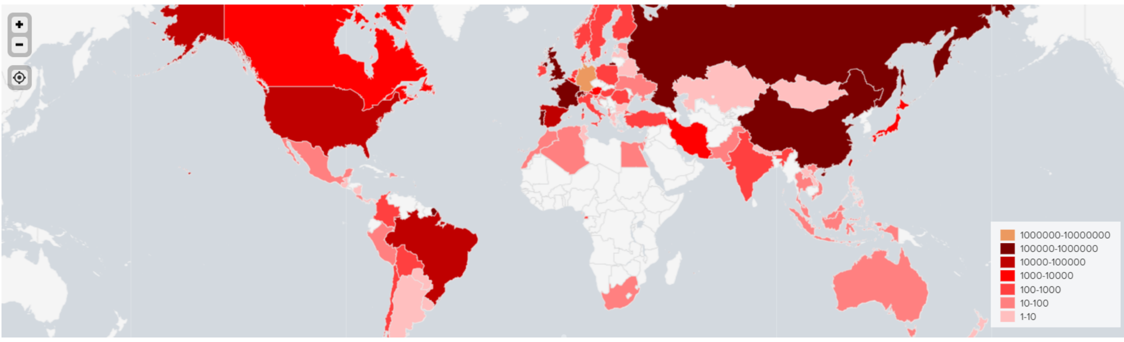


Figure 4: Worldwide Number of IGS File Downloads in 2021

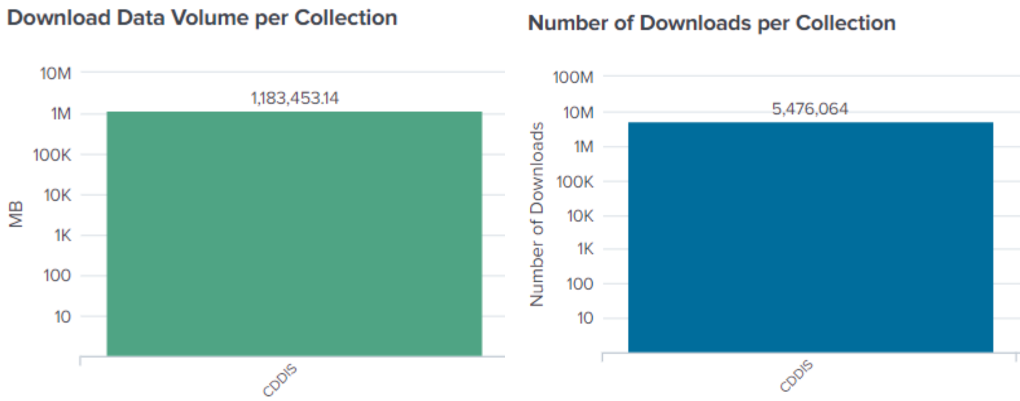


Figure 5: Volume and Number of IGS File Downloads

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

Figure 6: Volume and Number of IGS File Downloads

4 Planned 2022 Activities

Planned 2022 activities will include:

- Adaptive and evolutionary maintenance in line with IGS requirements.
- GSSC Now evolution in support to Navigation Science Programme Proposal - GENESIS.
- Integration of data processing pipelines for GNSS Science resulting from Galileo Science Office projects in the area of Machine Learning, IoT and Crowdsourcing.

WHU Data Center
Technical Report 2021

Q. Zhao, M. Li

GNSS Research Center, Wuhan University, Wuhan, China
E-mail: zhaoql@whu.edu.cn

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 2021 are summarized in this report, which also includes recent changes or improvments 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/).

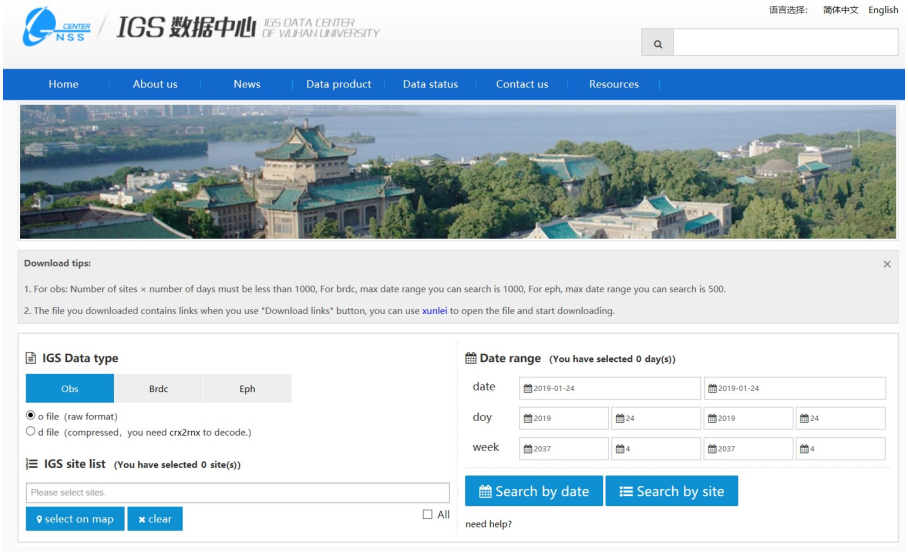


Figure 1: A snapshot of the website of WHU data center for data and products provision.

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 enable significant improvement of orbit predictions and error reduction for user applications.

WHU data center started to provide multi-GNSS rapid phase bias products in the bias-SINEX format along with self-consistent orbit, phase clock, code biases and attitude quaternion products since September 2021, and the products are traced back to the beginning of 2020 (ftp://igs.gnsswhu.cn/pub/whu/phasebias/). Five GNSS are included in our products: GPS, GLONASS, Galileo, BDS-2 and BDS-3.

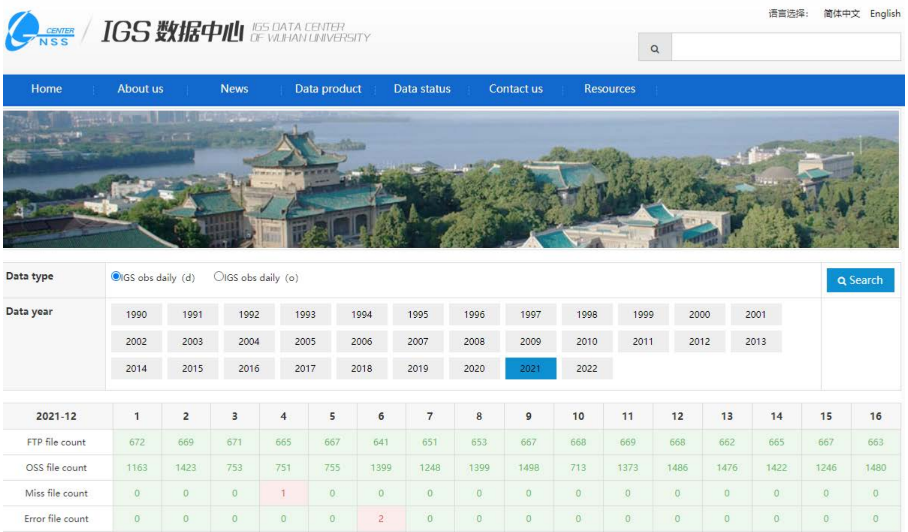


Figure 2: Data and products monitoring of WHU data center.

The WHU RT GIMs also are accessible via Wuhan Real Time Data Center (http://ntrip.gnsslab.cn) with Mountpoint `IONO00WHU0` and Wuhan Data Center (ftp://igs.gnsswhu.cn/pub/whu/MGEX/realtime-ionex) in IONEX format.

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 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 2021

J. Dostal, P. Neumaier, J. Schmidt, W. Söhne, A. Stürze, E. Wiesensarter

Federal Agency for Cartography and Geodesy (BKG)
Frankfurt am Main, Germany

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 (section 2) and real-time (section 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 several virtual machines placed at BKG's premises. It consists of a file server, a database server and an application server dedicated to data processing and web access. All relevant parts of BKG's GDC are backed-up on a daily basis.

2.2 Access

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. 1Hz) 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.

To ensure an as much as possible correct download, the number of simultaneous users of the GDC has been limited to 230.

As the FTP protocol has many security weaknesses, users are encouraged you to use the HTTPS protocol for downloading files. Support for downloading files via FTP will be turned off within the next year or years. Support for FTP uploads was already switched off in 2021. GNSS station operators and product managers are asked to use SFTP for uploading files.

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 approximately 550 globally distributed stations, roughly half of them belonging to the IGS network.

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` (near real-time) 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 providing some IGS products by mirroring from other IGS data centers, mainly from the CDDIS. Each project has some additional sub-directories: products, reports, and stations. For specific projects, more sub-directories might have been introduced.

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, see `https://igs.bkg.bund.de/file/errors`.

On the 'Station List' page `https://igs.bkg.bund.de/stations` 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.

2.5 System Usage

At the end of 2021 18.6 million files are stored in the GDC with an overall archive size of 14.2 TB. We are facing with approx. 70.000 uploads and 1.1 million downloads per day. There was no noteworthy difference in the number of downloaded files with respect to 2020. Approximately 1000 different users did visit the GDC websites per day.

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.

In 2021, a separate virtual machine was setup for each caster. The corresponding IPv4 addresses have changed as a result. The prefix "www" of the URL is no longer needed and will be omitted in the future.

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 2021):

- On the MGEX caster (`http://mgex.igs-ip.net`) are real-time data of approx. 57 streams provided (compared to 63 a year before). 52 streams are received in raw data format. Only two streams are still converted with the EuroNet software (Horváth , 2016)(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, and SBAS.
- On the EUREF caster (`http://euref-ip.net`) are approx. 210 data streams in RTCM3.0/1/2/3 format provided (compared to 209 a year before). There are still four streams available in the old RTCM 2.3 format.
- On the IGS caster (`http://igs-ip.net`) are approx. 275 data streams (compared

to 272 one year before) in RTCM3.0/1/2/3 format provided. Meanwhile, 199 MSM streams are coming directly from the receiver. 20 streams are generated from EuroNet, four from RTKLIB, nine from NRCanRTCM. There are still two streams available in the old RTCM 2.3 format (BOR1, DAEJ). All streams are provided with long mount-point names.

- On the PRODUCTS caster (http://products.igs-ip.net) are approx. 55 data streams in RTCM3.0/1/2- and 32 in the new IGS-SSR format provided. These streams divide in 73 clock & orbit correction streams from various organizations, four 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 were available by relaying, have finally stopped in 2021.

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. More information can be found at https://software.rtcm-ntrip.org/wiki/Sourcetable.

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+GLONASS as well as the combined product streams with the IGS station FFMJ00DEU.

3.5 Usage Statistics

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 4500 from approx. 150 different users during a typical day (compared to 3000 connections from 100 users a year before). 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 caster. In 2019 there was a remarkable increase in listening to the IGS 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.

The daily amount of incoming and outgoing traffic for our casters can be seen in figure 1, see below. After our casters moved to the new virtual servers in June, a discontinuity in the workload became apparent. This was caused by a caster software bug, that had no effect on the old servers. Meanwhile, this bug has been fixed and a new release of the caster software has been created.

4 Publications

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)

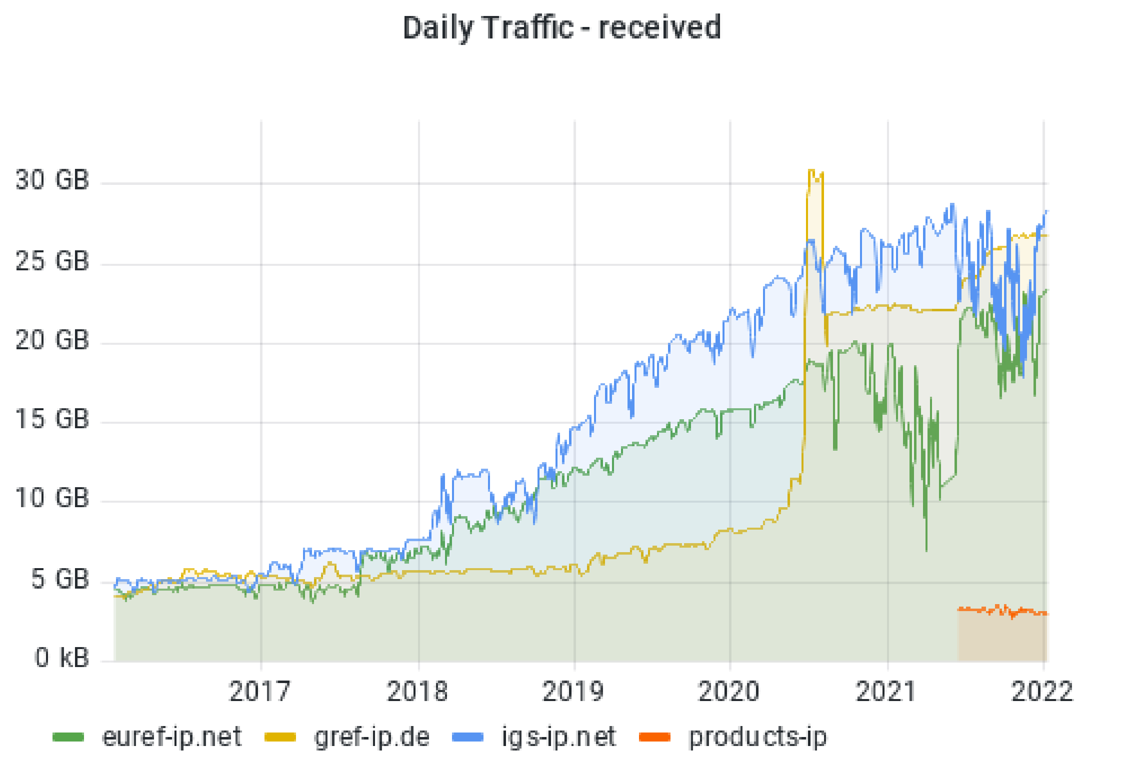
Horváth T. Alberding GNSS solutions supporting Galileo 3rd EuroGeographics PosKEN Meeting, Prague, Czech Republic 2016

