IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2022

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International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

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IGS INTERNATIONAL GNSS SERVICE

Technical Report 2022

IGS Central Bureau

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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 2022* 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 2022.

This report is available in electronic version at
https://files.igs.org/pub/resource/technical_reports/2022_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 Governing Board Annual Report 2022

F. Perosanz[1], R. Dach[2], L. Martire[3], A. Nilo[3,4], A.Ḃ. Craddock[3]

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1 Introduction

In 2024, the International GNSS Service will have been fulfilling its mission for thirty years. Still today, the Service and all of its members continue to provide and advocate for freely and openly available high-precision GNSS data and products. The delivery of the IGS core products (reference frame, orbits, clock, and atmospheric products) continues to drive the Service's activities. That being said, as part of its multi-GNSS excellence objective, the IGS also continues its steady transformation into a multi-GNSS service, as more and more multi-GNSS stations are added into the core IGS network.

The IGS is led by the Governing Board (GB), elected by Associate Members who represent the core of 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.

As such, we continue to engage with our International User Community and their partner organizations, including the Committee on GNSS (ICG), the International Association of Geodesy (IAG), and the Global Geodetic Observing System (GGOS). Accordingly, some GB members also participate in the governance of IAG and GGOS bureaux, commissions, and Working Groups (WGs); this ensures that the IGS retains its strong level of international interconnectivity, 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.

2 Membership and Governance

2.1 Membership Growth and Internal Engagement

The IGS membership consists of the Governing Board (GB) members, the Central Bureau (CB) members, and the Associate Members (AM). A schematic of the IGS structure is provided in Figure 1. As of early 2023, we count over:

- 350+ AMs (representing 100+ countries/regions),
- 150+ contributing organizations participating within the IGS, including:
  - 100+ agencies operating GNSS Network Tracking Stations,
  - 6 Global Data Centers,
  - 12 Analysis Centers,
  - 5 Product Coordinators,
  - 21 Associate Analysis Centers,
  - 24 Regional/Operational & Project Data Centers,
  - 13 Technical Working Groups, and
  - 2 Active Pilot Projects.

The 44 GB members guide the coordination of all of the aforementioned parties. The CB functions as the executive office of the Service through its 8 members (see Table 1 in Central Bureau Chapter), holding all of the components of the IGS together by providing continuous management and technology.

The IGS structure (Figure 1) is currently being reformatted based on the latest information. This is the 2020 version of this schematic. An updated structure will be released in 2023.

2.2 Governing Board Appointments and Current Status

The positions up for reelection at the end of December 2022 are detailed in Table 1 . The GB continues to be led by Felix Perosanz (CNES). Rolf Dach (AIUB) was elected by the GB in July 2022 as the new GB Vice Chair, a position that was previously vacant. Mayra Oyola-Merced (University of Wisconsin-Madison, formerly NASA JPL) stepped off her IGS duties mid-2022; her responsibilities were handed over to Léo Martire (NASA JPL) and Ashley Nilo (née Santiago, Raytheon Technologies), who respectively took the roles of CB Deputy Director and GB Executive Secretary. Table 2 summarizes the GB status at the end of 2022.

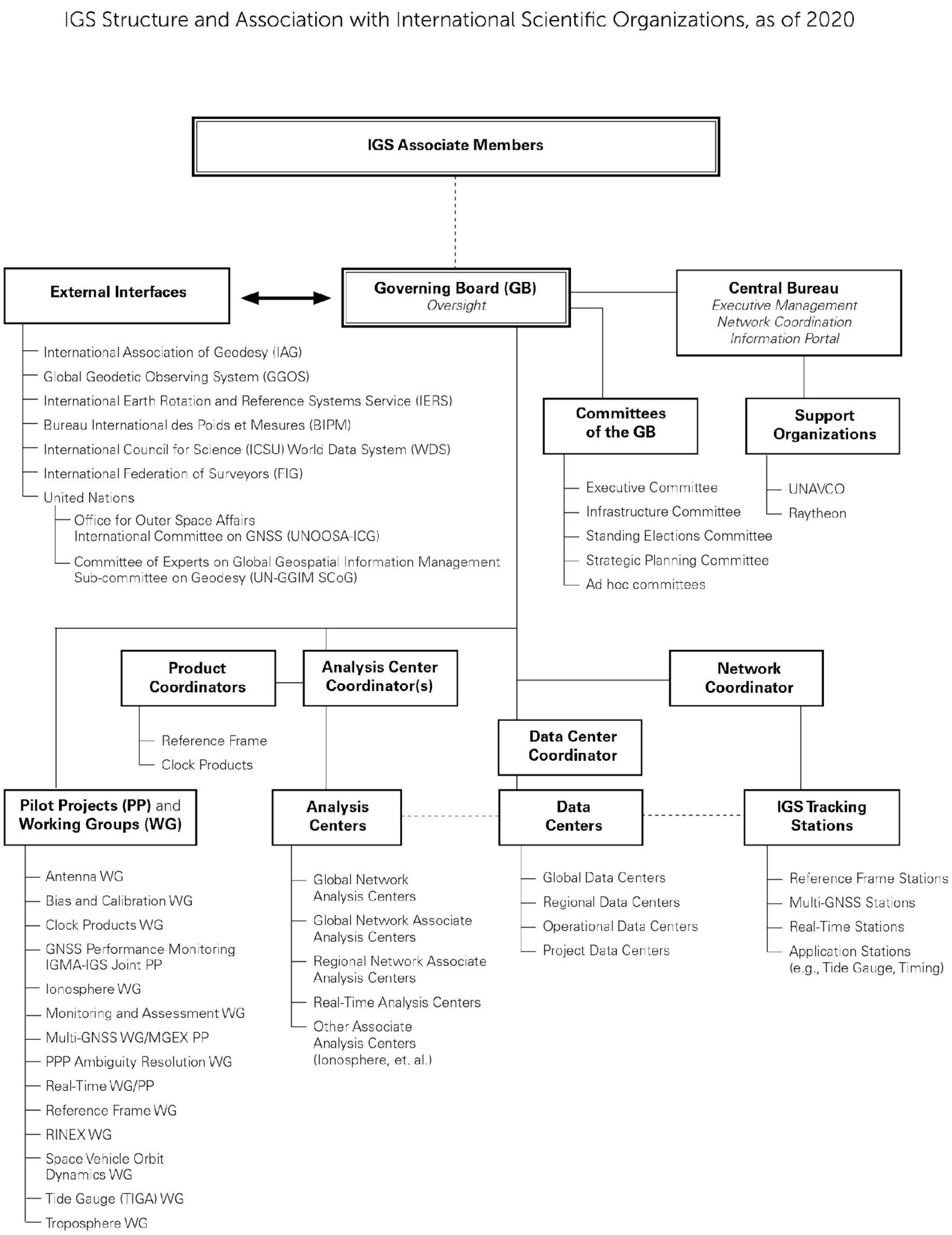

Figure 1: IGS structure map, as of 2020.

Table 1: 2022 mid-year and year-end GB elections summary. "(WG)"/"(PP)" denotes a role pertaining to a Working Group/Pilot Project.

(WG) PPP-AR Working Group Chair:
Simon Banville (NRCan, Canada) ⇒ Jianghui Geng (Wuhan University, China)

Governing Board Vice-Chair: vacant ⇒ Rolf Dach (AIUB, Switzerland)

(PP) GNSS for Weather and Climate Resiliency:
did not exist ⇒ Mayra Oyola-Merced (UW–Madison, USA)

Governing Board Executive Secretary:
Mayra Oyola-Merced (NASA JPL, USA) ⇒ Ashley Nilo (Raytheon, USA)

(WG) Clock Products Coordinator: Michael Coleman (Naval Research Laboratory) ⇒ renewed

Analysis Center Representative:
Rolf Dach (AIUB, Jan. to Jul.); vacant (Jul. to Dec.) ⇒ Sylvain Loyer (CNES/CLS, France)

NET Representative: Wolfgang Söhne (BKG, Germany) ⇒ renewed

Appointed Member: Elisabetta D'Anastasio (GNS Science, New Zealand) ⇒ renewed

Appointed Member: José Antonio Tarrío Mosquera (Universidad of Santiago de Chile) ⇒ renewed

Appointed Member: ZHAO Qile (Wuhan University, China) ⇒ term ended

BIPM Representative: Gérard Petit (BIPM, France) ⇒ Patrizia Tavella (BIPM, France)

IAG Representative: Basara Miyahara (GSI, Japan) ⇒ extended[1]

IERS Representative: Elisabetta D'Anastasio (GNS Science, New Zealand) ⇒ renewed

IERS Representative: Rolf Dach (AIUB, Switzerland) ⇒ renewed

FIG Representative: Suelynn Choy (RMIT, Australia) ⇒ Ryan Keenan (Positioning Insights, Australia)

(WG) SVOD Working Group Chair: Tim Springer (PosiTim, Germany) ⇒ vacant[2]

RT Analysis Center Coordinator: Loukis Agrotis (Symban, UK) ⇒ vacant[2]

(WG) RINEX Working Group Chair: Ignacio Romero (Canary Space Consulting, Spain) ⇒
candidate proposed by the WG: Francesco Gini[2]

(WG) RT Working Group Chair : André Hauschild (DLR, Germany) ⇒ Axel Rülke (BKG, Germany)

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[1] It was decided (at the 62$^{\text{nd}}$ GB meeting) that the IAG Representative term should align with the IAG elections; as such Miyahara-san's term was extended until mid-2023.

[2] Due to changes in the European legislation, these roles cannot be fulfilled anymore under the ESA/ESOC affiliation; see main text for details.

Table 2: Members of the IGS Governing Board, 2022, officially starting January 2023.
V: voting members; EC: members of the Executive Committee

Role	First and last Name	Affiliation	Country	V	EC
Board Chair	Felix Perosanz	Centre National d'Etudes Spatiales (CNES)	France	V	EC
Board Vice Chair, IERS Representative	Rolf Dach	Astronomical Institute, University of Bern	Switzerland	V	EC
Infrastructure Committee Coordinator	Markus Bradke	Deutsches Geo-ForschungsZentrum (GFZ)	Germany	V	EC
Governing Board Executive Secretary	Ashley Nilo	Raytheon Technologies	USA		EC
Central Bureau Director	Allison Craddock	NASA Jet Propulsion Laboratory (JPL)	USA	V	EC
Central Bureau Deputy Director	Léo Martire	NASA Jet Propulsion Laboratory (JPL)	USA		EC
Network Coordinator	David Maggert	UNAVCO	USA		
Appointed Member, IERS Representative	Elisabetta D'Anastasio	GNS Science	New Zealand	V	
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	
Analysis Center Coordinator	Thomas Herring	Massachusetts Institute of Technology (MIT)	USA	V	EC
Analysis Center Coordinator	Salim Masoumi	Geoscience Australia (GA)	Australia	V	
Data Center Coordinator	Patrick Michael	NASA Goddard Space Flight Center (GSFC)	USA	V	
Data Center Representative	Jianghui Geng	Wuhan University	China	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	Sylvain Loyer	Collecte Localisation Satellites (CLS)	France	V	
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	
BIPM/CCTF Representative	Patrizia Tavella	Bureau International des Poids et Mesures (BIPM)	France		

Table 2: Members of the IGS Governing Board, 2022, officially starting January 2023 (cont.) V: voting members; EC: members of the Executive Committee.

Role	First and last Name	Affiliation	Country	V	EC
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	
IERS Representative	Richard Gross	NASA Jet Propulsion Laboratory (JPL)	USA	V	
International Federation of Surveyors (FIG) Representative	Ryan Keenan	Positioning Insights	Australia		
Antenna Working Group Chair	Arturo Villiger	Astronomical Institute, University of Bern (AIUB)	Switzerland		
Bias & Calibration Working Group Chair	Stefan Schaer	Federal Office of Topography - swisstopo	Switzerland		
Clock Products Coordinator	Michael Coleman	Naval Research Laboratory (NRL)	USA	V	
IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair	vacant				
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		
PPP-AR Working Group Chair	Jianghui Geng	Wuhan University	China		
Real-time Analysis Coordinator	vacant			V	
Real-Time Working Group Chair	Axel Rülke	Federal Agency for Cartography and Geodesy (BKG)	Germany		
Reference Frame Coordinator	Paul Rebischung	Institut National de l'Information Géographique et Forestière (IGN)	France	V	
RINEX-RTCM Working Group Chair	Francesco Gini	ESA/European Space Operations Centre	Germany		
Satellite Vehicle Orbit Dynamics Working Group Chair	vacant				
TIGA Working Group Chair	Tilo Schöne	Deutsches GeoForschungsZentrum (GFZ)	Germany		
Troposphere Working Group, Chair	Sharyl Byram	United States Naval Observatory (USNO)	USA		
Weather and Climate Resiliency Pilot Project Chair	Mayra Oyola-Merced	University of Wisconsin-Madison	USA		

Since the last Technical Report, new members or positions are in green. Acting members, pending GB approval at this time, are in blue.

Loukis Agrotis, Ignacio Romero, and Tim Springer are contractors affiliated with ESA/ESOC. Due to changes in the European legislation and contractual constraints, they cannot represent ESA formally in any international bodies anymore, including the IGS. Subject to future discussions within the relevant WGs in 2023, Mr. Springer and Mr. Romero will be replaced by two permanent ESA staff, and Mr. Agrotis' role (as Real-Time Analysis Coordinator) will be discontinued. All three persons will remain contributors to their respective IGS components.

2.3 Committee on Sustainable Working Group Governance

Goal 3 of the IGS 2021+ Strategic Plan is to build a sustainable and resilient organization – the Committee on Sustainable Working Group Governance (CSWGG) is progressing this goal through identifying ways in which the technical Working Groups, Pilot Projects, and Committees can be invigorated to ensure ongoing sustainability and be in a better place to support the IGS in successfully achieving its mission.

During 2022, the Committee on Sustainable Working Group Governance (CSWGG) engaged with the community to develop several recommendations that aim to improve the sustainability of the Working Groups, Pilot Projects and Committees. These recommendations will be delivered throughout 2023 in the form of changes to the Terms of Reference, policy documents, and resources available to support the Working Group and Pilot Project Chairs.

3 Governing Board Meetings

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. For a summary of the 2022 GB meetings, see Table 2 in Chapter "IGS Central Bureau".

4 GB Accomplishments and Decisions in 2022

The past accomplishments and decisions can be found in the previous Technical Reports (`https://igs.org/tech-report/`). The accomplishments and decisions for 2022 are listed below:

- **GB 60 (May 2022):**

  Decision 60a-01: Next IGS Workshop to take place in Bern, Switzerland the first week of July in 2024.

Decision 60a-02: GB agrees to submit letter in support of Genesis-1, as long as the corrections are made to clarify the claims.