Weber, G., D. Dettmering, H. Gebhard, and R. Kalafus Networked Transport of RTCM 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



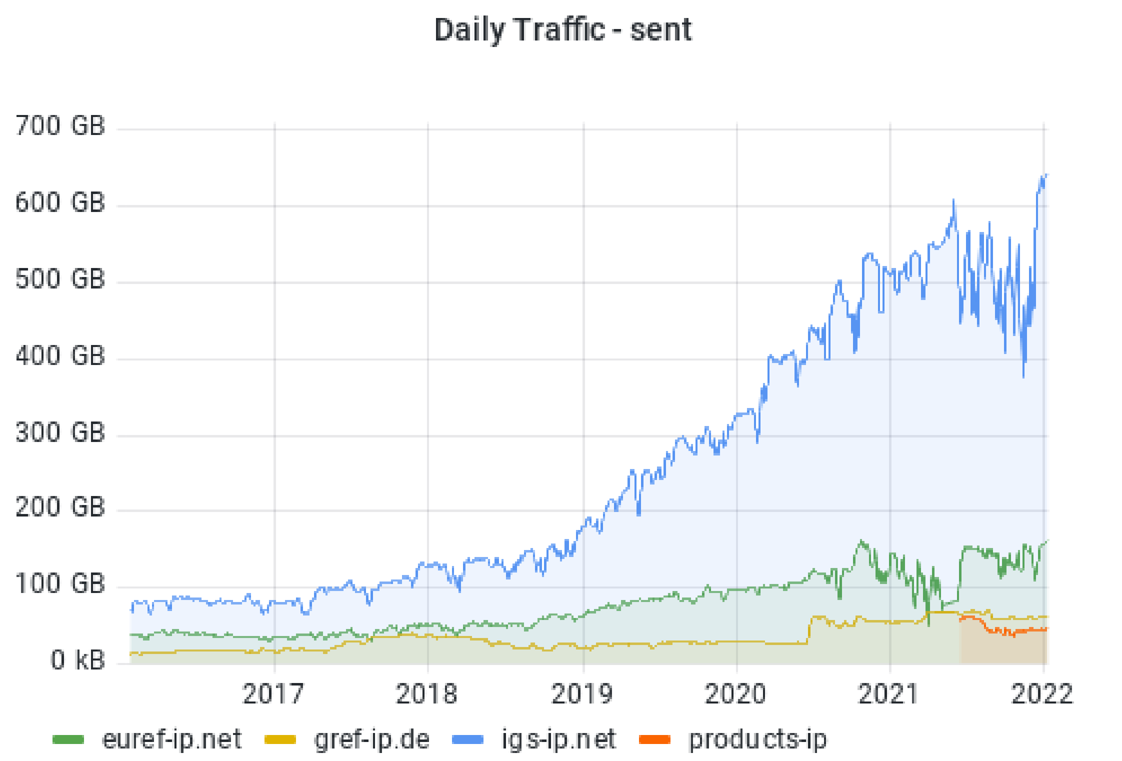


Figure 1: Daily received (i.e., upload to BKG, top) and sent (download from BKG) data volume at the BKG Broadcasters from 2016 to the end of 2021.

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2021

A. Villiger

Astronomisches Institut der Universität Bern
Sidlerstrasse 5, 3012 Bern, Switzerland
E-mail: arturo.villiger@aiub.unibe.ch

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 2021. 12 new antenna/radom combinations have been added. Moreover, preliminary values for the latest FOC satellite pattern where added.

Table 1: Updates of the phase center model `igs14_wwww.atx` in 2021 (`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
2188	16-Dec-2021	Added E223 (E34) and E224 (E10)
2186	29-Nov-2021	Added SPPSP85UHF NONE
2185	22-Nov-2021	Added J005 (J04)
		Added ASH701945B.99 NONE
		ASH701945B.99 SCIS
		ASH701945B.99 SCIT
2178	7-Oct-2021	Added GMXZENITH60 NONE
		STXSA1200 STXR
		TRM115000.00+S SCIT
		TRSAX4E02 NONE
2175	16-Sep-2021	Added SPPSP85 NONE
2163	24-Jun-2021	Added G078 (G11)
		Decommission date G046 (G11)
		Added SOKGRX3 NONE
2148	12-Mar-2021	Added LEIAS11 NONE
		SEPPOLANT_X_MF NONE

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, 504 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general/`) were considered. At that time, 102 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 2021. The overall situation regarding the stations with state-of-the-art robot-based calibrations is similar to the one from 2018. After an increasment of 6% from igs08 to igs14 in 2017 another 2% of the IGS stations are covered by robot calibrations. In 2021 the situation is slighty debraded but still 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

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%
JAN 2022	**igs14.atx:**	**93.5%**	**0.2%**	**4.6%**

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 2021. No changes to the existing satellite antenna entries and receiver antennas have been made.

4.1 Receiver calibrations

The IGS was by mid of 2019 in the comfortable position to have to sets of multi-GNSS calibrations available to chose from for the IGS-repro3. The first set, provided by the University of Bonn, of chamber calibrated receiver antenna patterns was made available to the IGS in 2018 and was hence used to analyze the potential of the disclosed Galileo satellite antenna PCO and PVs. After encouraging results of the test scenarios processed by CODE, ESA, and GFZ in preparation of the IGS AC Workshop 2019 in Potsdam Geo++ announced and released their multi-GNSS calibrations for the Rerpro3. Finally, the ACs concluded that the usage of the robot calibrations as the main source shall be kept as, in particular for older antennas, only robot calibrations are available. Nevertheless, chamber calibrations may be used to add additional Galileo calibrations to the repro3 data set (igsR3.atx).

4.2 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 (CSNO, 2020)

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

4.3 Future of the IGS repro3 ANTEX

The IGS Repro3 ANTEX was spefically made for the IGS Repro3 effort. Once the ITRF2020 is released the igsR3.atx file will be replaced by the IGS 20 ANTEX file. Note that for the IGS20 ANTEX file the z-compeonents of the satellite antenna pattern will change in order to be compatible with the ITRF 2020. In addition, the receiver antenna calibrations might be replaced by updated patterns. The update will be done in colaboration with the IGS Reference Working group as a change of the antenna pattern will impact the coordinates and will need to be taken into account for the IGS20 realization.

References

CAO QZS 1-4 Satellite Information URL http://qzss.go.jp/en/technical/qzssinfo/index.html

GSA Galileo IOV and FOC satellite metadata URL: https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata

China Satellite Navigation Office BeiDou Satellite information: URL http://www.beidou.gov.cn/yw/gfgg/201912/t20191209_19613.html

Rebischung. P. Reference Frame Working Group, Technical Report 2019 IGS Technical Report 2019, 2020

Rebischung P., A. Villiger, T. Herring and M. Moore Preliminary results from the third IGS reprocessing campaign Abstract G11A-03 presented at AGU Fall Meeting 2019, San Francisco, 9-13 Dec.

Villiger A., R. Dach, S. Schaer, L. Prange, F. Zimmermann, H. Kuhlmann, G. H.Wübbena, M. Schmitz, G. Beutler, and A. Jäggi GNSS scale determination using calibrated receiver and Galileo satellite antenna patterns. Manuscript under review in *Journal of Geodesy*, 2020.

Bias and Calibration Working Group Technical Report 2021

S. Schaer

Swiss Federal Office of Topography (swisstopo)
Seftigenstrasse 264, CH–3084 Wabern, Switzerland
E-mail: stefan.schaer@swisstopo.ch

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 meanwhile fully occupied 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 https://igs.org/wg/bias-and-calibration. For an overview of relevant GNSS biases, the interested reader is referred to (Schaer , 2012).

2 Activities in 2021

- 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,

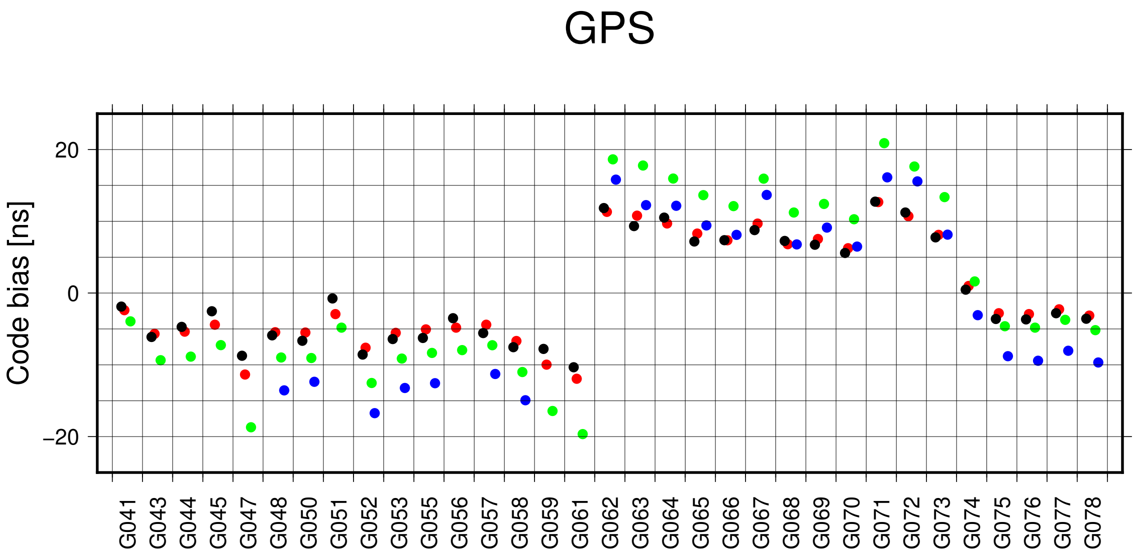


Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2022. Note that G043–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations and G074–G078 corresponds 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
`http://ftp.aiub.unibe.ch/CODE/CODE.BIA`
`https://cddis.gsfc.nasa.gov/archive/gnss/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
`http://ftp.aiub.unibe.ch/CODE/CODE_MONTHLY.BIA`
`https://cddis.gsfc.nasa.gov/archive/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-

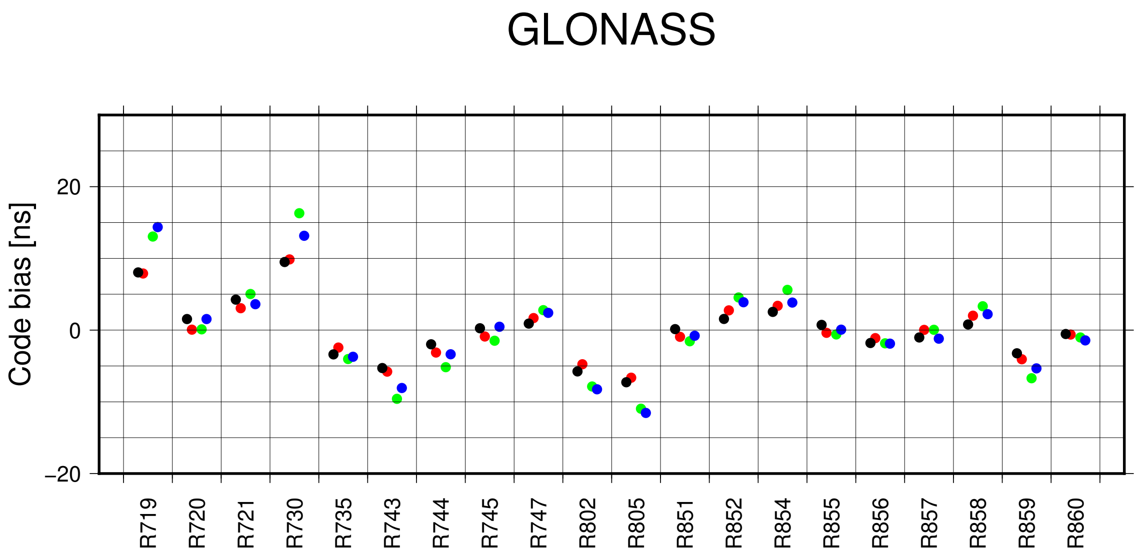


Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2022. Note that R719–R747 and R851–R860 correspond to GLONASS-M; R802–R805 correspond to GLONASS-K1 satellite generations. Legend: C1C (black), C1P (red), C2P (green), C2C (blue).

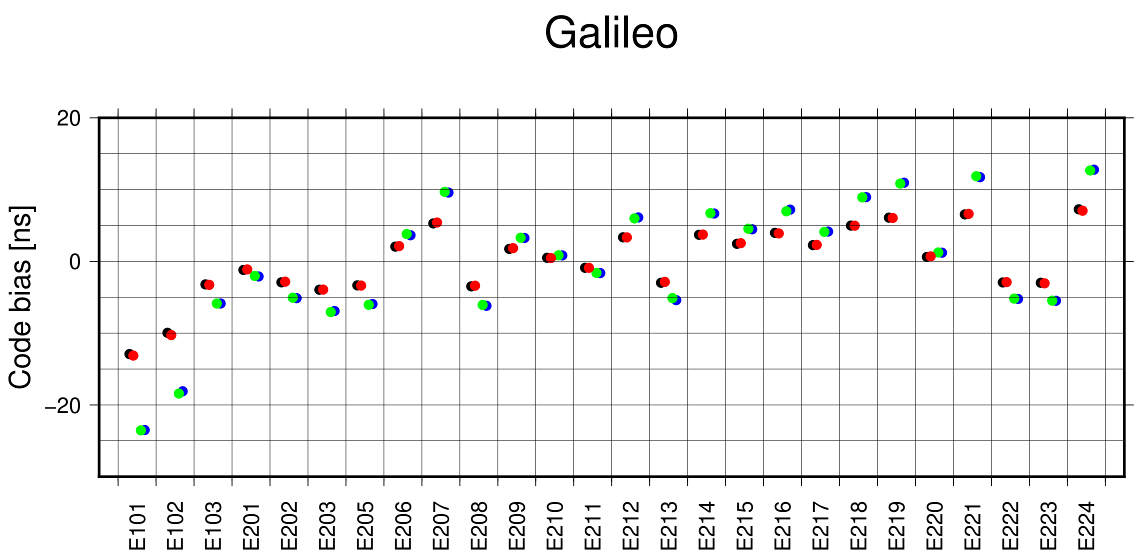


Figure 3: Observable-specific code bias (OSB) estimates for Galileo code observable types (using the RINEX3 nomenclature) and Galileo SV numbers, computed at CODE, for January 2022. Legend: C1X (black), C1C (red), C5Q (green), C5X (blue).