Decision 60a-03: GB 61 (Within the timeframe of the IGS Workshop) will be on Jun 23, 2022 (virtual, 2-hour condensed format)

Decision 60a-04: GB 62 (Within the timeframe of AGU) will be on Dec 11, 2022 (hybrid in-person, 5-hour "traditional" format with some modifications for virtual attendee timezones)

Decision 60b-01: The IGS approves the statement on the leap second by 90

Decision 60b-02: GB approves of proposed election process modifications for the upcoming vice-chair position election

- **GB 61 (June 2022):**

Decision 61-01: The IGS approves the Workshop Code of Conduct by 95.2% of the votes.

Decision 61-02: R. Dach has been approved as the new Governing Board Vice Chair by 84.2% of the votes, effective by the end of the IGS 2022 Virtual Workshop.

Decision 61-03: J. Geng has been approved as the next PPP-AR Working Group (WG) Chair by 90.9% of the votes effective immediately.

Decision 61-05: The GNSS for Weather Climate and Resiliency Pilot Project (WCR-PP) Proposal has been approved by 95.2% of the votes.

Decision 61-06: M. Oyola-Merced has been approved as chair of the WCR-PP by 100% of the votes.

Decision 61-06: The Associate Member (AM) application changes and modifications have been approved by 95% of the votes.

Decision 61-07: A. Santiago (now A. Nilo) has been approved as the next GB Executive Secretary by 100% of the votes effective immediately.

- **GB 62 (December 2022):**

Decision 62-01: Approved IGS Satellite Metadata File Description.

Decision 62-02: Approved renewing Elisabetta D'Anastasio as appointed member.

Decision 62-03: Approved renewing José Tarrío Mosquera as appointed member.

Decision 62-04: Approved renewing Rolf Dach as IGS representative to the IERS.

Decision 62-05: Approved renewing Elisabetta D'Anastasio as IGS representative to the IERS.

Decision 62-06: Approved renewing Basara Miyahara as IAG representative and to align his term with IAG elections.

Decision 62-07: Approved Patrizia Tavella as BIPM representative.

Decision 62-08: Approved renewing Michael Coleman as Chair of the Clock Working Group.

Decision 62-09: Approved Léo Martire as the new Central Bureau Deputy Director.

Decision 62-10: Approved Ryan Keenan approved as the new FIG representative.

Decision 62-11: [Post-GB62] Approved Axel Rülke (BKG) as the new Real-Time Working Group Chair.

Decision 62-12: [Post-GB62] Approved Ningbo Wang (CAS) as the Real-Time Working Group Vice Chair.

Decision 62-13: [Post-GB62] Approved the Guidelines for Long Product Filenames in the IGS.

5 Operational Activities

5.1 Network Growth and Coordination

Daily network operations are the heart of the IGS – various components of the service ensure that data and products are made publicly available at least on a daily basis. Over 500 IGS Network sites (see Figure 2) are maintained and operated globally by a broad

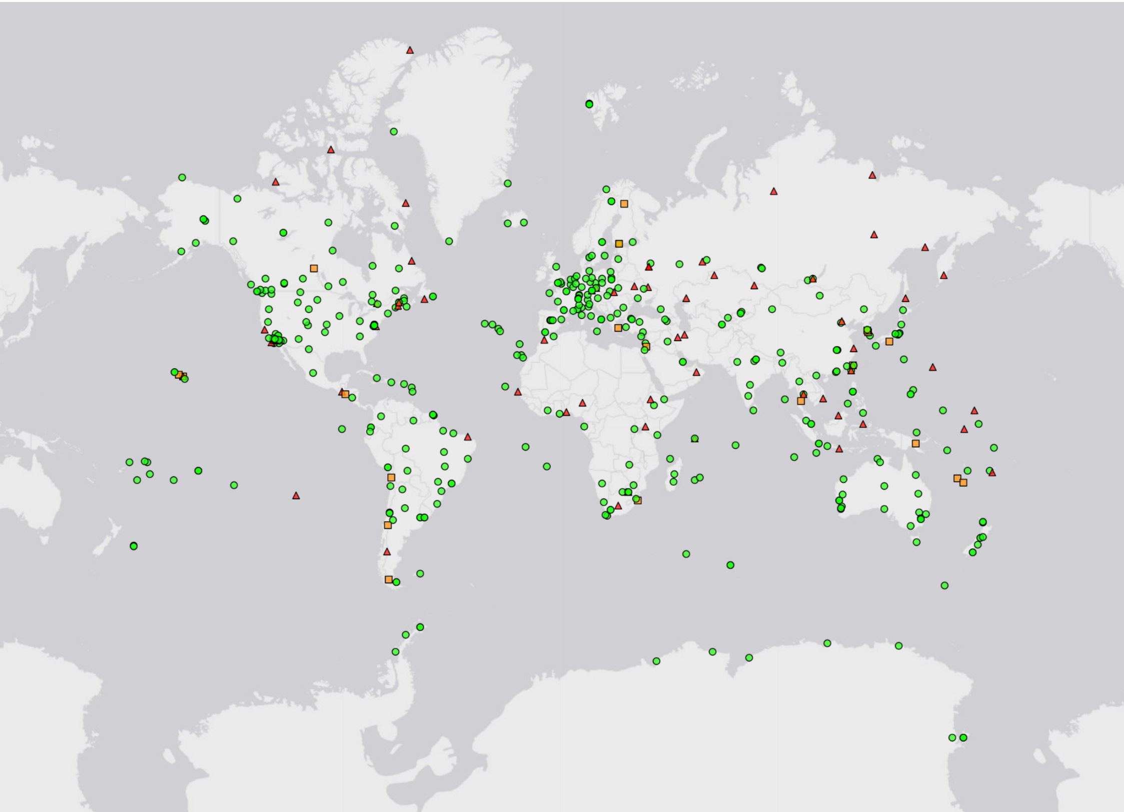

Figure 2: The IGS Network, as of the 12th of January 2023. The map showcases 513 stations in total, with 317 that track multi-GNSS and 301 that have real-time capabilities. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations.

array of institutions and station operators. Data continues to be available to the public and the scientific community, with latencies ranging from daily to real-time.

During 2022, 15 new stations were added to the IGS network, and 6 stations were identified for decommissioning; the list can be found in Table 2 in Chapter "Infrastructure Committee". The number of multi-GNSS stations increased from 353 to 363 (+10), while the number of real-time-capable stations increased from 292 to 302 (+10). The CB wishes to gratefully acknowledge the efforts of the institutions in charge of the stations, both new and decommissioned.

Additionally, in 2022, there were 40 changes to the `rcvr_ant.tab` file, 351 site log updates (≈29 per month), and 7 antenna changes (4 of them at IGS20 reference frame stations).

5.2 Product Generation and Performance

The IGS Analysis Center Coordination (`https://igs.org/acc`) continued to be jointly led by Salim Masoumi (Geoscience Australia) and Tom Herring (Massachusetts Institute of Technology). The operations are based at Geoscience Australia in Canberra, Australia, while the combination software is housed on cloud-based servers located in Australia and Europe; cloud operations ran smoothly throughout 2022. The IGS product generation continued to be carried out solely by personnel at Geoscience Australia. MIT provides scientific guidance and suggestions on products. The IGS continues to maintain a very high level of product availability. For more details, see also Section 2 in Chapter "Analysis Center Coordinator".

5.3 Switch of the Reference Frame to IGS20

With each new release of the International Terrestrial Reference Frame (ITRF), the IGS changes the reference frame to which its products are aligned and give access. At the same time, the opportunity is taken to update the set of ground and satellite antenna calibrations compiled in the IGS ANTEX file.

In 2022, the IGS adopted a new reference frame, called IGS20, as the basis of its products. IGS20 is closely related to the ITRF2020 reference frame, which was released in April 2022. An updated set of satellite and ground antenna calibrations, igs20.atx, also became effective at the same time and should be used together with IGS20. The IGS switched from `IGb14/igs14.atx` to `IGS20/igs20.atx` starting with the products of GPS week 2238 (27 November 2022).

At the same time as the switch to IGS20/igs20.atx, the IGS also adopted for its operational products the same conventions and models as used in its third reprocessing campaign (repro3; see `http://acc.igs.org/repro3/repro3.html`). This includes in particular the adoption of new long filenames for the IGS products (see guidelines).

For more detailed information about these changes, please see IGSMAIL #8238, IGSMAIL #8256, IGSMAIL #8274, Section 4.3 in last year's Tech Report and Section 4 in Chapter "Analysis Center Coordinator" and Section 2 in Chapter "Reference Frame Working Group".

5.4 Data Management

Twelve Analysis Centers and twenty-one 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. Collectively, the IGS produces more than 700 IGS final, rapid, ultra-rapid and GLONASS-only product files, as well as 133 ionosphere files weekly. Furthermore, troposphere files for more than 400 stations are produced on a daily basis. Delivery of the core reference frame, orbits, clocks, and atmospheric products continued. 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.

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 in 2017 to 62 TB over 453 million files at the end of 2022, supported by significant additional storage capabilities provided by Regional Data Centers. The intense interest of users in IGS data and products is reflected in the user activity recorded by the Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center:

- a total of 1.3 B files equating to 331 TB of GNSS data, and
- a total of 186 M files equating to 26.4 TB of GNSS products.

This averages to:

- 110.7 M files equating to 27.6 TB GNSS data from 17.7 K unique users per month, and
- 15.5 M files equating to 2.2 TB GNSS products from 11.1 K unique users per month.

6 Strategic Plan

The Governing Board worked toward initial implementation of the 2021+ IGS Strategic Plan, which was built upon the feedback of many IGS community members, and outlines key points of the IGS goals and the anticipated path to meet its objectives within the next decade. It was created over a two-year development period, detailed in the CB Chapter of the 2021 IGS Technical Report (`https://igs.org/tech-report/`), and released in 2021. In summary, it strives to serve the community with (a) facilitation, (b) coordination, (c) incubation, and (d) advocacy in three strategic goals: (1) Achieve Multi-GNSS Technical

Excellence, (2) Strengthen Outreach and Engagement, and (3) Build Sustainability and Resilience. The plan continues in the spirit of its previous strategic plans. It focuses on how the IGS maintains and enhances its leadership role within the broader GNSS community, as societal demands for GNSS products and services continue to grow. More details can be found in the reference document, at https://igs.org/strategic-planning/.

7 External Engagement

At the direction of the Governing Board, the Central Bureau works with various components of the **International Association of Geodesy (IAG)**, in order to promote communications and outreach. For instance, the IGS is involved with the IAG Communications and Outreach Branch, and the **Global Geodetic Observing System (GGOS)**. IGS Associate Members (AMs) and GB members also participate actively in the **United Nations Initiative on Global Geospatial Information Management (UN GGIM)** Sub-Committee on Geodesy (http://ggim.un.org/UN_GGIM_wg1.html), including contributing to the five focus groups developed for the UN GGIM Global Geodetic Reference Frame Roadmap.

In particular, the CB Director represents the IGS on behalf of the Governing Board in the **GGOS Coordinating Board**. The CB Director also serves as a point of contact between IGS and the **US Federal Advisory Board for Space-based Position, Navigation and Timing (PNT)**.

IGS is an Associate Member of the **International Committee on GNSS (ICG)**, based in the **United Nations Office for Outer Space Affairs (UNOOSA)**. Together with the International Federation of Surveyors (FIG), the International Association of Geodesy (IAG), and the Bureau International des Poids et Mesures (BIPM), IGS co-chairs the ICG's Working Group D (on "Reference Frames, Timing, and Applications"). The existing joint ICG-IGS International GNSS Monitoring and Assessment (IGMA) project, focusing on performance and interoperability metrics, continued its efforts throughout 2022 and reported at the 16th meeting of the ICG (ICG-16) in October 2022. Furthermore, at ICG-16, a new Task Force (TF) was established, entitled "Applications of GNSS for Disaster Risk Reduction""; see ICG's WG D's Recommendation #26.

8 Future Steps for 2023

The IGS continues to keep up with 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 the Service does not become tangential to the needs of our key stakeholders, the Associate Members.

The GB, CB, and Associate Members continue their efforts towards (and play key roles in) enhancing advocacy for the IGS. Accordingly, presentations at a variety of forums within our discipline and outside of it will 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 overall.

In terms of internal progress, we are currently reviewing, improving, and clarifying the IGS Terms of Reference (ToR). Moving through the years, different needs and edge cases were identified. The new version of the ToR will be released in 2023, and contribute to an even more sustainable IGS.

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.

9 Publications and Official IGS Citation

Official publications pertaining to the IGS are:

- IGS 2020 Technical Report
- IGS 2021 Technical Report

For those acknowledging the IGS in scholarly research and other works, it is recommended to cite the IGS chapter found in the 2017 Springer Handbook of Global Navigation Satellite Systems:

> Johnston, G., Riddell, A., Hausler, G. (2017). 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.

IGS Central Bureau Annual Report 2022

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1 Introduction

The International GNSS Service (IGS) is among the world's largest GNSS public and voluntary organisations, with almost thirty years of history. As of today, a total of more than 350 active members continuously and voluntarily contribute to working towards the IGS goals: advocacy for, development of, use of, and consistent provision of freely and openly available high precision GNSS data and products.

In order to sustain the multifaceted efforts of the IGS, the Central Bureau (CB) works to support and realise the IGS strategic goals of:

- achieving multi-GNSS technical excellence,
- strengthening public outreach and engagement, and
- building sustainability and resilience.

The CB work program is shaped by the directives and decisions of the IGS Governing Board (GB), which often tasks members of the CB with representing the outward face of IGS to a diverse global user community and the general public. For more information about the IGS Governing Board, please see Chapter "IGS Governing Board".

The CB is funded by the United States National Aeronautics and Space Administration (NASA) and hosted at the Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. This office is led by the CB Director Allison Craddock (NASA JPL, USA) with support from former Deputy Director Mayra Oyola-Merced (now University of Wisconsin-Madison) and current Deputy Director Léo Martire (NASA JPL). The CB also works as the command-and-control centre for tracking network operations, mostly overseen by the Network Coordinator, David Maggert (University Navstar Consortium, 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 hosted; these tasks are

Table 1: IGS Central Bureau staff and responsibilities, over the course of 2022. NASA is the National Aeronautics and Space Administration. JPL is the Jet Propulsion Laboratory (Pasadena, USA). UNAVCO is the University Navstar Consortium (Boulder, CO). JPL is managed by the California Institute of Technology (Caltech) for NASA.

Name	Affiliation	Role
Allison Craddock	NASA JPL	Director
Mayra I. Oyola-Merced	NASA JPL	Deputy Director (Jan. to July)
Léo Martire	NASA JPL	Acting Deputy Director (July to Dec.) Deputy Director (December)
Ashley Nilo (née Santiago)	Raytheon Technologies	Product Strategist
David Maggert	UNAVCO	Network Coordinator
David Stowers	NASA JPL	CBIS Advisor
Robert Khachikyan	Raytheon Technologies	CBIS Manager
Brian Kohan	Raytheon Technologies	CBIS Engineer
Rachel Pham	NASA JPL	CBIS Intern (June to December)

led by Robert Khachikyan (Raytheon, USA) and Ashley Nilo (née Santiago) (Raytheon). A list of the CB members along with their respective roles and responsibilities is given in Table 1 .