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.
- CODE's enhanced RINEX2/RINEX3 observation data monitoring was continued. Examples may be found at:
  http://ftp.aiub.unibe.ch/igsdata/odata2_day.txt
  http://ftp.aiub.unibe.ch/igsdata/odata2_receiver.txt
  http://ftp.aiub.unibe.ch/igsdata/odata3_gnss_day.txt
  http://ftp.aiub.unibe.ch/igsdata/odata3_gnss_receiver.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata2_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata2_d335_sat.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata3_gnss_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata3_gps_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata3_glonass_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata3_galileo_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata3_beidou_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/odata3_qzss_d335.txt
  http://ftp.aiub.unibe.ch/igsdata/y2021/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 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:

https://files.igs.org/pub/data/format/sinex_bias_100.pdf

Schaer et al. (2018) showed that the Bias-SINEX Format Version 1.00 is well suited to provide OSB information for PPP-AR in a consistent, very user-friendly manner. A user may just consider the given set of biases (in conjunction with a bias-consistent GNSS clock product) for all involved code and phase observations (and accordingly derived linear combinations, such as in particular the Melbourne-Wübbena LC as well as the ionosphere-free LC).

The following addendum from (Schaer et al. , 2021) should help to clarify any uncertainty regarding the sign rule for phase biases in Bias-SINEX. Finally, it contains some elementary rules that we consider useful within the scope of PPP-AR:

https://doi.org/10.1007/s00190-021-01521-9#appendices

References

Schaer, S. (2012): Activities of IGS Bias and Calibration Working Group. In: Meindl, M., R. Dach, Y. Jean (Eds): *IGS Technical Report 2011*, Astronomical Institute, University of Bern, July 2012, pp. 139–154.

Schaer, S. (2016): IGSMAIL-7387: Bias-SINEX V1.00 (and updated bias products from CODE). https://lists.igs.org/pipermail/igsmail/2016/001221.html.

Schaer, S. (2018): SINEX_BIAS—Solution (Software/technique) INdependent EXchange Format for GNSS Biases Version 1.00, October 3, 2018. https://files.igs.org/pub/data/format/sinex_bias_100.pdf.

Schaer, S. (2021): Bias and Calibration Working Group Technical Report 2020. In: A. Villiger and R. Dach (eds.) (2021): *International GNSS Service Technical Report*

2020 (IGS Annual Report). IGS Central Bureau and University of Bern; Bern Open Publishing; https://doi.org/10.48350/156425; pp. 197–202.

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

Schaer, S., A. Villiger, D. Arnold, R. Dach, L. Prange, A. Jäggi (2021): The CODE ambiguity-fixed clock and phase bias analysis products: generation, properties, and performance. Journal of Geodesy, Vol. 95 (8), first online June 28, 2021; https://doi.org/10.1007/s00190-021-01521-9.

Villiger, A., S. Schaer, R. Dach, L. Prange, A. Susnik, A. Jäggi (2019): Determination of GNSS pseudo-absolute code biases and their long-term combination. Journal of Geodesy, Springer Berlin Heidelberg, first online 10 May 2019; https://doi.org/10.1007/s00190-019-01262-w.

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

Ionosphere Working Group Technical Report 2021

A. Krankowski[1]*, *M. Hernandez-Pajares*[2], *K. Kotulak*[1], *A. Froń*[1],
P. Flisek[1], I. Cherniak[1], Q. Liu[2]

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

1 General goals

The Ionosphere Working group started the routine generation of the combine Ionosphere Vertical Total Electron Content (TEC) maps in June 1998. This has been the main activity so far performed 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 IAAC computes 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 (NRCAN)
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

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 and its extension towards low latitudes and Southern Hemisphere.

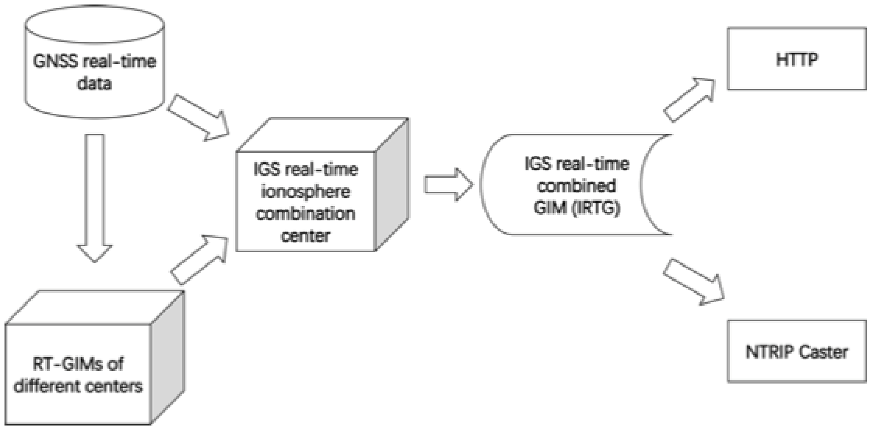


Figure 1: Data flow for the IGS real-time combined GIM.

5 The cooperative IGS RT-GIMs: a global and accurate estimation of the ionospheric electron content distribution in real-time

Within works carried out under the development of the real-time global ionospheric maps (RT-GIMs) the computation methods of RT-GIMs from four individual IGS ionosphere centers were assessed and a new version of IGS combined RT-GIM was introduced (Fig. 1, (Liu et al., 2021)).

The assessment of the RT-GIMs was carried out in two approaches: above the ocean the RT-GIM-derived VTEC values were compared with observation from the Jason-3 mission. Above the Continental part, dSTEC values were calculated from RT-GIMs and then compared with direct GPS-dSTEC observations. The quality of most IGS RT-GIMs is close to postprocessed GIMs (Fig. 1).

The real-time weighting technique for the generation of IGS combined RT-GIM performs well when it is compared with Jason-3 VTEC and dSTEC-GPS assessment. The real-time weights of RT-GIMs are defined as the normalized inverse of the squared rms of RT-dSTEC errors and represent the accuracy of RT-GIMs in the RT-dSTEC assessment. For each RT-GIM, the number of daily winning epochs is computed by counting the number of epochs within the day when the one RT-GIM is better than the other RT-GIMs (Fig. 2).

In addition, the GEC evolution of UPC RT-GIM and IGS combined RT-GIM is close to the GEC evolution of IGS combined GIM in post-processing mode and has an obvious response to the geomagnetic storm during the low-solaractivity period. Future improvements might include the following.

- Broadcast real-time rms maps that can be useful for the positioning users.
- Increase the accuracy of high-temporal-resolution RTGIMs. In addition, higher maximum spherical harmonic degrees might be adopted to increase the accuracy and spatial resolution of RT-GIMs.
- Coinciding with a much larger number of RT-GNSS receivers in the future, the dSTEC weighting might be improved by replacing the "internal" with the "external" receivers, i.e., not used by any real-time analysis centers. In this way the weighting would be sensitive as well to the interpolation–extrapolation error of the different real-time ionospheric GIMs to be combined.
- Increase the number of worldwide GNSS receivers used for the RT-dSTEC up to more than 100. This way we will be able to study the potential upgrade of the present global weighting to a regional weighting among other potential improvements in the combination strategy.

6 IGS ROTI Maps: current status and its extension towards low latitudes and Southern Hemisphere

Apart the continuous support of the actual ROTI maps product generation, the UWM team is working on the tasks of extension of ROTI maps to cover not only the Northern hemisphere high and middle latitudes but also the similar area of the Southern hemisphere, as well as equatorial and low latitude region (Cherniak et al., 2022). The ROTI Maps with the extended coverage are important for further climatological studies of the ionospheric irregularities' occurrence and spatial distribution and statistical assessment of the Earth's ionosphere responses to geomagnetic conditions of different intensity. In the recent years, the ground-based segment of GPS/GNSS permanent stations expanded considerably. It provides a great opportunity to extend the current IGS ROTI maps product towards coverage of the equatorial region and the Southern hemisphere. We present our recent development towards the new ROTI maps product based on the GPS observations from UNAVCO, IGS, CORS, SONEL, and EPN networks.

In order to evaluate extended ROTI maps performance, ability to represent well-known features of ionospheric irregularity development over the Southern hemisphere and at low latitudes was analyzed. This assessment was done by estimation and comparisons of patterns of the ionospheric irregularities behavior. For auroral and middle latitudes, we present the interhemispheric cross-analysis of ROTI-based ionospheric irregularities occurrence over the Northern and Southern hemispheres. To demonstrate performance of the ROTI maps over high/mid latitudes of the Southern hemisphere, we carried out the comparison study of irregularities development specified by ROTI maps for both the Northern and Southern hemispheres for the case of the recent geomagnetic storm that occurred in February 2022 (Fig. 3). The diurnal ROTI map for the most disturbed day

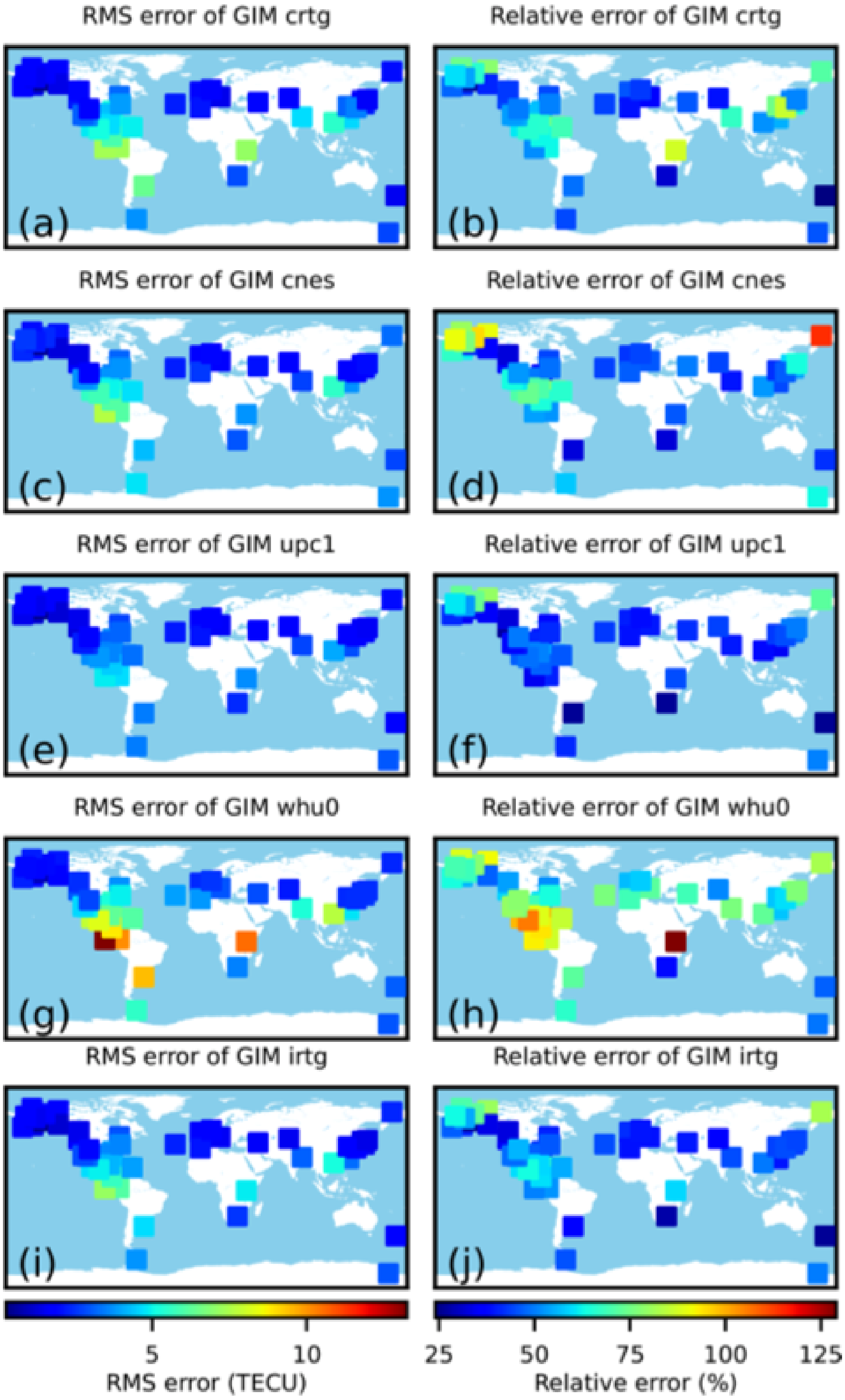


Figure 2: . The distribution of dSTEC-GPS results on 5 January 2021 (after the improvement of the UPC interpolation technique).