2 Summary of Accomplishments

This Section highlights the progress made by the IGS CB in 2022. As the impact of the COVID pandemic still affects the global community, the CB has continued to pursue means to hold IGS activities in both efficient and safe conditions. This essentially includes holding meetings virtually, or in a hybrid manner whenever possible. The CB continues to pay particular attention to equitably represent different regions of the world by adjusting the meeting times to various time zones and technology bandwidths. Aside from these considerations, the CB has achieved the following items:

1. Supported the timely delivery of data and products.
2. Supported the Committee on Sustainable Working Group Governance (CSWGG); see Section 2.3 in Chapter "IGS Governing Board".
3. Organised four Governing Board Meetings, three fully virtual and one hybrid, all successful.
4. Organised a year-end hybrid open Associate Member and Working Group Meeting, successfully, with 70+ participants; see https://igs.org/am-meetings.
5. Supported the Standing Elections Committee with the 2022 GB elections; see Sec-

tion 3.2 .

6. Released four new issues of "Constellations: the IGS Newsletter"; see https://igs.org/news .
7. Advertised five other important news items:
   a) a call for participation for the Weather and Climate Research Pilot Project (https://igs.org/news/wcrpp-call-for-participation/),
   b) the 2021 IGS Technical Report (https://igs.org/news/igs-technical-report-2021/),
   c) a call for nominations for the 2022 elections (https://igs.org/news/igs-call-for-nominations-2022/),
   d) the retirement of the Knowledge Base (kb.igs.org, see https://igs.org/news/kb-retiring/), and
   e) the important switch to IGS20/igs20.atx and repro3 standards following the release of ITRF2020 (https://igs.org/news/igs20/).
8. Developed and released the beta version of a completely re-built and improved Sitelog Manager (SLM) 2.0; see Section 4.4 .
9. Continued maintaining and improving the IGS website in general, including a redesign of the website structure for improved navigability.
10. Began development on a new and improved IGS Network System; see Section 5.1 in Chapter "IGS Governing Board".
11. Created a public IGS GitHub Repository to host items such as the SLM 2.0 open source code and GeodesyML (https://github.com/International-GNSS-Service)
12. Released the ITRF2020 multi-GNSS SINEX file IGS2020.snx, see IGSMAIL #8290
13. Created an introduction video on the IGS called "Discover the International GNSS Service" (https://www.youtube.com/watch?v=Ts6Hy-IY1PU)
14. Continued ensuring IGS compliance with the European Union General Data Protection Regulation (EU GDPR).
15. Organised two new stops for the Tour de l'IGS (a series of virtual mini-workshops on topics relevant to the IGS membership, stakeholders, and GNSS community in general); see https://igs.org/tour-de-ligs and Section 3.3 .
    a) GNSS Processing based on IGS products (17 Feb. 2022, hosted by AIUB)
    b) BDS Constellation Spotlight (27 Sep. 2022, hosted by Wuhan University)
16. Organised and led 6 Executive Committee (EC) meetings (see Table 2).
17. Supported the dissemination of newly developed IGS Products to include RINEX 4.0, new Guidelines for IGS Real Time Broadcasters and Stations, etc. .

18. Continued and enhanced the IGS' social media presence; see Section 5.1 .
19. Organised a week-long internal Central Bureau "retreat" in Boulder, Colorado, USA to complete and discuss the following initiatives:
    a) Revise CB Operations Plan and CB review panel preparations
    b) Create Transition Plan for Deputy Director and GB Executive Secretary roles and responsibilities
    c) Create new workshop organisation checklist and guidelines for future workshops
    d) Start on IGS Terms of Reference 2022 Revisions
    e) Refresh IGS Privacy Policy 2022
20. Represented the IGS and its community interests at various stakeholder levels, including:
    a) the United Nations International Committee on GNSS (ICG),
    b) the Subcommittee on Geodesy of the United Nations Committee of Experts on Global Geospatial Information Management (UN GGIM),
    c) the World Data System (WDS),
    d) the International Association of Geodesy (IAG) Inter-Commission Committee on Climate, and
    e) the IAG Global Geodetic Observing System (GGOS).

3 Executive Management

3.1 Meetings in 2022

The CB coordinated the necessary logistics and administrative organisation for three Governing Board (GB) meetings (two virtual and one hybrid), six Executive Committee (EC) virtual meetings, and an AM/WG (Associate Member & Working Groups) meeting. In addition, the CB organised and participated in two Standing Elections Committee virtual meetings in order to coordinate the 2022 GB elections, and Allison Craddock, Mayra Oyola-Merced, and Ashley Nilo participated in the Committee of Sustainability and Working Group Governance (CSWGG) meetings, chaired by IGS Network Representative, Ryan Ruddick (Geoscience Australia). Finally, the CB also helped organise the week-long and fully virtual IGS 2022 Boulder Workshop, in addition to two virtual mini-workshops (the Tour de l'IGS). A detailed list of these activities can be found in Table 2.

Table 2: 2022 meetings led or coordinated by the CB.

GB Meeting

08 March 2022 1400-1500 UTC (GB59X, virtual)
General topics: Extraordinary Meeting, Discussion of the IAG statement on Ukraine. Following the meeting, the IGS CB added a link to the IAG website on the IGS News page: https://igs.org/news/iag-statement-on-ukraine/.

02 to 03 May 2022, 2000-2200 UTC (GB60, virtual)
General topics: virtual IGS 2022 Boulder Workshop (GB vote on the workshop code of conduct); IGS 2024 Bern Workshop; AGU 2022 sessions; discussion on GB voting/non-voting roles; GENESIS presentation; letter of support for GENESIS (GB vote); presentation of the Japanese MIRAI system; Clock Products WG statement on leap seconds; GDPR; 2022 GB elections; CSWGG updates;
CB updates: Tour de l'IGS; CBIS; communications; SLM 2.0; IGS archives; AM management.

23 Jun. 2022 2000-2200 UTC (GB61, virtual)
General topics: DOIs for geodetic datasets, Analysis Center Charter, ITRF2020, virtual IGS 2022 Boulder Workshop (GB vote on the workshop code of conduct), 2022 GB elections, PPP-AR WG leadership transition (GB vote), Weather and Climate Resiliency Pilot Project proposal (GB vote on PP and PP Chair).
CB updates: Tour de l'IGS; AM management (GB vote on new application form); SLM 2.0; progress on the revision of the IGS Terms of Reference; staff changes (GB vote on Ashley Nilo as new GB Executive Secretary).

11 Dec. 2022 1900-2359 UTC (GB62, hybrid)
General topics: ITRF2020 (implementation, key issues/concerns identified at REFAG, UAW, and elsewhere); satellite metadata SINEX format (GB vote); CSWGG recommendations (report and discussion); 2022 GB elections (GB vote on 12 appointments/reappointments); SEC members turnover; Analysis Center Charter (charter update, and Japanese AC development update); CB review panel; capacity developments (IC and network); discussion on DOIs for geodetic datasets; International Federation of Surveyors (liaison handover, engagement plan); new ICG Task Force on Applications of GNSS for Disaster Risk Reduction; proposed 2023 meetings; other business (Ionosphere WG outreach, Technical Report reminder).
CB updates: Tour de l'IGS; CBIS; communications; strategic plan; IGS structure map; website structure map.

Table 2: 2022 meetings led or coordinated by the CB (cont.).

Executive Committee Meeting

21. Jan. 2022
General topics: Approval of GB59 minutes; drafting and approval of the geographic names policy.

28 Feb. 2022; 2100 UTC
General topics: Leap second whitepaper/declaration; IGS workshop (switching to virtual only); GB Vice Chair election and transition timeline; GB meeting timeline; approval of new Associate Members.
CB updates: staff changes (Mayra Oyola Merced transitioning out of CB).

13 Apr. 2022; 2000 UTC
General topics: Workshop status, GB Vice-Chair Elections, GB 60th Meeting, CB led initiatives for CB retreat, transition plans for the PPP-AR Working Group Chair Simon Banville, and IGS support for ESA on the new version of eGRAS.

02 Jun. 2022; 1900 UTC
General topics: Workshop planning, Workshop Code of Conduct, approval of new Associate Members.

20 Sep. 2022; 0500 UTC
General topics: 2022 GB elections; AM elections; CSWGG recommendations; approval of new Associate Members.
CB updates: IGS structure map; website structure map.

29 Nov. 2022; 2000 UTC
General topics: 2022 GB elections; CSWGG recommendations; Terms of Reference; IC updates (long product filenames).
CB updates: IGS structure map; website structure map; IGS archives; new ICG Task Force on Applications of GNSS for Disaster Risk Reduction.

Standing Elections Committee Meeting

03 Aug. 2022; 0400-0500 UTC 2022 GB elections.

01 Nov. 2022; 1000-1100 UTC 2022 GB elections.

Table 2: 2022 meetings led or coordinated by the CB (cont.).

Open Associate Member and Working Group Meeting

11 Dec. 2022 1500-1800 UTC (5th meeting, hybrid)
Working Groups, Pilot Projects, and Committees updates.

IGS 2022 Boulder Workshop

27 Jun. 2022 to 01 Jul. 2022, 1200-2100 UTC with long breaks (see https://igs.org/workshop/#agenda)

Day 1: Infrastructure Committee (IC), Data Centers (DC), RINEX WG, Clock Products WG, Antenna WG, Ionosphere WG.

Day 2: keynote 1 ("The role of UNAVCO and the GAGE Facility in Supporting the IGS and Global Geodesy: Current status, Upcoming Changes, and Ongoing Challenges" by Glen Mattioli), Multi-GNSS WG, Tide Gauge WG, Satellite Vehicle Orbit Dynamics WG, Troposphere WG.

Day 3: keynote 2 ("Tracking GNSS Signals through the Atmosphere: the Radio Occultation Technique and Its Applications to Severe Weather System Prediction" by Ying-Hwa "Bill" Kuo), Real-Time WG, International GNSS Monitoring and Assessment (IGMA), CB's Site Log Manager 2.0, GeodesyML.

Day 4: keynote 3 ("GPS Modernization" by Dave Hatch), Precise Point Positioning with Ambiguity Resolution WG, Reference Frame WG, Analysis Center Coordinator (ACC).

Day 5: Splinter Outbriefs, Closing Remarks.

Tour de l'IGS

The CB organised two Tour de l'IGS virtual mini-workshops in 2022; see Table 3.

3.2 Supporting and Coordinating Governing Board Elections

The Central Bureau routinely supports Governing Board elections, including serving in a support role on the GB Standing Elections Committee (SEC). This committee is responsible for issuing the call for nominations, applicant review, and strategic candidate search for GB positions that are nominated and elected by the Associate Members.

In 2022, CB staff took on additional responsibilities to fill temporary gaps in membership. In addition to his role on the CB (as CBIS Advisor), David Stowers also served on the IGS GB (as Data Center Representative), during which time he also served as a member of the SEC (alongside Ryan Ruddick[1] and Benjamin Männel[2]). Upon the completion of his service to the GB, Stowers' seat on the committee was temporarily filled by CB Deputy Director (Mayra Oyola-Merced first, and Léo Martire next) to the SEC.

Together with the SEC members, the CB contributed to coordinating this year's GB elections, participating significantly to: nominating and vetting the various candidates, contacting and coordinating with people whose terms were up for renewal, working with the EC for pre-approvals when relevant, and the proper handling of end-of-term cases.

The CB continued to lead administrative management of the GB elections, namely: posting the call for nominations and frequent reminders, ensuring that the nomination and voting processes were transparent and successfully carried out (at the 62$^{\text{nd}}$ GB meeting), and communicating the results of the appointments (after the 62$^{\text{nd}}$ GB meeting).

For more details about the 2022 GB elections and the current GB status, please see Section 2.2 in Chapter "IGS Governing Board".

3.3 Tour de l'IGS

In 2021, the IGS CB introduced a series of virtual mini-workshops, dubbed "Tour de l'IGS". Its focus is on topics of interest to the IGS membership, to stakeholders, and to the GNSS community in general. Initially, these events were organised in order to alleviate the impact of the COVID-19 pandemic (which delayed the IGS Boulder Workshop from 2020 to 2022); however, the GB and CB concluded that it would be a good practice to keep hosting these events several times a year. Each individual event in the Tour de l'IGS series is dubbed a "Stop" on a virtual world tour, with the overarching goal of covering a wide range of technical topics – such as space-borne and ground-based instrumentation, technology development, and scientific and societal applications. Table 3 summarises all of the past Tour de l'IGS stops. The agendas of all the Tour de l'IGS stops are available at https://igs.org/tour-de-ligs, while the presentations are available at https://igs.org/tour-de-ligs/presentations.

[1]R. Ruddick is in the GB as Network Representative (Geoscience Australia)
[2]B. Männel is in the GB as Analysis Center Representative (GFZ)

Table 3: Description of the past Tour de l'IGS stops..

1. **Topic:** "repro3" (IGS Third Reprocessing Campaign).
   Date: 02 Jun. 2021; 0400-0645 UTC.
   Scientific Organizing Committee: IGS CB.
   Talks:
   - Terrestrial frame solutions from the third IGS reprocessing: the IGS contribution to ITRF2020 (Paul Rebischung);
   - Highlights of IGS Contribution to ITRF2020 (Zuheir Altamimi);
   - Multi-GNSS orbit solutions from the third IGS reprocessing (Salim Masoumi);
   - Repro3 PPP-AR products (Simon Banville);
   - Multi-GNSS clock combinations on the repro3 using their combination software (Jianghui Geng);
   - Rigorous propagation of the Galileo-based terrestrial scale (Susanne Glaser).
2. **Topic:** "Infrastructure" (network stations and their configurations, data flow, and collection and distribution of GNSS data).
   Date: 01 Sep. 2021; 2000-2215 UTC.
   Scientific Organizing Committee: IGS CB.
   Talks:
   - IGS network, current and future work (Markus Bradke);
   - RINEX 4.0 (Ignacio "Nacho" Romero);
   - GeodesyML (Nick Brown);
   - Highlights from CDDIS (Pat Michael);
   - How to become an IGS Station? / Updates to the Site-Log Manager (David Maggert, Robert Khachikyan, Benjamin Juarez).
3. **Topic:** "GNSS Processing based on IGS Products"
   Date: 17 Feb. 2022; 1700-2000 UTC.
   Scientific Organizing Committee: Rolf Dach and Arturo Villiger (AIUB).
   Talks:
   - Observation Equation and Analysis Strategies (Rolf Dach);
   - Overview on Available IGS Products (Tom Herring);
   - Processing a Regional/Continental Dataset (Sonia Costa);
   - Antenna Calibrations (Arturo Villiger);
   - Clock Models and Interpolation for PPP (Michael Coleman, Urs Hugentobler);
   - Bias Handling and Ambiguity Resolution (Stefan Schaer);
   - Troposphere Modelling (Johannes Böhm).
4. **Topic:** "BDS Constellation Spotlight"
   Date: 27 Sep. 2022; 1200-1430 UTC.
   Scientific Organizing Committee: Jianghui Geng and Qile Zhao (Wuhan University).
   Talks:
   - BDS PPP-B2b Service (LU Jun);
   - BDS Network Analysis in GAMIT (Tom Herring);
   - Official BDS Satellite Antenna Phase Centers (GUO Jing);
   - BDS Orbits and Clocks (Peter Steigenberger);
   - BDS Coordinate Reference Frame (ZHOU Shanshi, on behalf of HU Xiaogong);
   - BDS Short Message Communication (ZHU Xiangwei).

4 Central Bureau Information Systems (CBIS)

4.1 Website Analytics

Since the IGS Website migration back in 2020, the CB has been able to better monitor website traffic and engagement. In 2022, the website transitioned from a session-based analytics to an event-based analytics, allowing more insight as to how users engage with the website.

The total number of users who have visited igs.org and files.igs.org increased by 35% from last year, going up from 87,199 to 117,880. There has also been a 52% increase in the total number of sessions, from 167,903 to 254,698. Additional notable statistics include 735,602 page views, 40,663 file downloads, and a 71% engagement rate (the percentage of sessions longer than 10 seconds or has at least 2 pageviews).

Other statistics have remained the same. Most users were desktop users and visited the website between 08:00-16:00 UTC Monday through Friday. About half of the users arrived at the website via organic search engines. Additionally, social media referral doubled when compared with previous years. Table 4 summarises the most visited pages and where the visits were coming from.

The IGS website has been key for the CB to support all IGS events, and especially the virtual ones. Besides featuring the advertisement of events and registration information, the website also serves as an online catalogue of recorded presentations and other resources to the community after an event has been completed. Notably, it features the latest IGS workshops (https://igs.org/workshops), the Tour de l'IGS series (https://igs.org/tour-de-ligs/, https://igs.org/tour-de-ligs-presentations), as well as the Open Associate Members and Working Group Meetings (https://igs.org/am-meetings/).

Table 4: Most visited pages and geographical location of the most visits , in terms of traffic to the IGS website, from 1 Jan 2022 to 31 Dec 2022.

Most Frequently Visited Pages: 1. Home Page 2. Network 3. Products 4. Data 5. Files.igs.org Home page 6. Formats and Standards 7. Access to Products 8. MGEX Data + Products 9. RINEX 10. Real-Time Service (RTS)

Most Page Visits, by Country/Region: 1. China 2. United States 3. India 4. Germany 5. Russia 6. Brazil 7. Turkey 8. France 9. Japan 10. Spain

4.2 Consolidating and Improving Access to Formats and Standards

Important formats and standards (https://igs.org/formats-and-standards), reference documents (https://igs.org/documents/), and a variety of news relevant to the community (https://igs.org/news/, https://igs.org/tech-report/) were consolidated and relocated to the main IGS website. This effort consolidated all current information in a more visible and easily accessible part of the Central Bureau Information Systems.

4.3 Substantial Overhaul and Update to Critical Network and Membership Information Systems

The IGS CB began the redesign and development on a number of CB-managed web applications, such as the Associate Member (AM) Database, Site Log Manager (SLM), and the IGS Network Mapping system. The IGS Associate Member Database is currently a list of all IGS Associate Members (https://igs.org/governance-management/#associate-members). In order to better keep track of active AMs, the IGS CB began developing a new AM database and registration system. The new registration form gathers more information about those applying to become members and ensures applicants meet the minimum requirements to become an AM. The new database better showcases members through a robust list and individual profile pages, enables members to update their own profiles, and reminds the users to renew their membership through a login system. The new AM database and registration forms will officially be released in 2023.

With the new and improved https://igs.org, and in an effort to condense our IGS websites and keep IGS content to either https://igs.org or https://files.igs.org, we have decided to retire the IGS Knowledgebase (https://kb.igs.org). Over the last year, the IGS CB analysed the traffic within https://kb.igs.org and ensured often visited pages were integrated into igs.org or archived on https://files.igs.org. Key information and documents previously on https://kb.igs.org can now be found through the search function or navigating the mega menu on https://igs.org The CB has also contacted the owners of any superseded files and other outdated content and archived or updated them accordingly. Remaining content within https://kb.igs.org (those that have little to no traffic and has very out of date information) has been backed up and archived internally for historical purposes within the Central Bureau and is available upon request.

To find archived/historical information, please visit https://files.igs.org. To search through https://files.igs.org, you can use the search bar on igs.org or use google search (search "site://https://files.igs.org/pub<KEYWORD>"). If you are unable to find what you need on igs.org or https://files.igs.org, please contact the IGS Central Bureau (cb@igs.org).

4.4 Site Log Manager and Network Map

The idea of open access data and products that facilitate collaborations, standardisation, and inclusivity is present in both the International GNSS Service (IGS) Mission and 2021+ strategic plan goals. Through the IGS Site Log Manager and Network map, open access data can help enable scientists to: visualise the geospatial coverage of the IGS Network, investigate the type of GNSS data from stations, view real time capabilities, and know the various GNSS data sources (CDDIS, etc.).

The IGS Site Log Manager (SLM) is a web-based online application designed for the purpose of managing the metadata of IGS GNSS ground-based sites. The IGS Network system currently serves as the public interface for any user from all over the world to view station metadata from the IGS SLM through a comprehensive station list and interactive station map.

In 2021, the CB identified issues in the current Site Log Manager, which included outdated technology that was soon to be deprecated and no support for possible new features needed in the IGS community such as GeodesyML, interoperability, and command line API. Similar issues with the network system were also identified at that time. Since the two systems go hand in hand, the CB sought to refine both systems, starting with the SLM, to be known as SLM 2.0. Being an international organisation with a wide range of geodetic scientists, early careers and decision makers, as well as a mission to provide open access data to the general public, the CB decided that the code for the new iteration of the SLM should be open access as well.

The primary goal of the new SLM and Network software is to maximise the reliability, accuracy, and searchability of site log metadata information. This will be achieved through easy moderation and review, automation, structured data, and broad adoption. To move away from the deprecating PHP version of the current SLM and Network system, the CB carefully researched the most robust and up to date technology – in the end deciding on building the new system using Python and the Django web framework. Along with resolving the identified technological issues, the CB gathered community feedback through a series of surveys and interviews to ensure this new system solved the needs of the users, and brought light to any user experience issues in the old systems. After putting together the SLM 2.0 functional specifications and obtaining results from user research, the CB development team began coding the new SLM 2.0 and Network system.

Through research findings and tests, the IGS was able to identify common steps users take when accessing the SLM as well as other minor pain points that disrupt their workflow. With these results, the IGS developed a new and improved user interface for the SLM, using the latest technology with improved editing, improved validation, a new alerts feature, and new list/map view.

The IGS SLM 2.0 beta version is open source and currently available on the new public IGS GitHub Repository (`https://github.com/International-GNSS-Service/SLM`).

By allowing users to access the SLM 2.0 code, other organisations can utilise this new and robust technology for their own needs and help the community move towards more consistent and seamless metadata editing.

For the IGS Network 2.0, the CB was able to identify key priorities to work on, the main theme seen is the need for customization for map, list, and downloads. Additional things to consider were visuals/aesthetics and certain data being hard to find. Keeping the users in mind, the IGS Network 2.0 now has new features using the latest technology including a new and improved layout, interactive map, and a new customizable station list/table.

The IGS SLM 2.0 beta is now available at `https://slmdemo.igs.org` and will continue testing from now until March 2023, after which it will replace the old SLM at `https://slm.igs.org`. The IGS Network 2.0 is still under development, and is estimated to be released mid-2023.

5 Coordination Efforts

5.1 Communication

Since 2021, in order to introduce the more diversified IGS portfolio, the CB has implemented a new communication plan bridging the gap between Working Groups, Associate Members, and the community in general.

First of all, the Tour de l'IGS makes up the more academic side of communications, and allowed more frequent interactions with and outreach to the community; see Section 3.3. Furthermore, the CB's Product Strategist (Ashley Nilo) significantly strengthened IGS social media presence (see IGS Twitter, LinkedIn, and YouTube feeds), increased diverse community engagement and collaborations through the regular circulation of the IGS Newsletter, and identified many other opportunities for IGS engagement. Finally, the CB members continued coordinating with other established United Nations (UN) components, such as the UN International Committee on GNSS (ICG), and identifying potential contributions of GNSS to the UN Sendai Framework for Disaster Risk Reduction (UNDRR) and the UN Sustainable Development Goals.

IGS followers on social media continued to grow in 2022, thanks to the growing and maintaining of mutually beneficial links to IGS Contributing Organisation communications representatives (such as UNAVCO, IAG, GGOS, or ITRF) and increased frequency of posting of quality content (74 posts in total, i.e. 6 per month on average). The increased cross-linking within the IGS website and across social media platforms, as well as promoting video resources available on the IGS website, were found to maintain the community resources as clear and useful as possible. Outside of promoting IGS news and events, the IGS CB engaged with followers by participating in International Holidays, such as `#IGSProfessorHighlight` for the `#InternationalDayofEducation`,

`#WomensHistoryMonth`, `#NationalInternDay` Highlight, and `#InternationalFriendshipDay`. All these efforts are coordinated by the CB's Product Strategist, Ashley Nilo.

To further increase community engagement and outreach, the Central Bureau created a short video introducing the IGS to the general public and those wishing to learn how to participate. The video focuses on the different components of the IGS and gives instructions on how someone can participate in the IGS and learn more. The video was released in May 2022 via YouTube and shared on the IGS mailing list and socials. To date, the video has had 659 views since its release.

Last year, the IGS launched "Constellations: The Newsletter of the International GNSS Service", a quarterly newsletter showcasing IGS and other relevant news and articles to our community members (`https://igs.org/newsletter/`). In 2022, issues three through six were released.

- The March 2022 (third) issue headlined the Hunga Tonga Hunga Ha'apai eruption, and how GNSS technology was able to capture its powerful climax on 15 January 2022. It also included the most recent updates from the IGS Governing Board and joined the global celebration for the International Women's History Month by highlighting some prominent IGS figures.
- The June 2022 (fourth) issue highlighted a CB-led contributing paper in the 2022 United Nations Global Assessment Report (GAR) on Disaster Risk Reduction discussing potential novel applications of GNSS for Air Quality. Additionally, it showcased information about the new release of the International Terrestrial Reference Frame, ITRF2020, from IAG President Zuheir Altamimi, announced the date and location of the next IGS Workshop and other highlights including announcing the new Governing Board Executive Secretary.
- The September 2022 (fifth) issue presented IGS20/igs20.atx: a new framework for the IGS products from Paul Rebischung (Reference Frame Coordinator) and Arturo Villiger (IGS Antenna WG Chair). It also highlighted Global Differential Global Positioning System-High Accuracy Service (GDGPS-HAS) from Al Feinberg (NASA Space Communications and Navigation (SCaN)), the new IGS GNSS 4 Weather and Climate Resiliency Pilot Project and other highlights, including announcing the new Governing Board Vice Chair, Rolf Dach.
- The December 2022 (sixth) and last issue of the year discussed Benefits of Galileo satellite metadata for ITRF2020, Towards Near-Real Time Detection of Tsunamis, the new ICG Task Force and other highlights, including the AGU Geodesy Section Award Winners.

A limited number of the last three issues were printed and distributed in person at the GB62 Meeting and AGU 2022 Fall Meeting.

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/.

In terms of statistics, the IGS Social Media accounts statuses are as follows:

Twitter (https://twitter.com/igsorg):

- 2000 followers (+269 since 2021, +22/month)
- 66195 tweet impressions
- 26704 profile visits
- 112 mentions

LinkedIn (https://www.linkedin.com/company/igsorg/):

- 1412 followers (+492 since 2021, +41/month)
- 1208 page views
- 473 unique visitors
- Top 3 Visitor Demographics:
  - 12.9% Research,
  - 11.1% Engineering, and
  - 9.4% Information Technology.

YouTube (https://www.youtube.com/igsorg):

- 349 subscribers (+128 since 2021, +13/month)
- 14193 views (+6072 since 2021, +506/month)

5.2 Network Coordination

Through the CB Network Coordinator and with the help of the Infrastructure Committee, the IGS CB coordinates the monitoring of station logs and RINEX metadata, and evaluates all new IGS station proposals on a regular basis. The CB Network Coordinator also responded to all inquiries received by the CB about data, products, or general IGS information. The CB Network Coordinator collaborates with the Antenna Working Group Chair and GNSS manufacturers to have their equipment added to the official IGS files (`rcvr_ant.tab` and `antenna.gra`).

Feedback after the IGS Virtual Workshop in 2022 had mentioned that some IGS Network stations were still lacking photos. This led the Network Coordinator to work with the relevant IGS station operators to obtain as many updated/new station photos as possible. As a result, forty-seven IGS stations had their photos updated.

Finally, the IGS CB continues to encourage station operators to define generic agency contact information (instead of person specific) in order to comply with EU GDPR guidance. For additional statistics and information about the IGS Network, please refer to the Infrastructure and Governing Board chapters of this report.

6 Future Steps for 2023

Future work of the CB in 2023 will be in alignment with the 2021+ Strategic Plan, and guided by direction and regular feedback from the Governing Board. Expected accomplishments will include the deployment of the new SLM and network map, as well as publishing open source code for the SLM to enable better engagement with the community, clearer interactions with the IGS website, and overall a better service to scientists and geodesists. The CB will continue to organise and/or co-lead the technical mini-workshop series through the Tour de l'IGS; future stops will include spotlights on various GNSS/RNSS providers, and prioritise engagement and outreach to underrepresented countries/regions, as well as increase advocacy efforts through highlighting and incubating novel scientific applications of IGS data and products (such as natural hazards early warning systems).

The CB will also encourage the addition of new stations to the IGS network, focusing in particular on regions of sparse coverage or that are underrepresented in the IGS. The CB will also continue to advocate for the addition (or conversion) of receivers capable of multi-GNSS tracking and/or real-time casting. Finally, the CB will continue to fulfil all of its regular administrative tasks and obligations, including event coordination, governance support, network coordination, and communications.

7 Acknowledgements

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Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2022

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1 Introduction

The IGS Analysis Center Coordinator (ACC) is responsible for monitoring the quality of products submitted by individual analysis centers, and combining them to produce the official IGS products. The IGS 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 performance. The different analysis centers contributing to the IGS operational products, are listed in Table 1. Table 1 also shows the abbreviations used across this report for the IGS products.

A major development in 2022 was the release of the combined multi-GNSS orbit, clock and observable-specific bias products, along with the computed satellite attitudes for the the third IGS reprocessing campaign (Repro3).