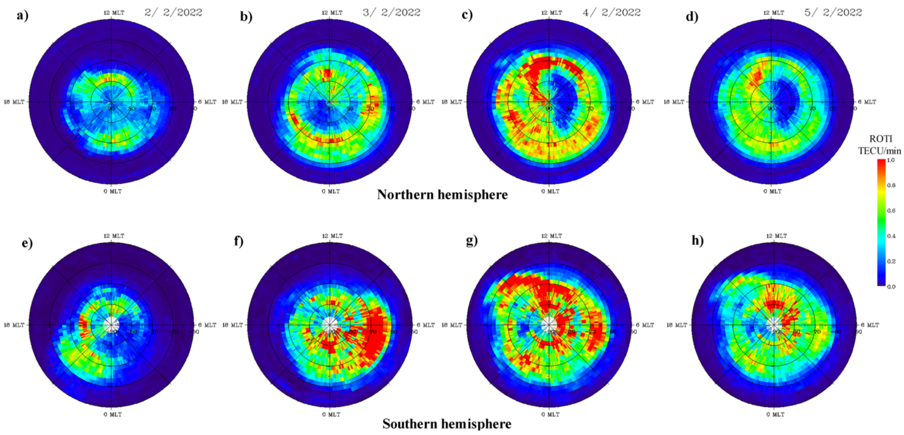


Figure 3: Daily GPS ROTI maps constructed for the Northern (upper row, a-d) and Southern hemispheres (e-h) for days of February 2 to February 5, 2022. Maps plotted in MLAT vs. MLT coordinates. The maps cover 50°-90°N MLAT for Northern and - 50°- -90°N MLAT for Southern hemispheres.

revealed both the large increase of ROTI magnitude and large-scale spatial expansion of the whole irregularities oval. Such pattern of the ionospheric response was observed in both hemispheres, but with some interhemispheric differences due to the opposite seasons in the Northern-Southern hemisphere.

For the low latitudes region, we examined sensitivity of the resulted ROTI maps to detect plasma irregularities associated with equatorial plasma bubbles development at low, moderate, and high solar activity periods during so called "bubble seasons". For all examined periods, the ROTI maps allow to recognize plasma irregularities related to plasma bubble phenomena during local post-sunset hours. The most intense and prolonged in time irregularities were developed during the solar maximum period and less pronounced at low solar activity period. The intensity as well as latitudinal and temporal extensions of EPB-related ionospheric irregularities detected by ROTI maps are related to the increase of background electron density due to solar flux variations. The ROTI maps are quite sensitive to reproduce such type of ionospheric irregularities variations (Fig. 4).

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

Space weather services strongly rely on prompt and accurate imaging of the ionosphere. A great example is GAMBIT (Global Assimilative Model of the Bottomside Ionosphere with Topside estimate) service, which has become a common ground for IGS and IRI to develop common products in a goal of assimilating GNSS-derived ionospheric observations

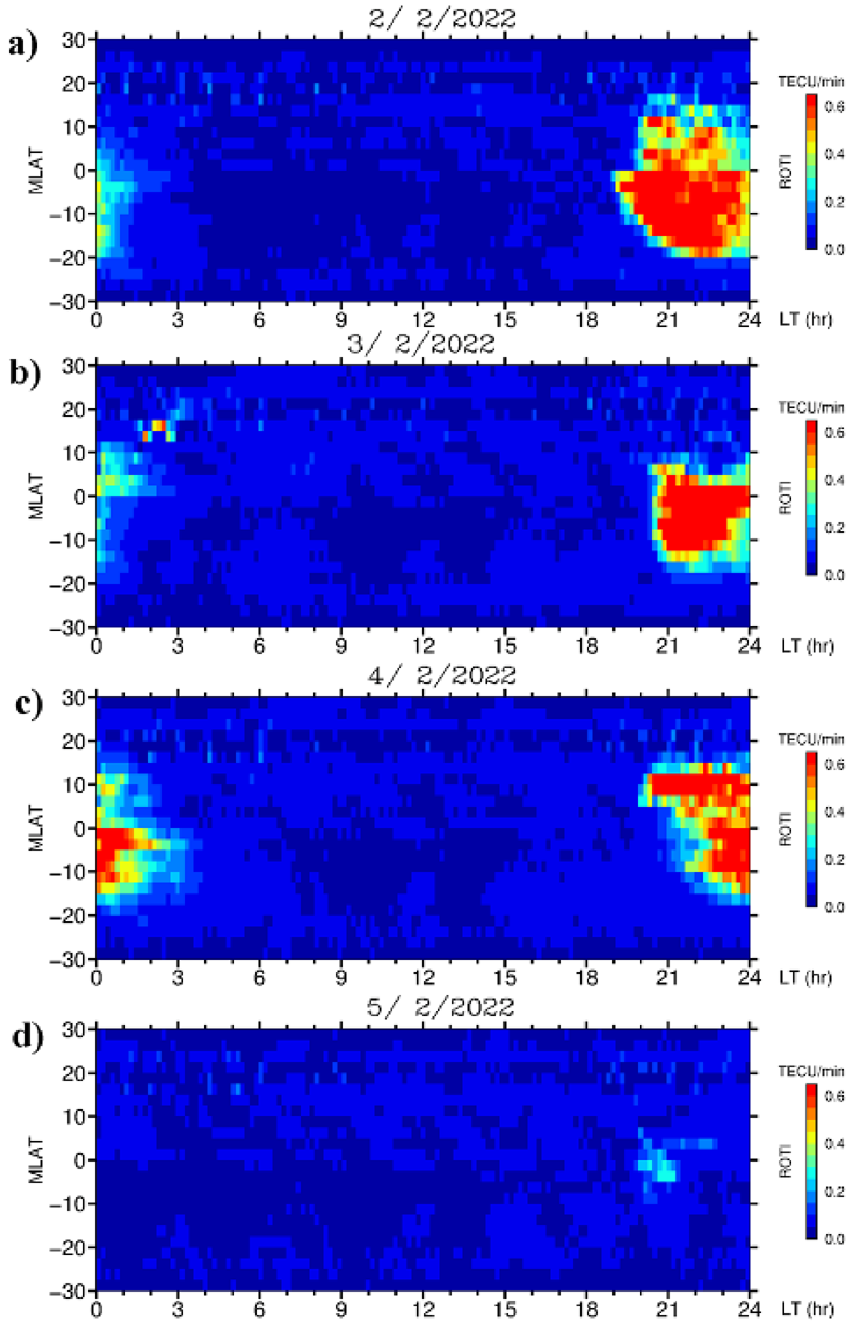


Figure 4: Daily GPS ROTI maps constructed for the equatorial region for (a-d) February 2–5, 2022. Maps are plotted in MLAT vs. MLT coordinates and cover 30°S-30°N MLAT and 00–24 MLT. Blue color corresponds to the absence or very weak ionospheric irregularities, red color – intense ionospheric irregularities occurrence.

into IRI empirical model. With recent introduction of near-real data streams from GIRO (Global Ionosphere Radio Observatory) and IGS it results in novel and reliable 4D data fusion service capable of solving ionosphere imaging tasks thanks to data fusion techniques which allowed the introduction of spatially quasi-continuous TEC data (Froń et al., 2020; Galkin et al., 2022).

The advantages of the ever-developing GAMBIT system can be further utilized in order to automatize the observations of the ionosphere, while works concentrated on lowering the latency of delivery of reliable and accurate ionospheric truth are a way towards robust service capable of detecting occurring ionosphere anomalies. The cooperation between IGS and IRI over data fusion is proving fruitful and will continue in further years, concentrating on improvement of current data products and introduction of new, if such need is recognized. Methods and standards for such products developed over the course of this cooperation allows both sides to quickly adapt to the needs of the GAMBIT system and provide it with data of the best quality possible (Fig. 5).

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 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.

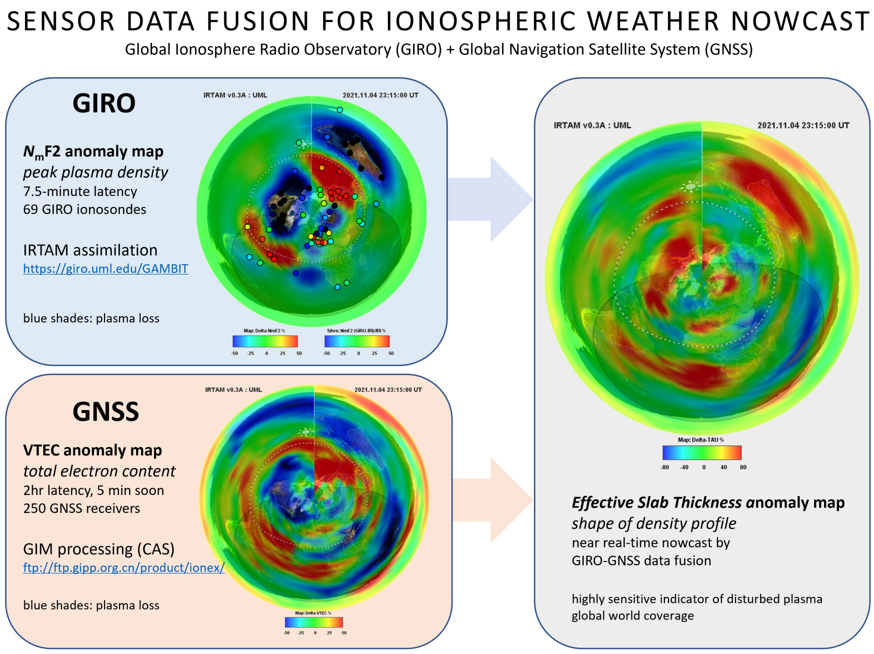


Figure 5: Sensor data fusion for ionospheric weather nowcast. Global Ionosphere Radio Observatory (GIRO) and Global Navigation Satellite System (GNSS)

References

A. Froń, Galkin I., Krankowski A., Bilitza D., Hernández-Pajares M-, Reinisch B., Li Z., Kotulak K., Zakharenkova I., Cherniak I. Towards Cooperative Global Mapping of the Ionosphere: Fusion Feasibility for IGS and IRI with Global Climate VTEC Maps, David Roma Dollase, Ningbo Wang, Paweł Flisek, Alberto García-Rigo, 2020, Remote Sens. 2020, 12(21), 3531; doi.: 10.3390/rs12213531

Q. Liu, Hernández-Pajares M., Yang H., Monte-Moreno E., Roma-Dollase D, Garcia-Rigo A., Li Z., Wang N., Laurichesse D., Blot A., Zhao Q., Zhang Q-, Hauschild A., Agrotis L., Schmitz M., Wübbena G., Stürze A., Krankowski A., Schaer S., Feltens J., Komjathy A., and Ghoddousi-Fard R. The cooperative IGS RT-GIMs: A reliable estimation of the global ionospheric electron content distribution in real time, Earth Syst. Sci. Data, 13, 4567–4582, 202, doi.: 10.5194/essd-13-4567-2021

I. Galkin, Froń A., Reinisch B., Hernández-Pajares M., Krankowski A., Nava B., Bilitza D., Kotula K., Flisek P., Li Z., Wang N. Global Monitoring of Ionospheric Weather by GIRO and GNSS Data Fusion, Atmosphere 13(3):371, 2022, doi.:10.3390/atmos13030371

I. Cherniak, Zakharenkova I., Krankowski A. IGS ROTI Maps: current status and its extension towards low latitudes and Southern Hemisphere, Sensors, 2022, (under review)

Multi-GNSS Working Group Technical Report 2021

P. Steigenberger[1], O. Montenbruck[1]

[1] Deutsches Zentrum für Luft- und Raumfahrt (DLR)
German Space Operations Center (GSOC)
Münchener Straße 20
82234 Weßling, Germany
E-mail: peter.steigenberger@dlr.de

1 Introduction

As in the previous years, the major task of the Multi-GNSS Working Group (MGWG) is the Multi-GNSS Pilot Project (MGEX). Furthermore, the MGWG supported the development of the RINEX 4.00 navigation file format providing additional information included in modernized navigation messages: CNAV and CNAV-2 for GPS and QZSS as well as CNAV-1/2/3 for BeiDou-3. More details are given in the report of the RINEX Working Group. Ningbo Wang joined the MGWG in 2021 as representative for CAS providing differential code biases to MGEX since many years.

2 GNSS Evolution

The GNSS satellite launches of 2021 are given in Table 1. Compared to the previous years, launch activities were pretty low. The fifth GPS III satellite nicknamed *Neil Armstrong* was launched in June 2021 but was still in testing as of December 2021. QZS-1R is the replenishment for the first QZSS satellite in an inclined geo-synchroneous orbit (IGSO). It is the first satellite capable of transmitting the L1C/B signal (IS-QZSS-PNT-004, 2021) that is supported in the RINEX format starting with version 4.00. Whereas L1C/B was transmitted during the in-orbit testing of QZS-1R, regular signal transmission is not expected before 2023. After a break of three years, two Galileo satellites were launched in December 2021. However, transmission of navigation signals did not start in 2021.

In 2021, three GPS Interface Specification documents were updated (IS-GPS-200M, 2021; IS-GPS-705H, 2021; IS-GPS-800H, 2021). A new version of the Galileo Interface Control Document (ICD) was published in January 2021 (European Union, 2021c). With this issue, three new

Table 1: GNSS satellite launches in 2021.

Date	Satellite	Type
17 Jun 2021	GPS III	MEO
26 Oct 2021	QZS-1R	IGSO
01 Dec 2021	Galileo FOC FM23/4	MEO

features are introduced to the I/NAV message transmitted within the Galileo E1 Open Service signal (Secondary Synchronisation Pattern, Reduced Clock and Ephemeris and Reed-Solomon Outer Forward Error Correction). The Service Definition Document for the Galileo Open Service was updated in November 2021 (European Union, 2021d).