Another significant development in 2022 was for the IGS to adopt a new reference frame, called IGS20, as the basis of its products. IGS20 is closely related to ITRF2020, which was released in April 2022. An updated set of satellite and ground antenna calibrations, igs20.atx, also became effective at the same time and is recommended to be used together with IGS20. The switch of IGb14/igs14.atx to IGS20/igs20.atx commenced from GPS week 2238 (27 November 2022). At the same time as this switch, the IGS also adopted for its operational products the same conventions and models as in its third reprocessing campaign (Repro3), including the adoption of new long filenames for the IGS products (see IGS long filenames).

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

Analysis center/IGS product	Description code
Center for Orbit Determination in Europe (CODE)	COD
Natural Resources Canada (NRCan)	EMR
European Space Agency (ESA)	ESA
GeoForschungsZentrum Potsdam (GFZ)	GFZ
Centre National d'Etudes Spatiales (CNES/CLS)	GRG
Jet Propulsion Laboratory (JPL)	JPL
Massachusetts Institute of Technology (MIT)	MIT
NOAA/National Geodetic Survey (NGS)	NGS
Scripps Institution of Oceanography (SIO)	SIO
The United States Naval Observatory (USNO)	USN
Wuhan University	WHU
IGS ultra-rapid adjusted part	IGA
IGS ultra-rapid predicted part	IGU
IGS real-time	IGC
IGS rapid	IGR
IGS final	IGS

2 Product Quality and Reliability

In 2022, the delivery of the ultra-rapid, rapid and final products were well within the expected latencies for most of the year (e.g. about 97.8% of the deliveries within the expected latency of 17-41 hours for the rapid products and about 98.5% within the expected latency of real time to 9 hours for the ultra-rapid products). There were 8 occasions where the IGS rapid products were delayed between 5 to 16 hours, and 6 occasions where the ultra-rapid products were delayed between 1 to 8 hours. The problems causing the delays included four occasions of problems in retrieving the analysis centre products or other required data from the global data centres, two occasions of a problem in converting satellite broadcast navigation files to the sp3 format required for rapid clock combinations, an occasion of reaching the limitation in the number of station clock entries which had to be relaxed in the combination software, and two occasions of a server issue in the combination server. Three of the delays (and/or re-submissions) of the rapid/ultra-rapid products occurred during the time of the switch to IGS20 and long filenames (GPS week 2238), mainly due to issues in providing the long filename products to the global data centres.

The clock products experienced difficulties in the timescale exchange, i.e. re-aligning of the clocks to the IGS time scale (see IGSMAIL #8224 for the IGS rapid clocks during GPS weeks 2216 to 2220, and GPS week 2223, as well as for the IGS final clocks during GPS weeks 2223 to 2227. These clock products were later corrected and resubmitted.

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. In 2022, for most weeks IGS received submissions from seven different ACs which were combined to produce IGS ultra-rapid products (see Table 2 for a list of ACs that are currently included in the combined solutions). Starting from the time of the switch of the IGS products to the IGS20 reference frame (i.e. GPS week 2238), GRG also started to submit ultra-rapid and rapid products in addition to final products. The GRG ultra-rapid and rapid products are not weighted in the combination at the moment, and are only included for comparison. Following assessment of their ultra-rapid and rapid products for a period of time, they may be weighted in future.

The combined IGS ultra-rapid orbit can be split into two components, a fitted portion based upon observations, and a predicted component reliant upon forward modelling of the satellite dynamics. The fitted portion of the ultra-rapid orbits continue to agree to the rapid orbits with a median value 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 value of 25 mm. 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.

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. GRG started submitting ultra-rapid solutions from 28 November 2022 (GPS week 2238), at the same time as the switch of the IGS products to the IGS20. The GRG ultra-rapid products are therefore included only for comparison at the moment, and may be weighted in future.

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

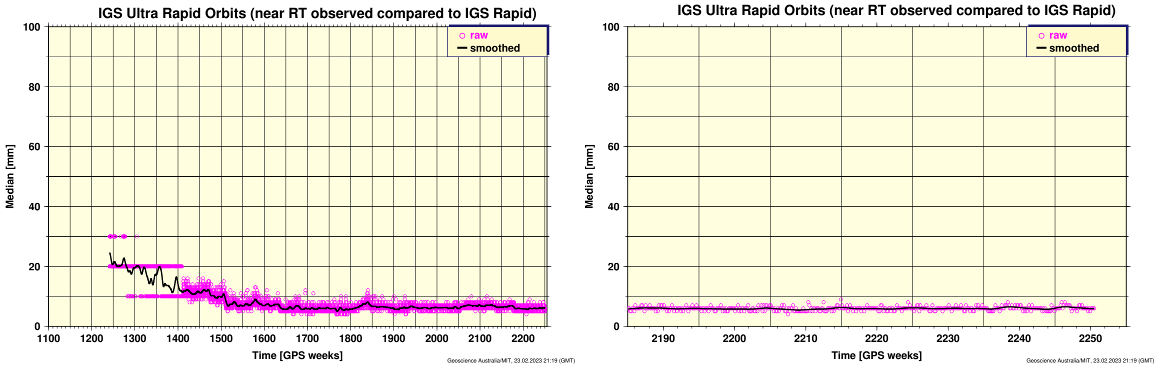

Figure 1: The median difference of the fitted component of the IGS ultra-rapid (IGU) combined orbits with respect to the IGS rapid (IGR) orbits. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

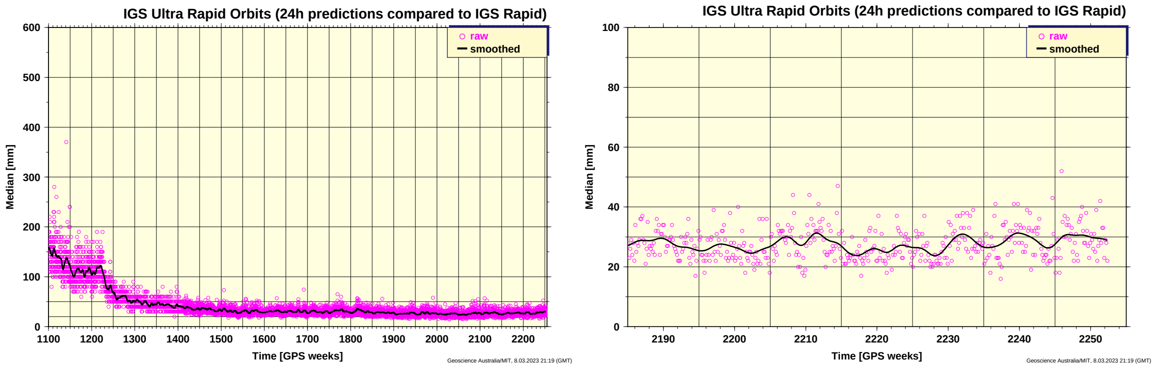

Figure 2: Median of IGU combined predicted orbits compared to IGR. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. Note the change in scale of the Y axis.

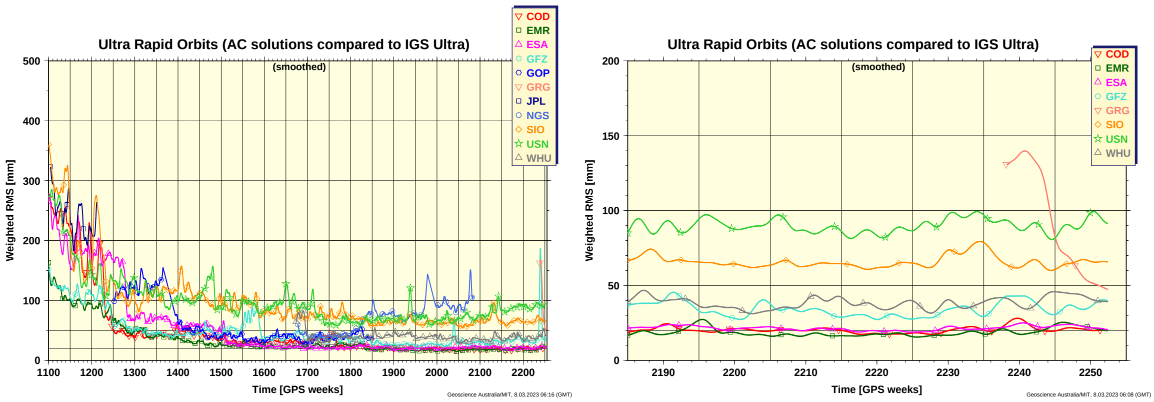

Figure 3: Weighted RMS of AC Ultra-rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. Note the change in scale of the Y axis.

2.2 Rapid

There were nine individual analysis centers that contributed to the IGS rapid products for most of 2022 (see Table 3). Similar to ultra-rapid, starting from the time of switch of the IGS products to the IGS20 reference frame (i.e. GPS week 2238), GRG started to submit rapid products. The GRG rapid products are not weighted in the combination at the moment, but are only included for comparison. Following assessment of their products for a period of time, they may be weighted in future.

The rapid orbit products from the different analysis centers weighted in the combination remained at a consistent level of below 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 picoseconds (ps) for the weighted centers (Figure 5).

In early 2022, the clock RMS values were higher than usual 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,

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. GRG started submitting rapid solutions from 28 November 2022 (GPS week 2238), at the same time as the switch of the IGS products to the IGS20. The GRG rapid products are therefore included only for comparison at the moment, and may be weighted in future.

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

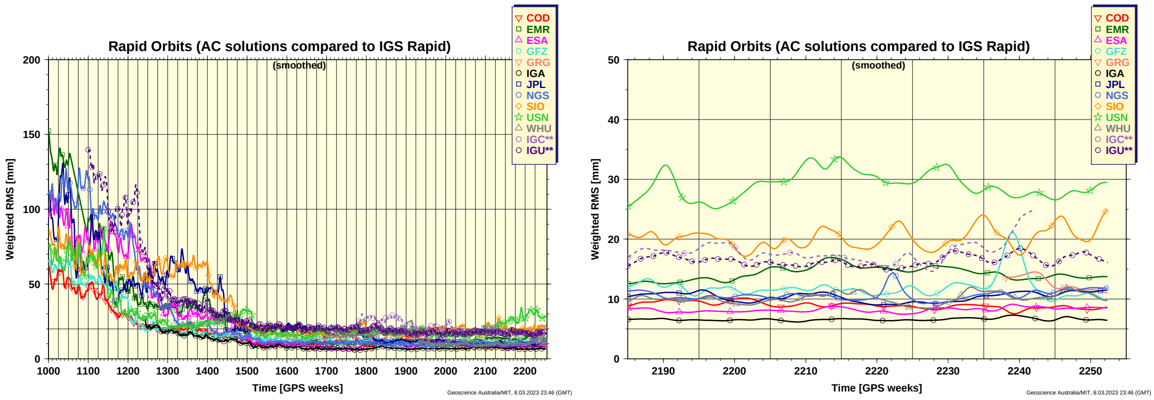

Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time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

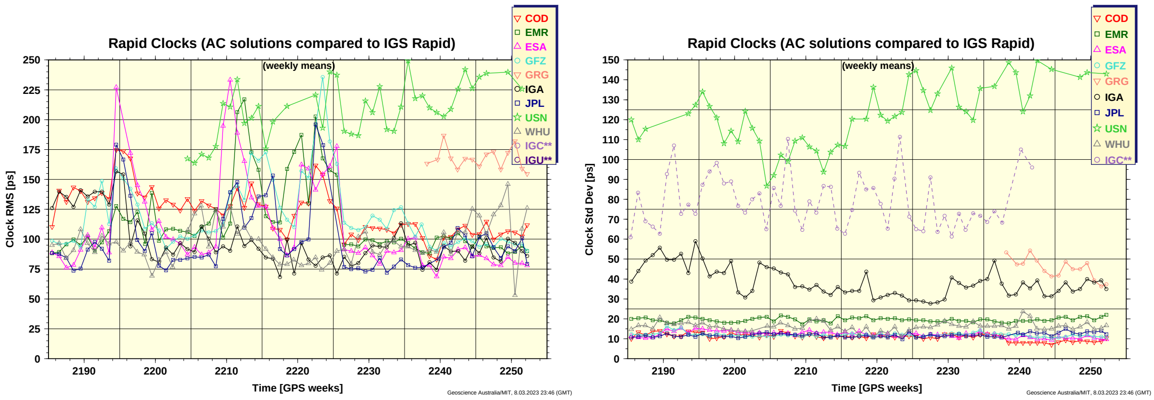

Figure 5: Weighted RMS (left) and standard deviation (right) of ACs Rapid clock submissions (smoothed). IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time stream. IGU** consists of four separate comparisons to IGR done each day over the first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

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 confusion with PRN allocations. There were similar degradations in the the analysis center clock RMS in mid-2022, GPS weeks 2210 to 2214 and 2221 to 2226.

2.3 Final

There are nine individual ACs contributing to the IGS final products (see Table 4). Starting from GPS week 2238, most of the analysis centres switched to submitting products in the IGS20 reference frame. The exceptions are EMR and JPL solutions that are still undergoing internal AC evaluations in IGS20. EMR have paused submitting final products until the assessments of the IGS20 products are completed. JPL are still submitting final products in the IGb14 reference frame; therefore, their final solutions have been excluded from the combination since GPS week 2238, but included for comparison, until they switch to IGS20. The higher RMS of the JPL orbits and clocks from GPS week 2238 is clearly observed in Figures 6 and 7.

Most AC final orbit solutions are comparable at around the 10 mm RMS level (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. A similar issue as for rapid clocks occurred for the final clocks during GPS weeks 2194 to 2198, 2210 to 2214, and 2221 to 2226, where the clock RMS values were higher than usual (Figure 7).

Table 4: ACs contributing to the IGS Final products; W signifies a weighted contribution, C is comparison only. JPL solutions have been excluded from the final combinations, but only included for comparison, since GPS week 2238, until they switch to IGS20.

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

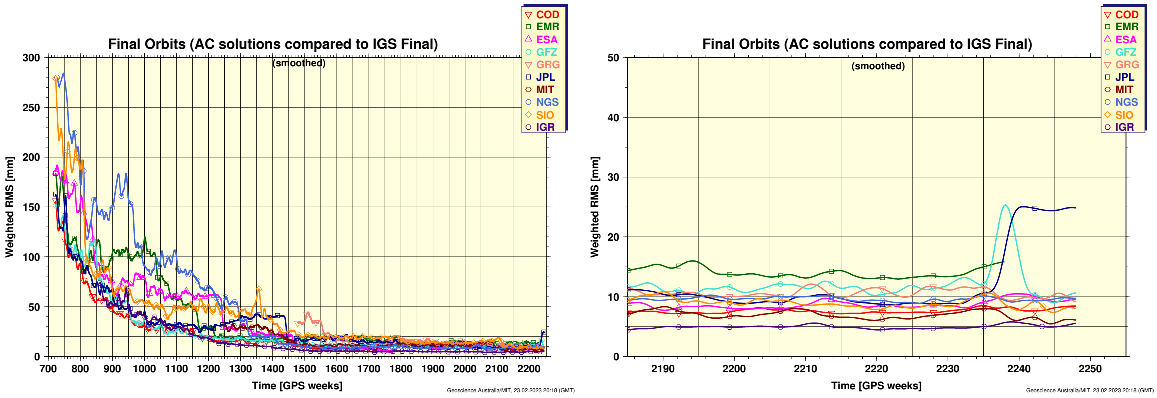

Figure 6: Weighted RMS of IGS Final orbits (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. Note the change in scale of the Y axis.