In May 2021, a test campaign for the Galileo High Accuracy Service (HAS; European GNSS Agency, 2020) started with transmission of corresponding corrections on the data component of the E6 signal. A test campaign was also conducted for the Galileo Open Service Navigation Message Authentication (OSNMA). A dedicated ICD for this test phase was published by European Union (2021a) accompanied by corresponding receiver guidelines (European Union, 2021b).

3 Network

As of January 2022, the IGS multi-GNSS tracking network comprises 370 stations, see Figs. 1 and 2. 10 stations are completely dormant and did not provide any observations in 2021.

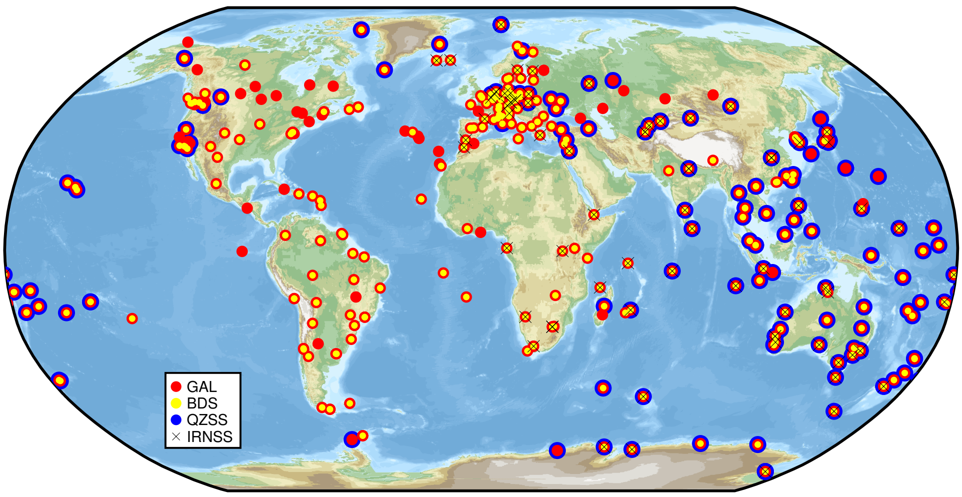


Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2022.

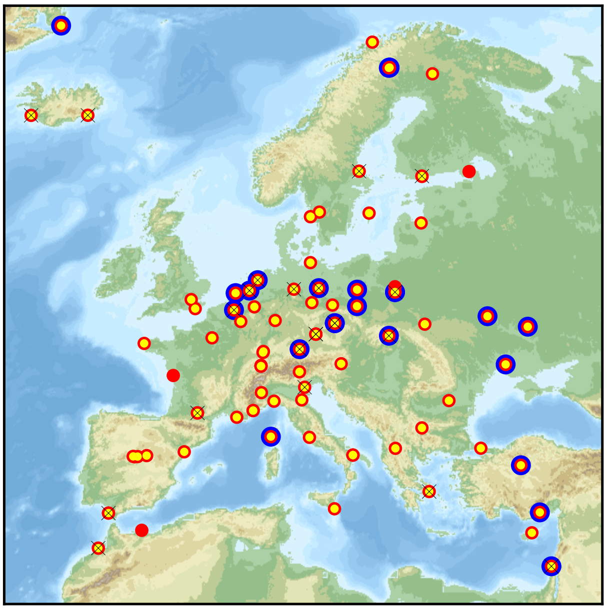


Figure 2: Distribution of European IGS multi-GNSS stations as of January 2022. See Fig. 1 for explanation of individual station labels.

4 Products

As of December 2021, five MGEX analysis centers (CODE, GFZ, IAC, SHAO, WU) provide orbit and clock products for the full range of global navigation systems, namely GPS, GLONASS, Galileo and BeiDou. Four of them, in addition, include the regional QZSS, see Table 2.

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	GRG0MGXFIN	GPS+GLO+GAL
CODE	COD0MGXFIN	GPS+GLO+GAL+BDS2+BDS3+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:

- 024/2021: switch from 15 min to 5 min orbit sampling for CNES/CLS
- 066/2021: inclusion of BDS-3 in CODE products

- Switch of CODE products form IGb14 reference frame and igs14.atx antenna calibrations to repro3 reference frame (IGS14R3) and extended igsR3.atx file including BeiDou and QZSS antenna calibrations as well as antenna phase center offsets for all GPS III satellites provided by the manufacturer Lockheed Martin.
- 136/2021: CNES/CLS starts provision of observable-specific biases compatible with their MGEX orbit and clock products (Loyer, 2021)
- 167/2021: GFZ provides uncalibrated phase delays as comment line in their clock products allowing for un-differenced ambiguity resolution (Deng, 2021). In addition, attitude information for all GPS, GLONASS, Galileo, BeiDou and QZSS satellites are provided in ORBEX format (Loyer et al., 2019).

Multi-GNSS differential code bias (DCB) products are generated by CAS (daily rapid product) and DLR (quarterly final product). Inclusion of BeiDou DCBs related to the BDS-3 signals B1C, B2a, and B2b, namely C2I-C1P, C2I-C5P, C2I-C7D DCBs started with the fourth quarter for the DLR product.

5 Satellite Metadata

The MGWG maintains the IGS satellite metadata file available at https://files.igs.org/pub/station/general/igs_satellite_metadata.snx. Cabinet Office, Government of Japan released detailed metadata for the new QZS-1R satellite three weeks after launch (Cabinet Office, 2021). Metadata for the two Galileo satellites launched in December 2021 are not yet available at the European GNSS Service Centre but mass and center of mass values are published on the website of the International Laser Ranging Service (ILRS) at https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/current_missions/galileo_all_com.html. However, SLR tracking of these satellites has not yet started as of January 2022.

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

References

Cabinet Office. QZS-1R satellite information. Technical Report SPI_QZS1R, 2021. URL https://qzss.go.jp/en/technical/qzssinfo/khp0mf0000000wuf-att/spi-qzs1r_211116.pdf.

Z. Deng. WL_UPD, integer clock and OBX from GFZ MGEX RAPID products, 2021. IGSMAIL-8068.

European GNSS Agency. Galileo High Accuracy Service (HAS) Info Note, 2020. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_HAS_Info_Note.pdf.

European Union. Galileo Open Service Navigation Message Authentication (OSNMA) User ICD for the Test Phase, 2021a. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OSNMA_User_ICD_for_Test_Phase_v1.0.pdf.

European Union. Galileo Open Service Navigation Message Authentication (OSNMA) Receiver Guidelines for the Test Phase, 2021b. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OSNMA_Receiver_Guidelines_for_Test_Phase_v1.0.pdf.

European Union. European GNSS (Galileo) Open Service Signal-In-Space Interface Control Document. OS SIS ICD Issue 2.0, 2021c. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OS_SIS_ICD_v2.0.pdf.

European Union. European GNSS (Galileo) Open Service: Service Definition Document. Technical Report Issue 1.2, European Global Navigation Satellite Systems Agency, 2021d. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-SDD_v1.2.pdf.

IS-GPS-200M. *Interface Specification IS-GPS-200: Navstar GPS Space Segment/Navigation User Segment Interfaces*, 2021. URL https://www.gps.gov/technical/icwg/IS-GPS-200M.pdf.

IS-GPS-705H. Navstar GPS Space Segment/User Segment L5 Interfaces. Technical report, Global Positioning System Directorate Systems Engineering & Integration, 2021. URL https://www.gps.gov/technical/icwg/IS-GPS-705H.pdf.

IS-GPS-800H. Navstar GPS Space Segment/User Segment L1C Interfaces. Technical report, Global Positioning System Directorate Systems Engineering & Integration, 2021. URL http://www.gps.gov/technical/icwg/IS-GPS-800H.pdf.

IS-QZSS-PNT-004. Quasi-Zenith Satellite System Interface Specification Satellite Positioning, Navigation and Timing Service. Technical report, Cabinet Office, 2021. URL http://qzss.go.jp/en/technical/download/pdf/ps-is-qzss/is-qzss-pnt-004.pdf.

S. Loyer. New GRM/GRG biases products, 2021. IGS-ACS-1443.

S. Loyer, O. Montenbruck, and S. Hilla. ORBEX: The orbit exchange format, draft version 0.09. Technical report, 2019.

Precise Point Positioning with Ambiguity Resolution Working Group Technical Report 2021

S. Banville[1]

[1] Natural Resources Canada, 588 Booth St,
Ottawa ON Canada, K1A 0Y7
E-mail: simon.banville@nrcan-rncan.gc.ca

1 Introduction

The precise point positioning with ambiguity resolution (PPP-AR) working group (WG) is pursuing its activities to offer combined satellite orbit, clock and bias products enabling PPP-AR solutions at the user end. The interoperability of products from IGS analysis centers (ACs) was first demonstrated by Banville et al. (2020), paving the way for combined products. The working group also promoted the exchange of satellite attitude information in the form of quaternions as a means of improving the consistency of satellite clock corrections among analysis centers and users (Loyer et al., 2021). Open source code describing satellite attitude models during eclipses has also been made available to software developers (Strasser et al., 2021).

At the time of writing, seven ACs provide phase biases for PPP-AR, see Table 1. Most ACs have already adopted the Bias SINEX format for disseminating bias information (Schaer, 2016). Remaining ACs are currently in the process of testing the conversion from their internal to the recommended format. Analysis centers are also striving to modernize their products to multi-GNSS, including Galileo biases into their products. Currently, GFZ, WHU and the Navigation Team at CNES even provide phase biases for BeiDou satellites.

In the past year, the working group focused on product combination in the context of the repro3 campaign. Four ACs generated phase biases for GPS starting, at the latest, in the year 2000. It is thus expected that the combined products should also contain these biases for the same period. For Galileo, three ACs contributed phase biases on the L1 and L5 signals, which should lead to the computation of combined biases for this system as well.

The repro3 satellite clock and bias combination, performed by Dr Jianghui Geng and his team at Wuhan University, uncovered an inconsistency regarding the application of phase center offset (PCO) corrections in the computation of biases. This issue is described in Section 2. Preliminary PPP results using the combined repro3 products are then presented in Section 3. Outreach activities are introduced in Section 4 and future work is proposed in Section 5.

2 Application of PCO Corrections to Biases

Several GNSS satellites have now been assigned different PCO values on each frequency in the IGS ANTEX file. Consequently, geometry-free biases such as differential code biases (DCBs) or widelane (aka Melbourne-Wübbena) biases will take on different values whether or not PCO corrections have been applied to the raw observables. Furthermore, transforming these geometry-free biases into observable-specific biases (OSBs), such as the ones defined within the IGS Bias SINEX format, will again result in inconsistencies.

This issue was encountered during the IGS repro3 clock/bias combination, where some analysis centers applied the PCO corrections and others not, resulting in inconsistent biases (Geng et al., 2022). When users of these products also use a different convention (e.g. applying PCO corrections when the analysis center did not), estimated parameters may be affected and issues with ambiguity resolution might occur, resulting in sub-optimal solutions.

At a virtual meeting of the IGS PPP-AR WG held on 16 September 2021, analysis centers of the IGS have agreed that applying PCO corrections to biases is the way forward given multi-GNSS and multi-frequency signals. Therefore, all IGS analysis centers computing such biases will be required to adopt this convention. Similarly, users of IGS products will need to adopt this convention as well to ensure consistency.

This convention will be adopted at the same time as the switch to ITRF 2020, planned around the summer of 2022. This timeframe allows for several months to make the necessary changes in AC and user software, if necessary. The IGS repro3 product combination is underway, and this convention will be applied to the combined biases, ensuring that users can process long time series using a unique convention.

3 Preliminary Results from Repro3 Combined Products

The repro3 campaign serves as a framework to provide and validate long time series of products enabling PPP-AR solutions. These products contain the following innovations with respect to current products provided by the IGS:

- a consistent combination of clocks and biases following Banville et al. (2020), includ-

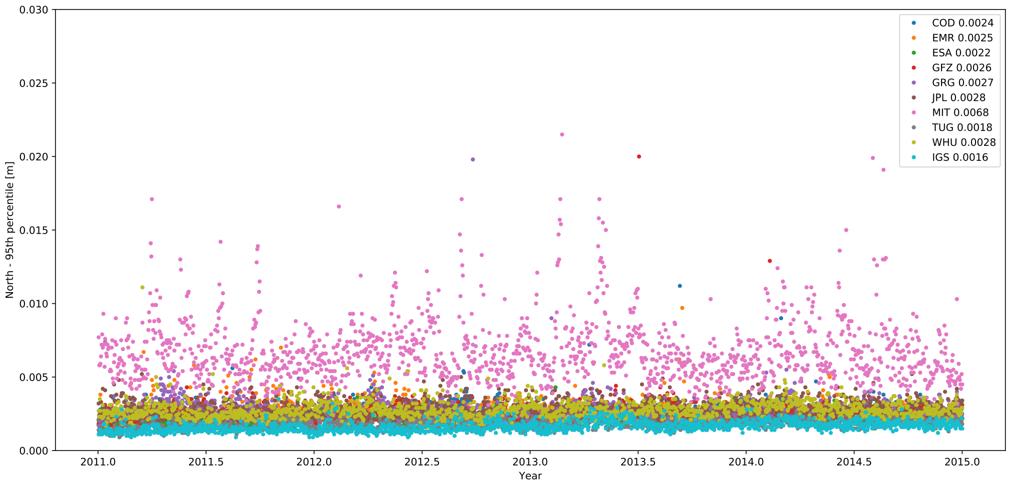


Figure 1: 95^{th} percentile for the north residuals of PPP(-AR) solutions for the 2011-2014 period (preliminary results).

ing phase biases enabling PPP-AR;

- satellite attitude in the form of quaternions, consistent with the combined satellite clocks. These quaternions are computed using the GROOPS software developed at TU Graz (Mayer-Gürr et al., 2021);
- a combination of both GLONASS and Galileo satellite clocks;
- satellite clock corrections provided at a 30-second interval (not available in previous reprocessing campaigns).

To assess the quality of the combined products, PPP (or PPP-AR, whenever phase biases are provided) solutions were computed using products from all ACs. Since this exercise is ongoing, it has currently only been performed for the period of 2011-2014. On each day, approximately 80 stations were used, mostly core stations participating in the definition of the IGS reference frame. For every daily solution from a given AC, a 7-parameter Helmert transformation was computed with respect to the daily combined station position combination to remove frame alignment discrepancies. From these transformations, the 95th percentiles of the residuals, expressed in the local frame (north, east and up directions), are provided in Figures 1-3.

Figure 1 shows the 95^{th} percentile for the north residuals for all ACs on a daily basis. Most ACs offer a similar level of accuracy and, consequently, time series are often superposed. To offer better insights into the performance of each AC, the mean for all AC time series is provided in the legend. The combined orbit, clock and bias products, labeled IGS, perform well and offer the best agreement with the combined position solutions.

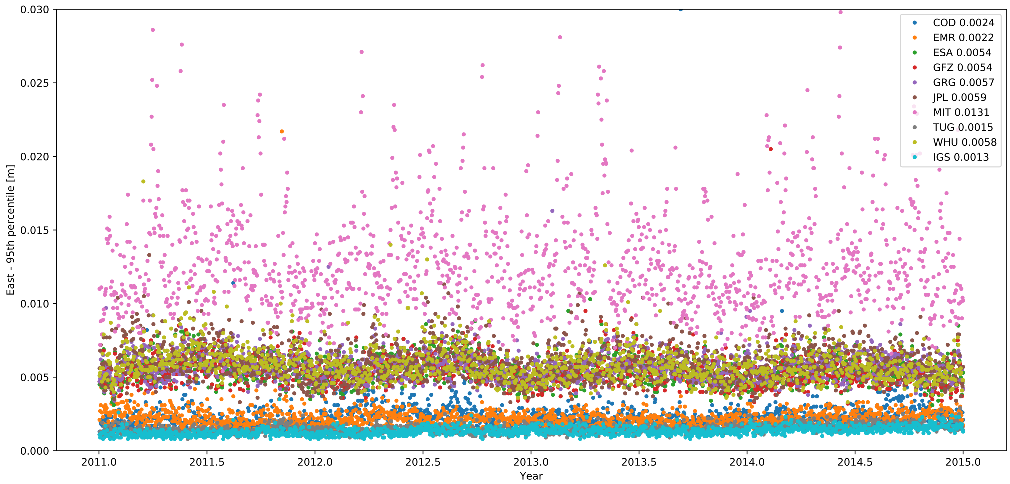


Figure 2: 95^{th} percentile for the east residuals of PPP(-AR) solutions for the 2011-2014 period (preliminary results).

Figure 2 displays the 95^{th} percentile for the east residuals. In this case, one can clearly identify ACs providing phase biases and enabling PPP-AR solutions. The 95th percentile values are reduced by over 50% with respect to PPP solutions with float ambiguities.

In Figure 3, the 95^{th} percentile for the up residuals are presented. Results are consistent with the previous plots, showing the good performance of the combined products. All results presented are GPS-only solutions; the addition of GLONASS did not provide a significant impact to these statistics, and Galileo satellites were too few during this period to make any contribution to the solutions.

4 Outreach

To promote the adoption of standards and products from the IGS PPP-AR WG among the user community, a special issue entitled "GNSS Precise Point Positioning: Towards Global Instantaneous cm-Level Accuracy" was put together in the Remote Sensing journal. Among the papers published in the special issue, we note the analysis of the impact of satellite attitude quaternions on PPP-AR solutions (Yang et al., 2021), as well as research using uncombined data processing based on observable-specific biases as adopted in the Bias SINEX format (Naciri and Bisnath, 2021; Psychas et al., 2021; Zhao et al., 2022).

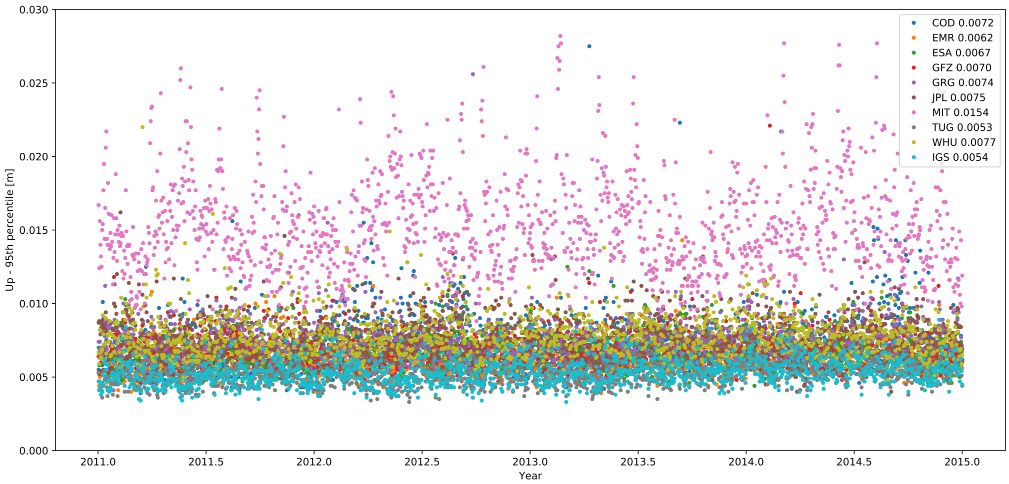


Figure 3: 95^{th} percentile for the up residuals of PPP(-AR) solutions for the 2011-2014 period (preliminary results)

5 Future Work

Over the upcoming year, the main focus of the PPP-AR WG will be the completion of the repro3 satellite clock and bias combined products, as well as their evaluation in the form of PPP-AR solutions. Once these products are released, users of IGS products will have access to long time series of products to compute homogeneous PPP-AR solutions over more than two decades.

To coincide with the adoption of ITRF2020, the PPP-AR WG will promote and monitor the adoption of the new convention on the application of PCO corrections to the computation of biases. Furthermore, the modernization of the satellite clock combination process will be suggested for operational purposes, which includes: the consistent combination of biases, the generation of attitude quaternions and the inclusion of other GNSS constellations such as GLONASS and Galileo.

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.

References

Banville S, J. Geng, S. Loyer, S. Schaer, S. Springer, and S. Strasser On the interoperability of IGS products for precise point positioning with ambiguity resolution. Journal of Geodesy, 94(10), 2020.

Geng J., W. Wen, Z. Yan, and S. Mao Repro3: an initial clock/bias combination. Presented at the IGS Analysis Centers Meeting Workshop, 19 Jan 2022.

Loyer S., S. Banville, J. Geng, S. Strasser Exchanging satellite attitude quaternions for improved GNSS data processing consistency. Advances in Space Research, https://doi.org/10.1016/j.asr.2021.04.049, 2021.

Mayer-Gürr T., S. Behzadpour, A. Eicker, M. Ellmer, B. Koch, S. Krauss, C. Pock, D. Rieser, S. Strasser, B. Suesser-Rechberger, N. Zehentner, and A. Kvas GROOPS: A software toolkit for gravity field recovery and GNSS processing. Computers and Geosciences, 155, 2021. https://doi.org/10.1016/j.cageo.2021.104864

Naciri N. and S.Bisnath Approaching Global Instantaneous Precise Positioning with the Dual- and Triple-Frequency Multi-GNSS Decoupled Clock Model. Remote Sensing, 13(18), 3768, 2021 https://doi.org/10.3390/rs13183768

Psychas D., P.J.G. Teunissen, and S. Verhagen A Multi-Frequency Galileo PPP-RTK Convergence Analysis with an Emphasis on the Role of Frequency Spacing. Remote Sensing, 13(16), 3077, 2021. https://doi.org/10.3390/rs13163077

Schaer S. Bias-SINEX format and implications for IGS bias products. In: IGS Workshop, 8–12 February, Sydney, Australia, 2016.

Strasser S., S. Banville, A. Kvas, S. Loyer, and T. Mayer-Gürr. Comparison and generalization of GNSS satellite attitude models. Abstract submitted to the European Geophysical Union (EGU) General assembly 2021.

Yang S., Q. Zhang, X. Zhang, and D. Liu Impact of GPS/BDS Satellite Attitude Quaternions on Precise Point Positioning with Ambiguity Resolution. Remote Sensing, 13(15), 3035, 2021. https://doi.org/10.3390/rs13153035

Zhao L., P. Blunt, and L. Yang Performance Analysis of Zero-Difference GPS L1/L2/L5 and Galileo E1/E5a/E5b/E6 Point Positioning Using CNES Uncombined Bias Products. Remote Sensing, 14(3), 650, 2022. https://doi.org/10.3390/rs14030650

Table 1: Contributors to phase biases enabling PPP-AR

Product Line	Bias SINEX	GNSS	Start Date
Center for Orbit Determination (COD)			
Product Line	Bias SINEX	GNSS	Start Date
Rapid	Yes	G	2019-001
		E	2019-272
Final	Yes	G	2019-001
MGEX	Yes	G, E	2018-182
Repro3	Yes	G	2014-001
		E	2000-124
Natural Resources Canada (EMR)			
Product Line	Bias SINEX	GNSS	Start Date
Repro3	Yes	G	2000-001
German Research Center for Geosciences (GFZ)			
Product Line	Bias SINEX	GNSS	Start Date
MGEX	No	G, E, C	2021-167
MGEX	Yes	G, E, C	2021-190
Centre National d'Études Spatiales/Collecte Localisation Satellites (GRG)			
Product Line	Bias SINEX	GNSS	Start Date
Final	No	G	2009-305
MGEX	No	G	2009-305
		E	2018-214
MGEX	Yes	G, E	2021-136
Repro3	No	G	2000-124
		E	2017-001
Centre National d'Études Spatiales/Navigation Team			
Product Line	Bias SINEX	GNSS	Start Date
Rapid	Yes	G, E ,C	2019-001
Real Time	Yes	G, E, C	2019-001
Graz University of Technology (TUG)			
Product Line	Bias SINEX	GNSS	Start Date
Repro3	Yes	G	1994-001
		G (L5)	2010-240
		E	2013-001
Wuhan University (WHU)			
Product Line	Bias SINEX	GNSS	Start Date
MGEX	Yes	G, E, C	2020-001

Reference Frame Working Group Technical Report 2021

P. Rebischung[1,2]

[1] Université de Paris, Institut de physique du globe de Paris
CNRS, IGN, F-75005 Paris, France
[2] ENSG-Géomatique, IGN, F-77455 Marne-la-Vallée, France

After a brief overview of the operational IGS SINEX combination results in 2020 and 2021 (Section 1), this report summarizes results from the combinations of the SINEX solutions provided by the different Analysis Centers (ACs) who contributed to the third IGS reprocessing campaign (repro3; Section 2). Section 3 finally summarizes the analysis of the combined IGS repro3 station position time series which was carried out as part of the ITRF2020 preparation.

1 Operational SINEX combinations

Figure 1 shows the WRMS of the AC station position residuals from the daily IGS SINEX combinations of years 2020-2021, i.e., the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed.

The WRMS of the AC station position residuals have remained at similar, stable levels as in the previous years, with only one notable exception: on GPS week 2113 (decimal year: 2020.51), COD switched the generation of their final solutions from one-day to three-day orbital arcs (while still providing daily station position estimates for the IGS SINEX combinations). With this switch, the WRMS of COD's residuals have slightly but consistently increased, i.e., this switch caused COD's SINEX solutions to slightly depart from the mean of the other ACs.

The AC Earth Orientation Parameter residuals from the IGS SINEX combinations of years 2020-2021 show similar scatters and characteristics as in the previous years. They are therefore not shown in this report.

2 repro3 SINEX combinations

In 2021, ten IGS Analysis Centers finalized a third reanalysis (repro3) of the history of GNSS observations acquired by a global tracking network, using updated models and methodologies. The contributing ACs provided, among other products, daily terrestrial frame solutions including station position and Earth Rotation Parameter (ERP) estimates. The AC terrestrial frame solutions have been combined on a daily basis, and the daily combined repro3 terrestrial frame solutions form the IGS contribution to ITRF2020.

A list of the AC repro3 contributions can be found in IGSMAIL-8044. Details on the repro3 SINEX combination products, the main modeling updates since the previous repro2 campaign and their (expected) impacts on terrestrial frame solutions, and the SINEX combination strategy can be found in IGSMAIL-8026. The repro3 SINEX combination products are now available at:

- `https://cddis.nasa.gov/archive/gnss/products/${wwww}/repro3`
- `ftp://igs.ign.fr/pub/igs/products/${wwww}/repro3`
- `ftp://igs-rf.ign.fr/pub/repro3/${wwww}`

where ${wwww} stands for the 4-character GPS week number.