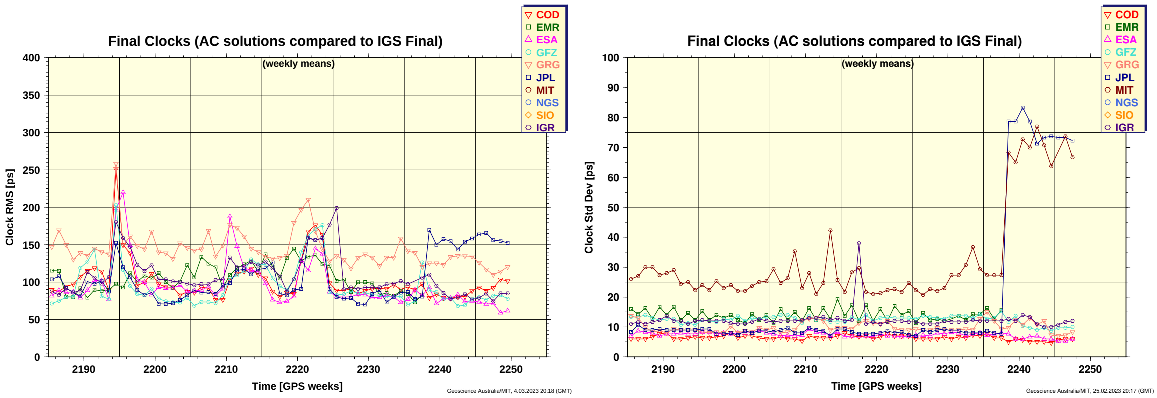

Figure 7: Weighted RMS (left) and standard deviation (right) of IGS Final clocks (smoothed). Note the change in scale of the Y axis.

3 Release of the combined products for the third IGS reprocessing campaign

The third IGS reprocessing campaign (Repro3) was 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 were then combined and submitted as the IGS contribution to the next version of the International Terrestrial Reference Frame, ITRF2020. In 2022, the combination of IGS Repro3 multi-GNSS orbits, clocks and observable-specific biases, consistent of GPS, GALILEO and GLONASS solutions, was completed, and the products were published in the global data centres (see [IGSMAIL-8248]) for the period of 1994 to the end of 2020. The orbit combinations were performed by the IGS Analysis Centre

Coordinator at Geoscience Australia, the clock and bias combinations were performed at Wuhan University led by the IGS PPP-AR Working Group. Also, the reference attitudes for the solutions were computed in Graz University of Technology. More details on the combination strategy and available products can be found in [IGSMAIL-8248] and the IGS ACC technical report of 2021 in Villiger and Dach (2022).

The Repro3-like multi-GNSS (GPS, GALILEO and GLONASS) combinations are planned to become operational to be able to provide demonstration of the ultra-rapid, rapid and final products. The operational demonstration multi-GNSS products will use the same new combination software developed and used for the Repro3. The new version of the combination software is more flexible than the current version as it includes orbits from multi-GNSS satellites 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. In addition to this, the IGS ACC is contributing to the IGS multi-GNSS task force in a collaboration with the multi-GNSS working group to develop a new fully multi-GNSS combination software by consolidating the efforts made by different IGS-affiliated organisations.

4 Transition to the new reference frame, Repro3 standards and long filenames

Starting with the products of GPS week 2238 (27 November 2022), the IGS adopted a new reference frame, called IGS20, along with the corresponding igs20.atx antenna file. IGS20 is closely aligned with ITRF2020 which was released in April 2022. At the same time as this switch, the IGS also adopted for its operational products the same conventions and models as in its third reprocessing campaign (Repro3), including the adoption of new long product filenames for the IGS products (see IGS long filenames). Detailed descriptions of the changes occurring as a result of this switch are described in IGSMAIL #8238 and IGSMAIL #8256. A Guideline for the transition of the IGS products to long filenames is also provided with examples to help users in making necessary changes in their software to continue to be able to retrieve the IGS products.

The switch to the IGS20/igs20.atx and Repro3 standards occurred after a trial period during GPS weeks 2222 to 2237 (7 August 2022 - 26 November 2022). During this trial period, while the official IGS products were still being provided in the IGb14/igs14.atx reference frame and short filenames, additional products were provided in IGS20/igs20.atx and Repro3 standards (including long filenames). This was to ensure the IGS20/igs20.atx/Repro3-standard products were of expected accuracies, and for the users to perform necessary tests before the products were only provided in the new reference frame and in long filenames.

5 Future Work

In 2023, the Repro3 combinations are planned to be performed and published for the period between 2021 until 27 November 2022 (the time of the switch to the IGS20) to have a full set of reprocessed products for the whole period since 1994. A major focus of the IGS ACC will be on making the multi-GNSS (GPS, GALILEO and GLONASS) Repro3-like products operational for ultra-rapid, rapid and final lines of product as demonstration products. After a period of evaluations, these demonstration multi-GNSS products will initially replace the current experimental GLONASS products, while the GPS-only solutions will still remain the IGS official products until validations confirm the quality and robustness of the multi-GNSS solutions to be comparable to the GPS-only solutions. To fully achieve the accuracy that Galileo is capable of, more multi-GNSS ground antenna will need full L1, L2, and L5 frequency calibrations. The ACC will coordinate with the antenna working group to determine a priority list of antennas that need L5 calibrations. If the L1/L2 calibrations of these antennas are not changed, it will be possible to add the L5 calibrations to the IGS20 ANTEX file. The IGS ACC is also actively contributing to the multi-GNSS task force in collaboration with the multi-GNSS working group and a number of IGS analysis centres to develop an improved version of a fully multi-GNSS combination software.

References

Schaer, S.. SINEX BIAS—solution (software/technique) INdependent EXchange Format for GNSS BIASes version 1.00. In *IGS workshop on GNSS biases, Bern, Switzerland*, 2016.

Villiger, A. and R. Dach, editors. *International GNSS Service Techincal Report 2021 (IGS Annual Report)*. IGS Central Bureau and University of Bern; Bern Open Publishing, 2022.

Center for Orbit Determination in Europe (CODE) Analysis Center Technical Report 2022

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1 The CODE consortium

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

- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland
- Federal Office of Topography swisstopo, Wabern, Switzerland
- Federal Agency of Cartography and Geodesy (BKG), Frankfurt a. M., Germany
- Institute for Astronomical and Physical Geodesy, Technical University of Munich (IAPG, TUM), Munich, Germany

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

2 CODE products available to the public

A wide range of GNSS solutions based on a rigorously combined GPS/GLONASS/Galileo data processing scheme is computed at CODE supporting the following IGS legacy product chains:

- **Ultra-rapid series** with several updates per day (GPS+GLONASS+Galileo).
  The ultra-rapid products contain also a prediction for near-real time applications.
  List of result files are provided in Table 1 .
- **Rapid series** is computed once per day (GPS+GLONASS+Galileo).
  Note that there is an update of the rapid solution, see (Dach et al., 2015) .
  List of result files are provided in Table 2 .
- **Final series** is submitted once per week (GPS+GLONASS+Galileo).
  Until GPS week 2037 (November 27th, 2022) the final solution did only consider GPS+GLONASS measurements.
  List of result files are provided in Table 3 .

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/

With GPS week 2238, the IGS started to use a new product filenaming scheme. The tables provide both, the new and old product filenames.

Furthermore. CODE contributes to the IGS MGEX project with 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/

Up to the inclusion of Galileo into CODE's final solution in GPS week 2238 (November 28th, 2022), the triple-system solution (GPS, GLONASS, Galileo) from CODE's rapid processing is also kept accessible at:
ftp://ftp.aiub.unibe.ch/CODE/yyyy_M or
http://www.aiub.unibe.ch/download/CODE/yyyy_M/

An overview of the related product files is given in Table 4.

Table 5 compiles the product files submitted by CODE to the IGS data centers.

Within the table the following abbreviations are used:

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

Table 1: CODE's ultra-rapid products available through anonymous ftp.

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

`COD0OPSULT.SP3` (old: `COD.EPH_U`)
CODE ultra-rapid GNSS orbits (GPS+GLONASS+Galileo) with 5 minutes sampling

`COD0OPSULT.ERP` (old: `COD.ERP_U`)
CODE ultra-rapid ERPs belonging to the ultra-rapid GNSS orbit product

`COD0OPSULT.TRO` (old: `COD.TRO_U`)
CODE ultra-rapid troposphere product, troposphere SINEX format

`COD0OPSULT.SNX` (old: `COD.SNX_U`)
SINEX file from the CODE ultra-rapid solution containing station coordinates, ERPs, and satellite antenna Z-offsets

`COD0OPSULT_TRO.SNX` (old: `COD_TRO.SNX_U.Z`)
CODE ultra-rapid solution, as above but with troposphere parameters for selected sites, SINEX format

`COD0OPSULT.SUM` (old: `COD.SUM_U`)
Summary of stations used for the latest ultra-rapid orbit

`COD0OPSULT.ION` (old: `COD.ION_U`)
Last update of CODE rapid ionosphere product (1 day) complemented with ionosphere predictions (2 days)

`COD0OPSPRD_05D.SP3` (old: `COD.EPH_5D`)
Last update of CODE 5-day orbit predictions, from rapid analysis, including all active GPS, GLONASS, and Galileo satellites

`COD0OPSULT_yyyyddd0000_01D_05M_ORB.SP3` (old:`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)

`COD0OPSULT_yyyyddd0000_01D_01D_ERP.ERP` (old: `CODwwwwd.ERP_U`)
CODE ultra-rapid ERPs belonging to the above ultra-rapid GNSS orbits

The CODE ultra-rapid products are provided with static filenames containing the latest results.

Result files for CODE 5-day GNSS *orbit predictions*
available at ftp://ftp.aiub.unibe.ch/CODE

`COD0OPSPRD_yyyyddd0000_05D_05M_ORB.SP3` (old: `CODwwwwd.EPH_5D`)
CODE 5-day GNSS orbit predictions

`COD0OPSPRD_yyyyddd0000_21D_06H_ERP.ERP` (old: `CODwwwwd.ERP_5D`)
CODE predicted ERPs belonging to the predicted orbits

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 2: CODE's rapid products available through anonymous ftp.

CODE *early rapid* products: GPS+GLONASS+Galileo; third day of a 72-hour solution
available at ftp://ftp.aiub.unibe.ch/CODE

`COD0OPSRAP_yyyyddd0000_01D_05M_ORB.SP3` (old: `CODwwwwd.EPH_R`)
CODE early rapid GNSS orbits with 5 minutes sampling

`COD0OPSRAP_yyyyddd0000_01D_01D_ERP.ERP` (old: `CODwwwwd.ERP_R`)
CODE early rapid ERPs belonging to the early rapid orbits

`COD0OPSRAP_yyyyddd0000_01D_30S_CLK.CLK` (old: `CODwwwwd.CLK_R`)
`COD0OPSRAP_yyyyddd0000_01D_30S_CLK.CLK_V2`
CODE GNSS clock product related to the early rapid orbit, clock RINEX format (versions 3.04 and 2.00)

`COD0OPSRAP_yyyyddd0000_01D_01H_TRO.TRO` (old: `CODwwwwd.TRO_R`)
CODE rapid troposphere product, troposphere SINEX format

`COD0OPSRAP_yyyyddd0000_01D_01D_SOL.SNX` (old: `CODwwwwd.SNX_R.Z`)
SINEX file from the CODE rapid solution containing station coordinates, ERPs, and satellite antenna Z-offsets

`COD0OPSRAP_yyyyddd0000_01D_02H_TRO.SNX` (old: `CODwwwwd_TRO.SNX_R.Z`)
CODE rapid solution, as above but with troposphere parameters for selected sites, SINEX format

`COD0OPSRAP_yyyyddd0000_01D_01D_OSB.BIA`
code/phase biases related to the early rapid orbit and clock corrections, Bias-SINEX format
Note: Integer-cycle clocks in conjunction with accompanying code/phase biases enable PPP-AR (ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT)

`COD0OPSRAP_yyyyddd0000_01D_30S_ATT.OBX`
Satellite attitude, ORBEX format

CODE *final rapid* products: GPS+GLONASS+Galileo; middle day of a long-arc solution
where the rapid observations were completed by a subsequent ultra-rapid dataset
available at ftp://ftp.aiub.unibe.ch/CODE

`CODMOPSRAP_yyyyddd0000_01D_05M_ORB.SP3` (old: `CODwwwwd.EPH_M`)
CODE final rapid GNSS orbits with 5 minutes sampling

`CODMOPSRAP_yyyyddd0000_01D_01D_ERP.ERP` (old: `CODwwwwd.ERP_M`)
CODE final rapid ERPs belonging to the final rapid orbits

`CODMOPSRAP_yyyyddd0000_01D_30S_CLK.CLK` (old: `CODwwwwd.CLK_M`)
`CODMOPSRAP_yyyyddd0000_01D_30S_CLK.CLK_V2`
CODE GNSS clock product related to the final rapid orbit, clock RINEX format (versions 3.04 and 2.00)

`CODMOPSRAP_yyyyddd0000_01D_01D_OSB.BIA`
code/phase biases related to the final rapid orbit and clock corrections, Bias-SINEX format
Note: Integer-cycle clocks in conjunction with accompanying code/phase biases enable PPP-AR (ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT)

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 2: CODE's rapid products available through anonymous ftp (continued).

Result files for CODE *rapid ionosphere* solution
available at ftp://ftp.aiub.unibe.ch/CODE

`COD0OPSRAP_yyyyddd0000_01D_01H_GIM.INX.gz` (old: `CORGddd0.yyI`)
CODE rapid ionosphere product, IONEX format
`COD0OPSRAP_yyyyddd0000_01D_01H_GIM.ION` (old: `CODwwwwd.ION_R`)
CODE rapid ionosphere product, Bernese format
`COD0OPSRAP_yyyyddd0000_01D_01D_GIM.RNX` (old: `CGIMddd0.yyN_R`)
Improved Klobuchar-style coefficients based on CODE rapid ionosphere product, RINEX format

`COD0OPSPRD_yyyyddd0000_01D_01H_GIM.INX.gz` (old: `COPGddd0.yyI`)
CODE ionosphere predictions, IONEX format
`COD0OPSPRD_yyyyddd0000_01D_01H_GIM.ION` (old: `CODwwwwd.ION_P`)
CODE ionosphere predictions, Bernese format
`COD0OPSPRD_yyyyddd0000_01D_01D_GIM.RNX` (old: `CGIMddd0.yyN_P`)
predictions of improved Klobuchar-style coefficients, RINEX format

Result files for CODE *bias product* generation
available at ftp://ftp.aiub.unibe.ch/CODE

`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 3: CODE's final products available through anonymous ftp.