Figure 2 shows the complete network of 1905 stations present in the combined repro3

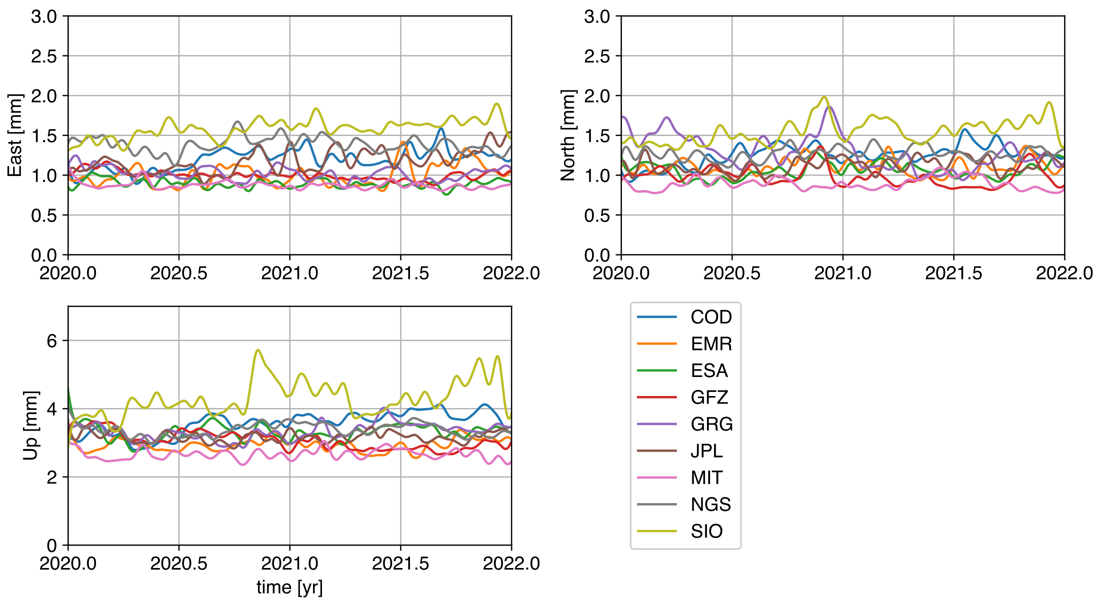


Figure 1: WRMS of AC station position residuals from the 2020-2021 daily IGS SINEX combinations. All time series were low-pass filtered with a 10 cpy cutoff frequency.

SINEX solutions. It includes in particular all current and former IGS stations, all GNSS stations co-located with other space geodetic techniques, stations proposed by regional and national network representatives for being part of ITRF2020, and stations selected by the ULR AC for being co-located with tide gauges and having long, stable position time series. Compared to repro2, a larger number (1397) and fraction (73 %) of stations have time series with more than 1000 daily points in repro3. It should also be noted that the repro3 station position time series are generally more complete than in repro2. This is thanks to the effort made by several ACs of having processed the stations they selected as exhaustively as possible, i.e., whenever they had observations available.

To assess the weights of the different ACs in the daily repro3 combinations, the formal errors of station position estimates were extracted from the AC solutions after they had been pre-processed and re-weighted for the daily combinations. Daily median formal errors were then computed for each AC and each East, North, Up component. Figure 3 shows smoothed time series of these median formal errors. They can be considered both as a measure of the level of agreement between the daily AC solutions and as a proxy for the AC weights in the daily combinations.

Like in repro2, the overall level of agreement between AC solutions significantly improves

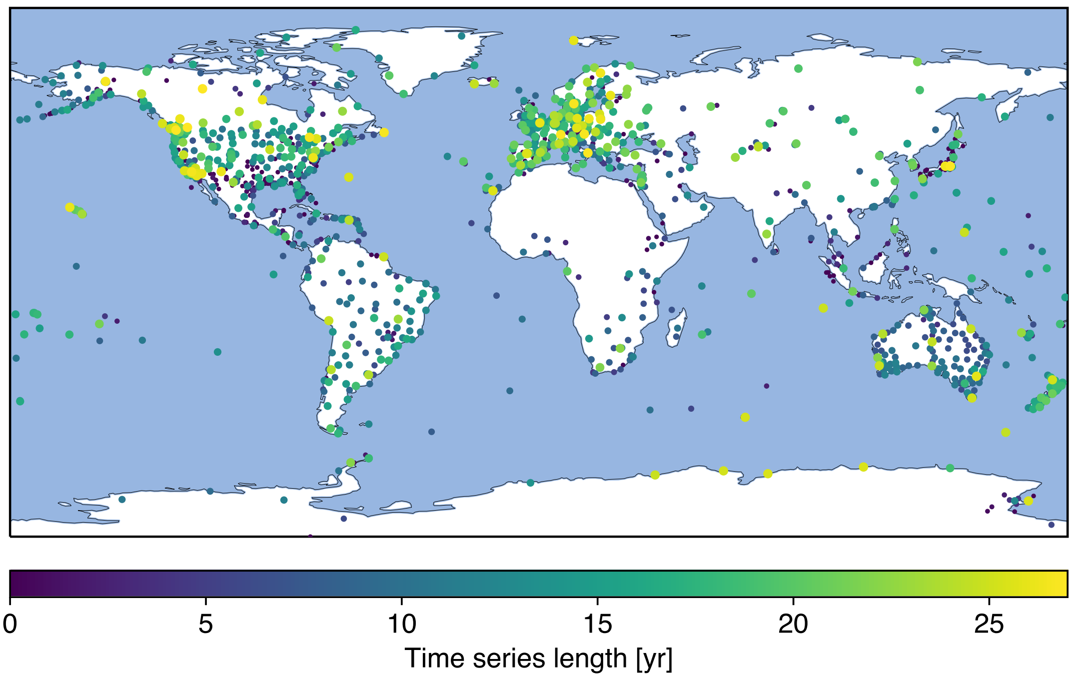


Figure 2: repro3 station newtork. The sizes and colors of the dots indicate the lengths of the repro3 combined position time series.

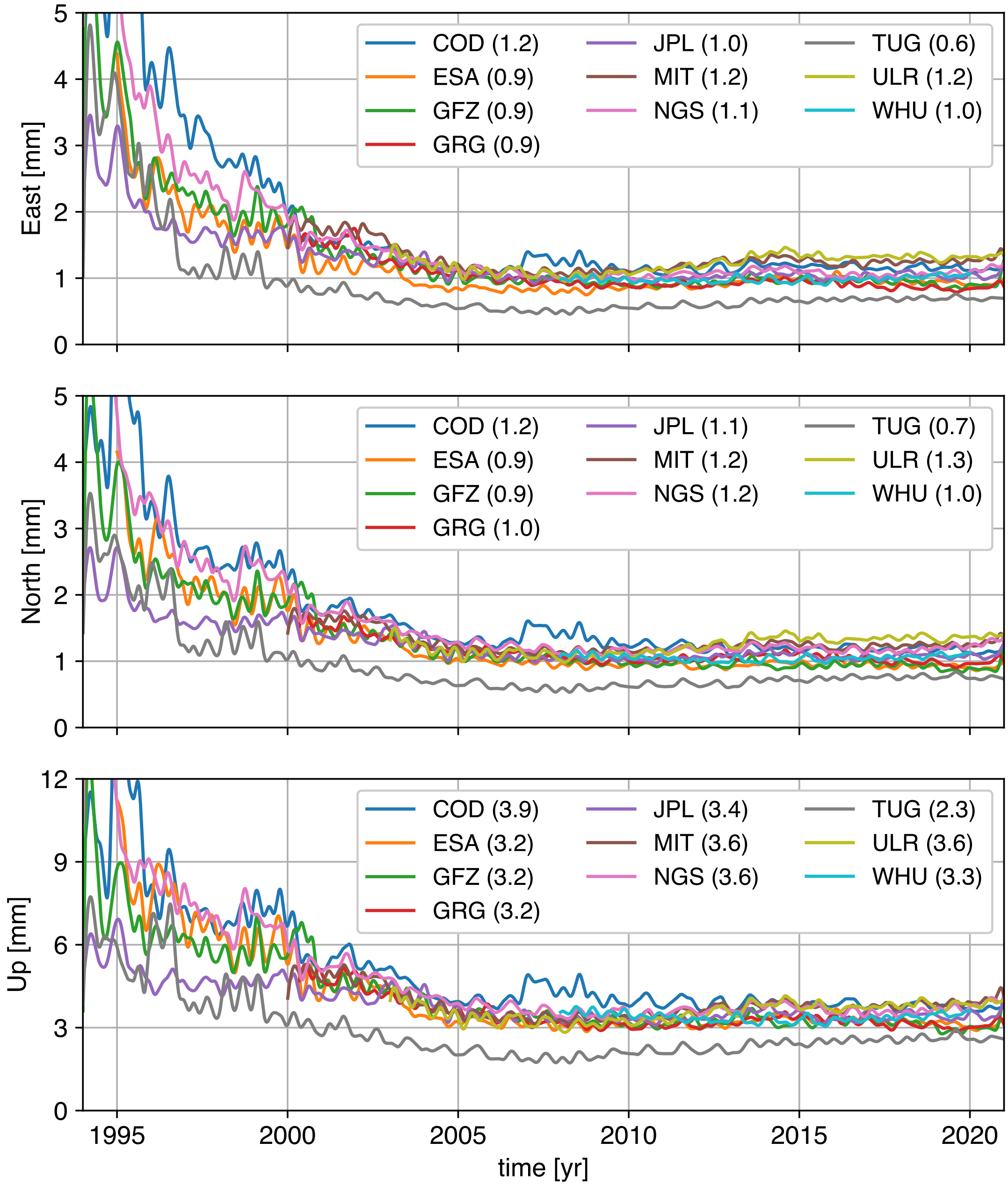


Figure 3: Median formal errors of station positions in daily re-weighted AC repro3 solutions. All time series were low-pass filtered with a 2.5 cpy cutoff frequency. The numbers in the legends are the medians of the time series of daily median formal errors for the period after 2005.0, in mm.

with time until about 2005, along with modernization of both the GPS constellation and the ground tracking network. After 2005, the overall level of agreement between ACs remains at a stable level. With only one exception (TUG), the adjusted median station position formal errors are then close to 1 mm in East and North and between 3 and 4 mm in Up for all ACs, which are similar levels as observed in repro2. A notable difference with repro2 is that, TUG still excepted, all AC contributions to repro3 appear to be of very homogeneous quality. Consequently, while some AC contributions had been excluded from the repro2 SINEX combinations, no such exclusion was necessary in repro3. The predominance of TUG in the daily SINEX combinations has been confirmed by an independent comparison of station position time series extracted from the different AC repro3 solutions by means of a generalized three-cornered hat method. The question of which analysis specificities can explain the higher precision of TUG's station position estimates however remains open.

More details on the repro3 SINEX combination results can be found in (Rebischung, 2021,a). A paper to be submitted to Journal of Geodesy is also in preparation.

3 Analysis of repro3 station position time series

After the daily combined repro3 SINEX solutions were made available, and as part of the ITRF2020 preparation, a detailed analysis of the combined repro3 station position time series was carried out. The first step of this analysis was to identify all offsets present in the series, and model at the same time the post-seismic displacements recorded in certain series. A manual iterative approach was used, with the aid of ancillary data (equipment changes, predicted co-seismic displacements) and of statistical tests. A total of 3054 offsets were thus detected in the repro3 series, half of them due to equipment changes, 23% to earthquakes and 27% to other unknown causes. This corresponds to one offset every 6.3 years in average. The list of identified offsets and the adjusted post-seismic deformation models will be made available along with ITRF2020.

After offsets were identified, the residuals from piecewise linear + post-seismic deformation models were studied. Figure 4 shows the average Lomb-Scargle periodograms of these residuals (only data after 1997.0 and time series longer than 1000 days and at least half complete were used; only time series longer than 1/f contribute to the average power at frequency f). The light colors are for the raw repro3 residual time series. The dark colors are for residual time series corrected for atmospheric, oceanic and hydrological loading deformation based on the models provided by Boy (2021) for ITRF2020.

As expected, loading corrections reduce the annual signal amplitudes in the repro3 series by ≈50% in vertical, ≈20% in horizontal. Besides, as previously shown by Gobron et al. (2021), it clearly appears in Figure 4 that loading corrections also have a strong impact on the nature and amplitude of the background noise in the vertical residual series. The average vertical background noise can be well described by a usual white + power-law noise model after loading corrections, but not before. As a consequence, fitting white + power-law noise models to GNSS height time series uncorrected for loading deformation can yield strongly biased noise parameters and velocity uncertainties.

On top of the background noise, several clusters of spectral peaks are visible in Figure 4. A first cluster of peaks cover harmonics of both the annual frequency and the GPS draconitic frequency, with annual signals dominating over the first draconitic harmonic, but draconitic signals taking over from the second harmonic on. Altough the amplitudes of draconitic errors have been slightly reduced from the repro2 to the repro3 series (Rebischung, 2021), they nevertheless remain an important error source. Furthermore, an analysis of the longest repro3 series showed that the draconitic signals are not stationary with time, but can slowly vary in amplitude and phase, which can be expected from the long-term evolution of the GPS constellation and of the satellites' β angles. Like for loading deformation, failure to account for the non-stationarity of the draconitic signals may result in biased noise models and velocity uncertainties (Rebischung et al., 2021)).

Another cluster of spectral peaks is found around periods of 14 days. All individual peaks in this cluster can be attributed to tide model errors, although different propagation mechanisms are actually at play. The question of which tide model(s) are responsible remains to be investigated.

Finally, clusters of GLONASS-related spectral peaks around harmonics of 8 days are seen in Figure 4. They were absent from the repro2 series, as only two ACs had processed GLONASS data in repro2, whereas a majority of ACs processed GLONASS data in repro3. These peaks are likely explained by GLONASS orbit modeling errors (Rebischung et al., 2021).

References

Boy, J.-P. Contribution of GGFC to ITRF2020. http://loading.u-strasbg.fr/ITRF2020/ggfc.pdf

Gobron, K., P. Rebischung, M. Van Camp, A. Demoulin, and O. de Viron Influence of aperiodic non-tidal atmospheric and oceanic loading deformations on the stochastic properties of global GNSS vertical land motion time series. Journal of Geophysical Research: Solid Earth, 126(9), https://doi.org/10.1029/2021JB022370

Rebischung, P. Terrestrial frame solutions from the third IGS reprocessing. Abstract EGU21-2144 presented at EGU General Assembly 2021, 19-30 Apr., https://doi.org/10.5194/egusphere-egu21-2144

Rebischung, P. Terrestrial frame solutions from the third IGS reprocessing: the IGS contribution to ITRF2020. Presented at Tour de l'IGS: 1st stop, https://files.igs.org/pub/resource/pubs/workshop/2021/02-Rebischung.pdf, https://www.youtube.com/watch?v=cjHcxzkYaLE

Rebischung, P., C. Collilieux, L- Métivier, Z. Altamimi, and K. Chanard Analysis of IGS repro3 station position time series. Abstract G53A-04 presented at AGU Fall Meeting 2021, New Orleans, 13-17 Dec., https://doi.org/10.1002/essoar.10509008.1

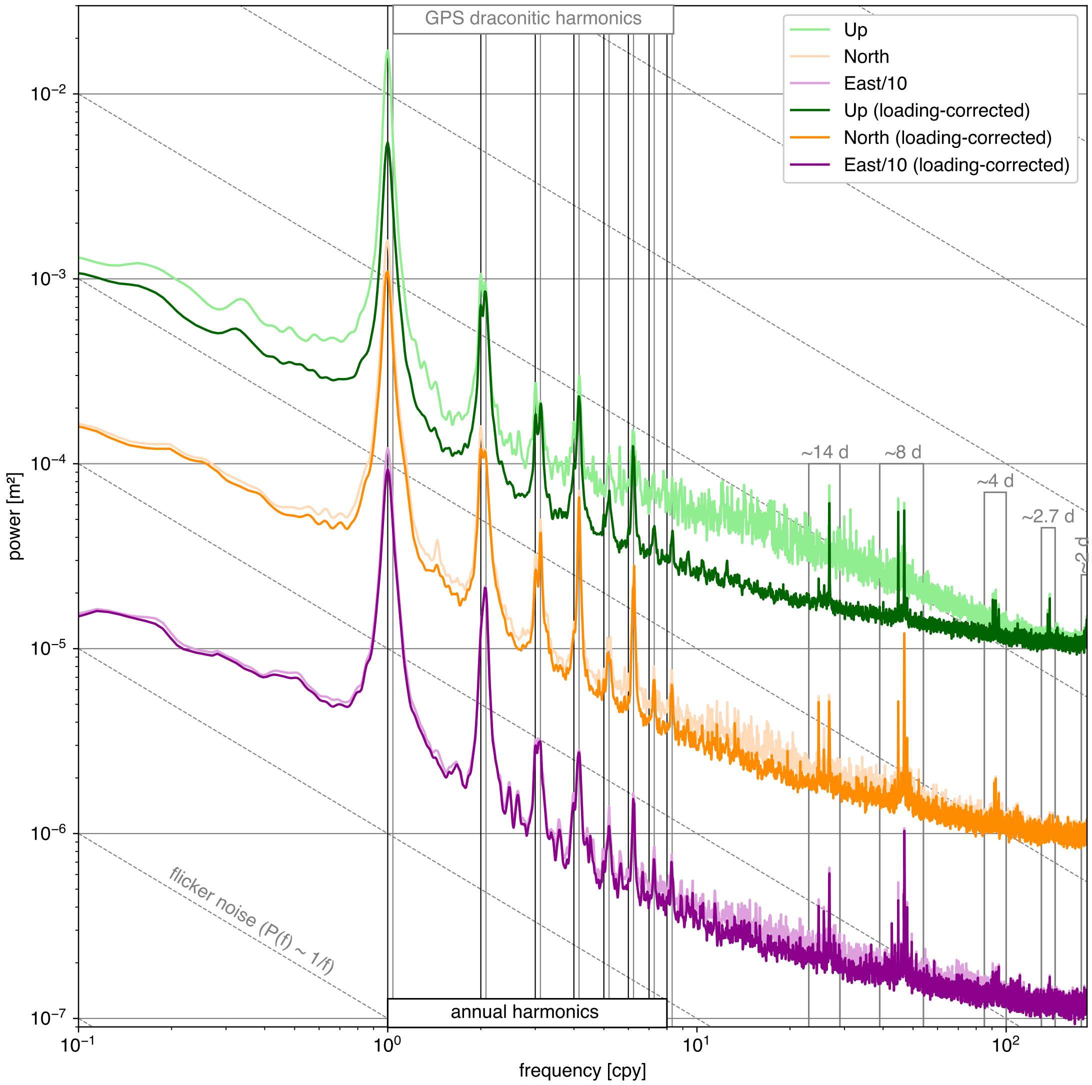


Figure 4: Average Lomb-Scargle periodograms of repro3 residual time series, with and without loading corrections. See details in the text.

RINEX Working Group Technical Report 2021

I. Romero

ESA/ESOC, Germany
Ignacio.Romero@esa.int

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 adjusted during 2021 due to additions and retirements, and is current and correct on the IGS website; https://www.igs.org/wg/rinex/#members

3 Summary of Activities in 2021

Over 2021 the most important development has been the approval of the RINEX 4.00 format definition standard published with a date of 1 December 2021. This version of RINEX modernizes the navigation file format to accommodate all navigation messages; Legacy and Modern as transmitted by many of the GNSS. The RINEX 4.00 Observation files remain backward compatible to RINEX 3.00 but the Navigation files are no longer backward compatible and this is why a major version number was necessary for this format upgrade.

The new RINEX 4.00 format definition has been approved by the RTCM SC-104 and by the IGS Governing Board and can be found here; https://igs.org/wg/rinex/#documents-formats

All official RINEX file versions are valid for IGS station data files, but all stations are encouraged to become multi-GNSS and to switch to RINEX 4.00 was soon as it is practical and supported by their equipment vendors so that all GNSS navigation messages get properly recorded.

Additionally the RINEX WG members list was reviewed and updated as needed. 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 2022 Activities

During 2022 the RINEX WG will monitor and clarify the existing RINEX 4.00 standard as it starts to be implemented and stations start to transition.

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 by the Working Group.

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, A. Santamaría-Gómez, N. Teferle, D. Thaller, L. Sánchez, 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 2021

- TIGA-AC's contributed to the IGS-repro3 campaign with dedicated TIGA and GNSS@TideGauge solutions. ULR processed a network of 468 GNSS@TideGauge stations and GFZ a network of 254 GNSS@TideGauge.
- TIGA Network operator at SONEL 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 2021 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 1229 (TIGA: 122 stations, with 18 decommissioned) stations (600 stations active, 187 stations decommissioned). Still there are 175 stations where the GNSS data is not (yet) available for scientific research.

3 Related important Outreach activities and publications in 2021 (selected)

- Participation IGS Governing Board Meetings, January, August and December 2021
- IGS Associate Member Meeting, 06 December 2021
- Oelsmann J., Passaro M., Dettmering D., Schwatke C., Sánchez L., Seitz F. (2021): The zone of influence: Matching sea level variability from coastal altimetry and tide gauges for vertical land motion estimation, Ocean Science, 17 (1), pp. 35 – 57, doi: 10.5194/os-17-35-2021
- Frederikse T., Adhikari S., Daley T.J., Dangendorf S., Gehrels R., Landerer F., Marcos M., Newton T.L., Rush G., Slangen A.B.A., Wöppelmann G. (2021) Constraining 20th-Century Sea-Level Rise in the South Atlantic Ocean, Journal of Geophysical Research: Oceans, 126 (3), doi: 10.1029/2020JC016970
- Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., Antonioli, F., Artale, V., Carminati, E., Ferrarin, C., Fofonova, V., Nicholls, R. J., Rubinetti, S., Rubino, A., Sannino, G., Spada, G., Thiéblemont, R., Tsimplis, M., Umgiesser, G., Vignudelli, S., Wöppelmann, G., and Zerbini, S. (2021) Sea-level rise in Venice: historic and future trends (review article), Nat. Hazards Earth Syst. Sci., 21, 2643–2678, doi: 10.5194/nhess-21-2643-2021
- Siriwardane-de Zoysa, R., Schöne, T., Herbeck, J., Illigner, J., Haghighi, M., Simarmata, H., Porio, E., Rovere, A., & Hornidge, A.-K. (2021). The 'wickedness' of governing land subsidence: Policy perspectives from urban Southeast Asia. Plos One, 16(6): e0250208. doi: 10.1371/journal.pone.0250208

- Bott, L.-M., Schöne, T., Illigner, J., Haghshenas Haghighi, M., Gisevius, K., & Braun, B. (2021). Land subsidence in Jakarta and Semarang Bay – The relationship between physical processes, risk perception, and household adaptation. Ocean & Coastal Management, 211: 105775. doi: 10.1016/j.ocecoaman.2021.105775
- Yang, L., Jin, T., Gao, X., Wen, H., Schöne, T., Xiao, M., & Huang, H. (2021). Sea Level Fusion of Satellite Altimetry and Tide Gauge Data by Deep Learning in the Mediterranean Sea. Remote Sensing, 13(5): 908. doi: 10.3390/rs13050908

4 TIGA Working Group Members in 2021

Working group members are listed in Table 1.

Table 1: TIGA Working Group Members in 2021

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
Daniala Thaller		BKG	Germany

IGS Troposphere Working Group Technical Report 2021

S. M. Byram

United States Naval Observatory
3450 Massachusetts Avenue Northwest
Washington DC 20392 USA
sharyl.m.byram.civ@us.navy.mil

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 2021

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).

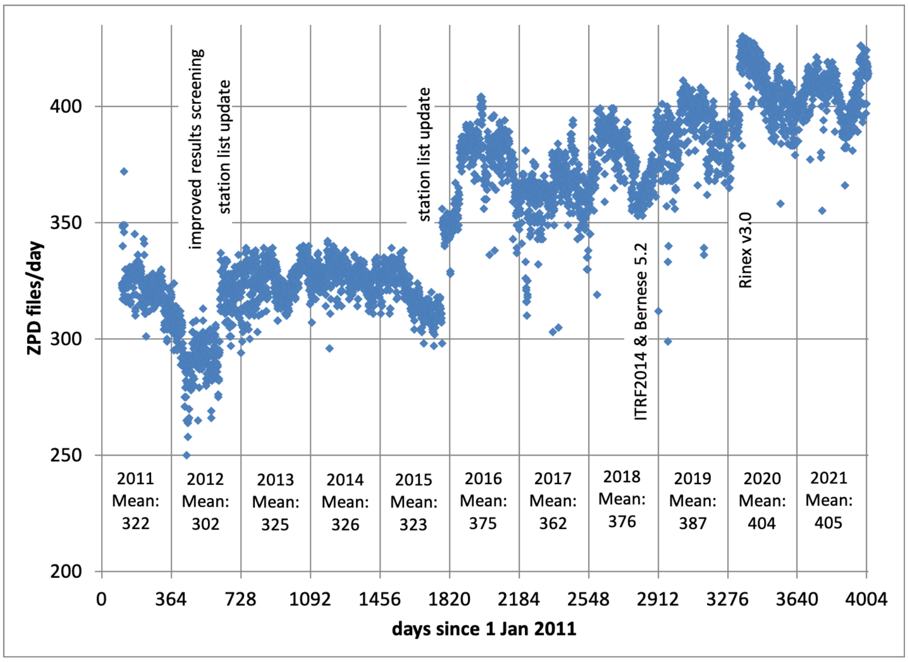


Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011–2021. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011)

Fig. 1 shows the number of receivers for which USNO computed IGS FTEs 2011-2021. The average number of quality-checked station result files submitted per day in 2021 was 405. 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 15.9 million in 2021.

3 IGS Troposphere Working Group Activities 2021

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 2022. Communications on news and activities were distributed via the TWG mailing list.

3.1 Working Group Projects: 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 organizations and other communities; its work is further supported by the EUREF Technical Working Group as well as E-GVAP 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.

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.m.byram.civ@us.navy.mil.

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

- contact Dr. Sharyl Byram at sharyl.m.byram.civ@us.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

References

Byram, S. and C. Hackman. Computation of the IGS Final Troposphere Product by the USNO. IGS Workshop 2012, Olstzyn, Poland, 2012.

Boehm, J., A. Niell, P. Tregoning, and H. Schuh. Global Mapping Function (GMF): A New Empirical Mapping Function Based on Numerical Weather Model Data. *Geophysical Research Letters*, 33(7):L07304, 2006. doi: 10.1029/2005GL025546, 2006.

Dach, R., S. Lutz, P. Walser, and P. Fridez. (eds.) Bernese GNSS Software Version 5.2. (user manual) Astronomical Institute of University of Bern, Bern, Switzerland, 2015.

Douša, J. and G. Gyõri. Database for Tropospheric Product Evaluations – Implementation Aspects. *Geoinformatics*, 10:39–52, 2013.

Gyori, G. and J. Douša. GOP–TropDB Developments for Tropospheric Product Evaluation and Monitoring – Design, Functionality and Initial Results. *IAG Symposia Series*, 143 (in press), Springer, 2015.

Hackman, C., G. Guerova, S. Byram, J. Douša, and U. Hugentobler. International GNSS Service (IGS) Troposphere Products and Working Group Activities. FIG Working Week 2015, presentation/paper #7696, Sofia, Bulgaria, May, 2015.

Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb. Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks. *J. Geophys. Res.*, 102(B3):5005–17, 1997.

IGS CENTRAL BUREAU
NASA Jet Propulsion Laboratory
California Institute of Technology
M/S 238-540
4800 Oak Grove Drive
Pasadena, California 91101
United States of America

www.igs.org | cb@igs.org

EDITOR
Astronomical Institute
University of Bern
Sidlerstrasse 5
3012 Bern
Switzerland
www.aiub.unibe.ch

The IGS is a service of Global Geodetic Observing System International Association of Geodesy International Union of Geodesy and Geophysics

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