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

`yyyy/COD0OPSFIN_yyyyddd0000_01D_05M_ORB.SP3.gz` (old: `yyyy/CODwwwwd.EPH.Z`)
CODE final GPS+GLONASS(+Galileo) orbits

`yyyy/COD0OPSFIN_yyyyddd0000_01D_01D_ERP.ERP.gz` (old: `yyyy/CODwwwwd.ERP.Z`)
CODE final ERPs belonging to the final orbits

`yyyy/COD0OPSFIN_yyyyddd0000_01D_30S_CLK.CLK.gz` (old: `yyyy/CODwwwwd_v3.CLK.Z`)
`yyyy/COD0OPSFIN_yyyyddd0000_01D_30S_CLK.CLK_V2.gz` (old: `yyyy/CODwwwwd.CLK.Z`)
CODE final clock product, clock RINEX format (versions 3.04 and 2.00), 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/COD0OPSFIN_yyyyddd0000_01D_05S_CLK.CLK.gz` (old: `yyyy/CODwwwwd_v3.CLK_05.Z`)
`yyyy/COD0OPSFIN_yyyyddd0000_01D_05S_CLK.CLK_V2.gz` (old: `yyyy/CODwwwwd.CLK_05S.Z`)
CODE final clock product, clock RINEX format (versions 3.04 and 2.00), 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/COD0OPSFIN_yyyyddd0000_01D_01D_OSB.BIA.gz` (old: `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/COD0OPSFIN_yyyyddd0000_01D_30S_ATT.OBX.gz` (old: `yyyy/CODwwwwd.OBX.Z`)
Satellite attitude information in ORBEX format

`yyyy/COD0OPSFIN_yyyyddd0000_01D_01D_SOL.SNX.gz` (old: `yyyy/CODwwwwd.SNX.Z`)
CODE daily final solution, SINEX format

`yyyy/COD0OPSFIN_yyyyddd0000_01D_01H_TRO.TRO.gz` (old: `yyyy/CODwwwwd.TRO.Z`)
CODE final troposphere product, troposphere SINEX format

`yyyy/COD0OPSFIN_yyyyddd0000_01D_01H_GIM.INX.g` (old: `yyyy/CODGddd0.yyI.Z`)
CODE final ionosphere product, IONEX format

`yyyy/COD0OPSFIN_yyyyddd0000_01D_01H_GIM.ION.gz` (old: `yyyy/CODwwwwd.ION.Z`)
CODE final ionosphere product, Bernese format

`yyyy/CGIMddd0.yyN.Z`
Improved Klobuchar-style ionosphere coefficients, navigation RINEX format

`yyyy/COD0OPSFIN_20230080000_07D_07D_SOL.SNX.gz` (old: `yyyy/CODwwww7.SNX.Z`)
CODE weekly final solution, SINEX format (only for Sunday of the related week)

`yyyy/COD0OPSFIN_yyyyddd0000_07D_01D_SUM.SUM.gz` (old: `yyyy/CODwwww7.SUM.Z`)
CODE weekly summary file (only for Sunday of the related week)

`yyyy/COD0OPSFIN_yyyyddd0000_07D_01D_ERP.ERP.gz` (old: `yyyy/CODwwww7.ERP.Z`)
Collection of the 7 daily CODE-ERP solutions of the week (only for Sunday of the related week)

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

`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

Table 4: CODE's MGEX products available through anonymous ftp.

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

`yyyy/COD0MGXFIN_yyyyddd0000_01D_05M_ORB.SP3.gz` (old: `yyyy/COMwwwwd.EPH.Z`)
CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format

`yyyy/COD0MGXFIN_yyyyddd0000_01D_12H_ERP.ERP.gz` (old: `yyyy/COMwwwwd.ERP.Z`)
CODE MGEX final ERPs belonging to the MGEX final orbits

`yyyy/COD0MGXFIN_yyyyddd0000_01D_30S_CLK.CLK.gz` (old: `yyyy/COMwwwwd_v3.CLK.Z`)
(old: `yyyy/COMwwwwd.CLK.Z` version 2.00)
CODE MGEX final clock product consistent to the MGEX final orbits, clock RINEX format (version 3.04), 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/COD0MGXFIN_yyyyddd0000_01D_01D_OSB.BIA.gz` (old: `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.

— (old: `yyyy/COMwwwwd.DCB.Z`)
GNSS code biases related to the MGEX final clock correction product, Bernese format (provision terminated because the information is included in the BIAS SINEX file)

`yyyy/COD0MGXFIN_yyyyddd0000_01D_30S_ATT.OBX.gz` (old: `yyyy/COMwwwwd.OBX.Z`)
Satellite attitude information in ORBEX format

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 See `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT` for the usage of the phase biases.

Since GPS week 2238 (November 28th, 2022), CODE's final product series contains the same three systems as the rapid products the provision of these rapid product files as a long-term archive was terminated.

Table 5: CODE final products available in the product areas of the IGS data centers.

Files generated from three–day long–arc solutions:

`CODOOPSFIN_yyyyddd0000_01D_05M_ORB.SP3.gz` (old: `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

`CODOOPSFIN_yyyyddd0000_01D_01D_ERP.ERP.gz` (old: `codwwwwd.erp.Z`)
GNSS ERP (pole, UT1−UTC) solution belonging to the COD–orbit files in IGS IERS ERP format

`CODOOPSFIN_yyyyddd0000_01D_01D_SOL.SNX.gz` (old: `codwwwwd.snx.Z`)
GNSS daily coordinates/ERP/GCC from the long–arc solution in SINEX format

`CODOOPSFIN_yyyyddd0000_01D_30S_CLK.CLK.gz` (old: `codwwwwd_v3.clk.Z`)
`CODOOPSFIN_yyyyddd0000_01D_30S_CLK.CLK_V2.gz` (old: `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 (versions 3.04 and 2.00)

`CODOOPSFIN_yyyyddd0000_01D_05S_CLK.CLK.gz` (old: `codwwwwd_v3.clk_05s.Z`)
`CODOOPSFIN_yyyyddd0000_01D_05S_CLK.CLK_V2.gz` (old: `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 (versions 3.04 and 2.00)

`CODOOPSFIN_yyyyddd0000_01D_01D_OSB.BIA.gz` (old: `codwwwwd.bia.Z`)
CODE daily code and phase bias solution corresponding to the above mentioned clock products

`CODOOPSFIN_yyyyddd0000_01D_30S_ATT.OBX.gz` (old: `codwwwwd.obx.Z`)
Satellite attitude information in ORBEX format

`CODOOPSFIN_yyyyddd0000_01D_01H_TRO.TRO.gz` (old: `codwwwwd.tro.Z`)
GNSS 2–hour troposphere delay estimates obtained from the long–arc solution in troposphere SINEX format

`CODOOPSFIN_yyyyddd0000_07D_01D_ERP.ERP.gz` (old: `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

`CODOOPSFIN_yyyyddd0000_07D_01D_SUM.SUM.gz` (old: `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 3.

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

`CODOOPSFIN_yyyyddd0000_01D_01H_GIM.INX.gz` (old: `CODGddd0.yyI.Z`)
GNSS hourly global ionosphere maps in IONEX format, including satellite and receiver P1−P2 code bias values

`CODNOPSFIN_yyyyddd0000_01D_01H_GIM.INX.gz` (old: `CKMGddd0.yyI.Z`)
GNSS daily Klobuchar-style ionospheric (alpha and beta) coefficients in IONEX format

`CODKOPSFIN_yyyyddd0000_01D_01H_GIM.INX.gz` (old: `GPSGddd0.yyI.Z`)
Klobuchar-style ionospheric (alpha and beta) coefficients from GPS navigation messages represented in IONEX format

Table 5: CODE MGEX products available in the product areas of the IGS data centers.

Files generated from three–day long–arc MGEX solutions:
`COD0MGXFIN_yyyyddd0000_01D_05M_ORB.SP3.gz` CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format
`COD0MGXFIN_yyyyddd0000_01D_12H_ERP.ERP.gz` CODE MGEX final ERPs belonging to the MGEX final orbits
`COD0MGXFIN_yyyyddd0000_01D_30S_CLK.CLK.gz` CODE MGEX final clock product consistent to the MGEX final orbits, clock RINEX 3.04 format, with a sampling of 30 sec for the GNSS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`COD0MGXFIN_yyyyddd0000_01D_01D_OSB.BIA.gz` GNSS code and phase (GPS and Galileo only) biases related to the MGEX final clock correction product, Bias SINEX format v1.00
`COD0MGXFIN_yyyyddd0000_01D_30S_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 4.

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 .

3 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. 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.

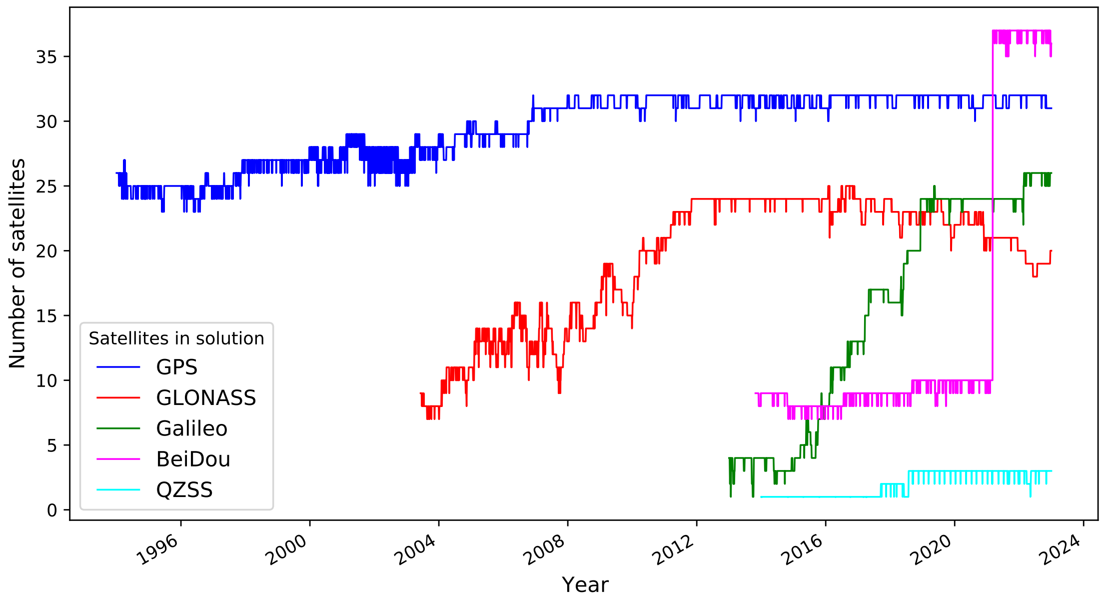
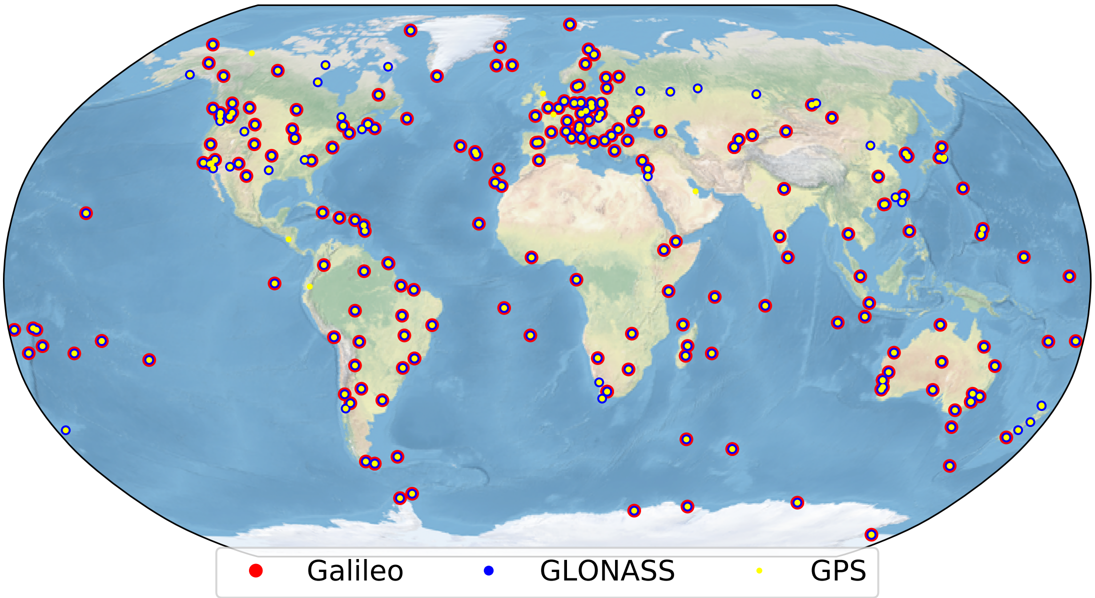
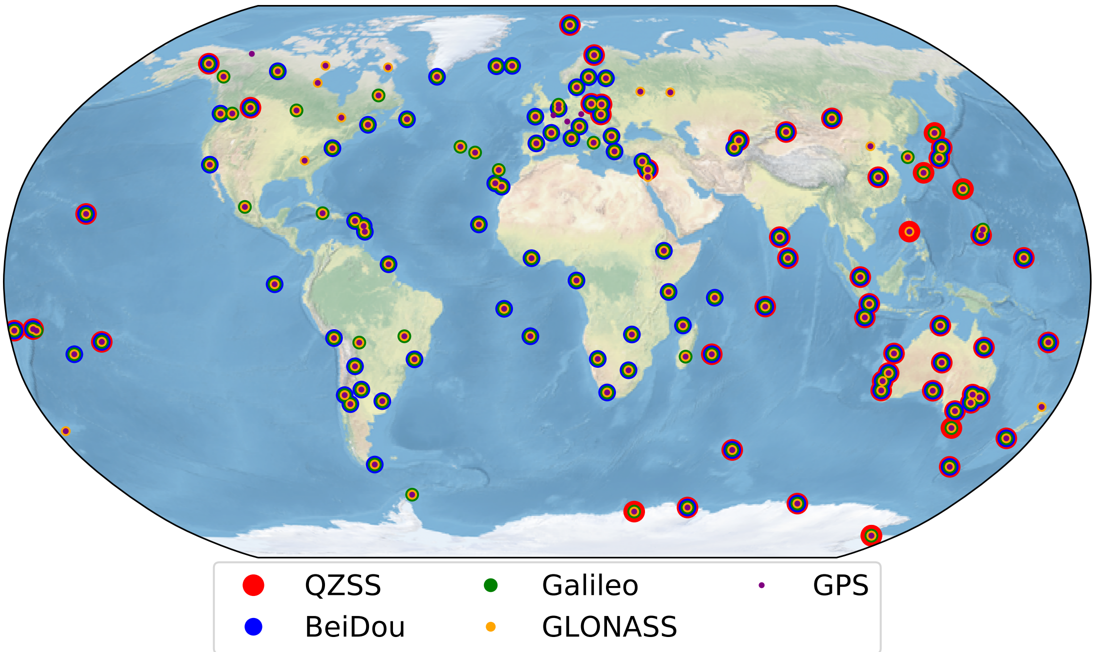


Figure 1: Development of the number of satellites in the CODE orbit products.



(a) final solution (more than 250 stations)



(b) MGEX solution (140 stations)

Figure 2: Network used for the processing at CODE by the end of 2022.

4 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. (2022).

In Section 4.1 we give an overview of important development steps in the year 2022. The most prominent change was the switch from IGb14 to IGS20 end of November 2022. It was prepared by a parallel processing where selected results obtained by the CODE analysis center are presented in Section 4.2 .

4.1 Overview of changes in the processing scheme in 2022

Table 6 gives an overview of the major changes implemented during the year 2022. 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 6 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.

4.2 Introducing the IGS20 reference frame at CODE

In the time frame between August 7$^{\text{th}}$ to November 26$^{\text{th}}$, 2022 (GPS weeks 2222 to 2237) CODE did compute the final solution already with the new reference frame and modelling in parallel to the legacy final solution. The following changes of the background with respect to the legacy solution have been applied:

- Reference frame: IGb14 ⇒ IGS20
- Antenna corrections: IGS14.atx ⇒ IGS20.atx
- High-frequency pole model: IERS2010 ⇒ Desai and Sibois (2016)
- Mean pole model: IERS2010 ⇒ IERS2010, version 1.2.0
- Galileo included also in the final processing chain (including associated ionosphere analysis)
- Epoch sampling now increased to 5 minutes in the final orbit files as well
- Rigorously ignore measurements where related receiver antenna calibrations are unavailable
- New bias convention regarding the satellite antenna corrections is used for both the Melbourne-Wübbena linear combination (of fundamental importance for phase biases of the PPP-AR) and the geometry-free linear combination (critical for DCB, or correspondingly derived OSB information from ionosphere analysis)
- Consider misalignment of the receiver antennas with respect to North

Table 6: Selected events and modifications of the CODE processing during 2022.

Date	DoY/Year	Description
19-Jan-2022	019/2022	Hatanaka tools switched from version 4.0.8 to 4.1.0
24-Jan-2022	024/2022	Counting of ambiguities corrected in the processing protocols
25-Apr-2022	115/2022	Software and configuration updates introduced: • Switch from ECOM2 to ECOM2-D1/ECOM2-YD1 (Sidorov et al., 2020) changed from 12.0 to 14.0 beta angle • Transform parameters from ECOM2-D1/ECOM2-YD1 to ECOM2 when both models are mixed in a long-arc solution Due to these changes the Galileo orbits are not automatically removed from the ultra-rapid orbit solution during the transition phase between the two models.
06-May-2022	123/2022	Ambiguity resolution between BeiDou-2 and BeiDou-3 omitted.
06-Jul-2022	184/2022	Increase sampling for attitude reporting in final and MGEX solution series from 900 to 30 seconds.
04-Aug-2022	216/2022	Prepare the CODE metadata base to extent the station list to be considered after the switch to IGS20 reference frame. Start the processing of the final series based on IGS20 reference frame, antenna calibrations, and processing models in parallel to the legacy series based on IGb14 .
19-Oct-2022	291/2022	QIF ambiguity resolution strategy tuned for non-GPS satellite constellations; the main improvement is reflected in the percentage of ambiguities resolved for Galileo.
28-Nov-2022	331/2022	Switch from IGb14 to IGS20 coordinates and antenna corrections (start of GPS week 2238): • Reference frame: IGb14 ⇒ IGS20 • Antenna corrections: IGS14.atx ⇒ IGS20.atx • High-frequency pole model: IERS2010 ⇒ Desai and Sibois (2016) • Mean pole model: IERS2010 ⇒ IERS2010, version 1.2.0 • Galileo included also in the final processing chain (including associated ionosphere analysis) • Epoch sampling now increased to 5 minutes in the final orbit files as well • Rigorously ignore measurements where related receiver antenna calibrations are unavailable • New bias convention regarding the satellite antenna corrections is used for both the Melbourne-Wübbena linear combination (of fundamental importance for phase biases of the PPP-AR) and the geometry-free linear combination (critical for DCB, or correspondingly derived OSB information from ionosphere analysis) • Consider misalignment of the receiver antennas with respect to North • Station selection (also with regard to multi-GNSS) expanded for processing • Switch to long product filenames for published result files • Inclusion of second midnight epoch in submitted product files (specifically in all `ORB.SP3`, `ATT.OBX` for seamless interpolation, as well as exclusively in our final high-rate `CLK.CLK` to ultimately allow for continuity checks)
07-Dec-2022	342/2022	Correct predictions for ERP files obtained in the 06 o'clock ultra-rapid solution.

- Station selection (also with regard to multi-GNSS) expanded for processing
- Switch to long product filenames for published result files
- Inclusion of second midnight epoch in submitted product files (specifically in all `ORB.SP3`, `ATT.OBX` for seamless interpolation, as well as exclusively in our final high-rate `CLK.CLK` to ultimately allow for continuity checks)

The intension of the parallel solution was to establish and verify the setup for the planned switch to the new reference frame, see GPS week 2238 in Table 6 . The most important aspect is in this context whether the daily GNSS solution does better fit into the coordinates of the reference frame stations. This is tested with a Helmert transformation between the coordinates obtained with minimum constraint solution with respect to the coordinates in the related reference frame. The RMS of the residuals are shown in the top plot of Figure 3 . A clear improvement in the new reference frame IGS20 is visible – as expected. Whereas the estimated translation and rotation parameters mainly show systematic effects due to the station selection, it is noticeable that the scale can be perfectly recovered in the IGS20 based solution. The offset in the scale for the IGb14 based solution corresponds to about 3 mm on the Earth surface, which can be explained (among others) by the aging of the reference frame.

In Figure4 the orbit overlaps for the GPS satellites at midnight between consecutive day are compared when using the old and new setup. The middle day is extracted from a three-day long-arc solution as described in Dach et al. (2021) . The results are equivalent with a potential slight benefit for the IGS20 based solution, possible due to the updated satellite antenna model.

5 Finalizing the recent IGS-Reprocessing

As a global analysis center CODE contributed to the IGS reprocessing effort for the ITRF2020. 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 7 . During the year 2022 the series have been completed until end of November when the IGS changed to the updated modelling. 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 .

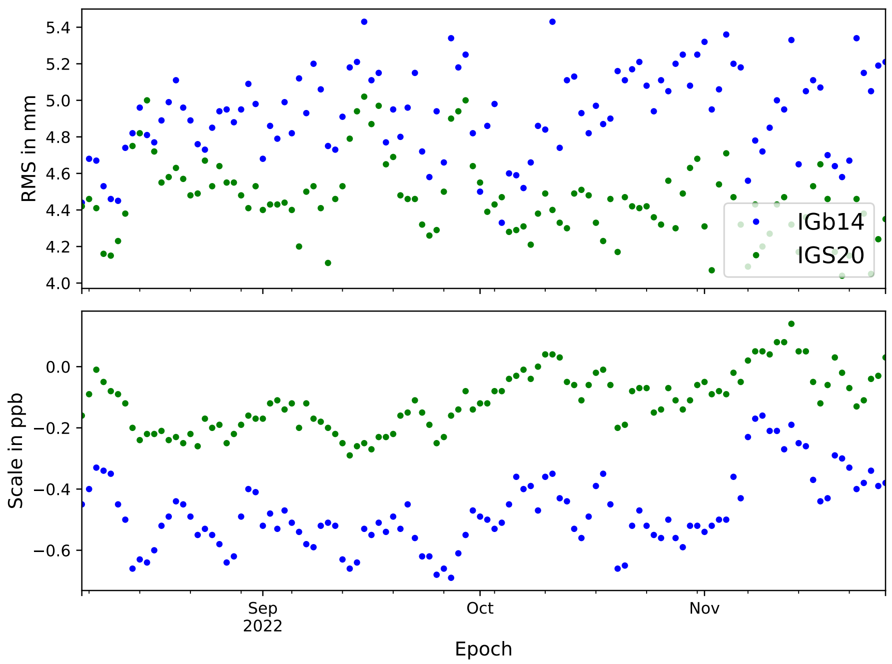
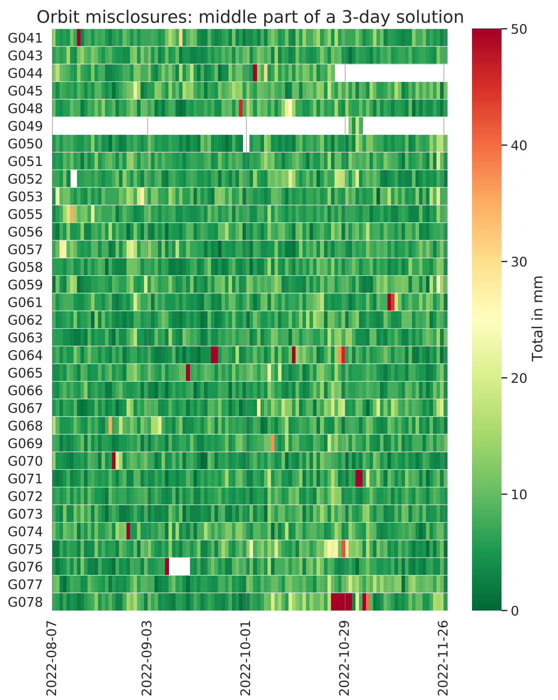
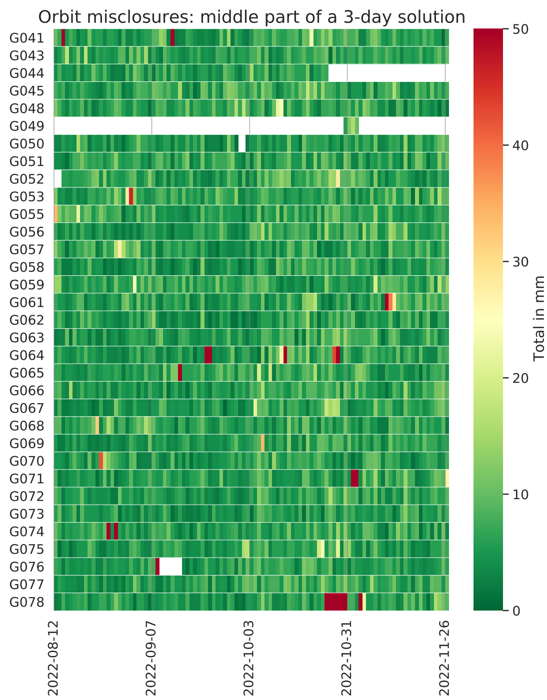


Figure 3: Coordinate comparison of the solution to the reference frame.



(a) IGb14 reference frame and IGS14 antenna model



(b) IGS20 reference frame and antenna model

Figure 4: Orbit overlaps during the period of parallel processing.

Table 7: 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.gz`
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.gz`
GNSS ERP (pole, UT1-UTC) solution in IGS ERP format

`COD0R03FIN_yyyyddd0000_01D_01D_SOL.SNX.gz`
GNSS daily coordinates/ERP/GCC from the long-arc solution in SINEX 2.01 format

`COD0R03FIN_yyyyddd0000_01D_30S_CLK.CLK.gz`
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.gz`
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.gz`
CODE daily code and phase bias solution corresponding to the above mentioned clock products in Bias SINEX 1.00 format

`COD0R03FIN_yyyyddd0000_01D_15M_ATT.OBX.gz`
Satellite attitude information in ORBEX format

`COD0R03FIN_yyyyddd0000_01D_01H_CNT.TRO.gz`
GNSS 1-hour troposphere delay estimates obtained from the long-arc solution in troposphere SINEX 2.0 format

`COD0R03FIN_yyyyddd0000_07D_01D_ORB.ERP.gz`
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.gz`
Analysis summary for 1 week on the long-arc solutions of the week; labeled with the starting day of the week

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) .

6 Development of a combined EOP product at BKG

The publicly available daily Earth Orientation Parameter (EOP) products provided by the International Earth Rotation and Reference Systems Service (IERS) – e.g., IERS

Bulletin A, IERS C04 – are based on the combination of individual space-geodetic EOP solutions. In this approach, parameter solutions estimated separately from the observation data of the individual space-geodetic techniques (i.e., VLBI, GNSS, SLR and DORIS) are combined independently. As a result, correlations between the parameters are lost. Compared to the combination on observation and normal equation level, this is the least rigorous combination method.

Current activities at BKG are focused on the development of a combination strategy with the main objective of improving consistency between space-geodetic techniques through common parameters, in particular EOP, and thereby improving the resulting EOP estimates. In addition, we want to generate an EOP product that is characterized by a continuous, daily and regular temporal resolution, which is available with the shortest possible latency. This is especially important for the highly variable dUT1.

Each of the space-geodetic techniques has individual strengths and contributes differently to the estimation of geodetic parameters. As an example, satellite techniques are not able to determine the rotation of the Earth in an absolute sense, thus, the parameter dUT1 cannot be separated from the motion of the orbital node of the satellite. As a consequence, VLBI is essential to determine the full set of EOPs including dUT1.

Since the VLBI observation and correlation process is generally not fully automated, continuous operation is not feasible, and the derived products – such as the EOPs – are available with longer latencies only. As a result, the VLBI observations must be organized session-wise with a limited observation time and a subset of radio telescopes. Essentially, the IVS organizes two different types of observation campaigns that are suitable for regular EOP determination:

1. The 24-hour Rapid (RAP) sessions are conducted every Monday and Thursday. Due to the global network with up to 15 antennas, they are suitable for the determination of all five EOPs, but have no daily scheduling and a comparably long latency of up to 15 days until the availability of the products (e.g. SINEX file).
2. For daily monitoring of dUT1, the so-called VLBI Intensives (INT) sessions of one-hour duration and a sparse network of two or three antennas are organized at least once a day. They are not suitable for the determination of other EOP components, but have a latency of two days or even less and are usually scheduled for each day. Since 2019, an increasing number of new VLBI Global Observing System (VGOS) Intensive campaigns has been conducted in addition to the legacy S/X Intensives. As a result, two to four INT sessions per day are available now.

For the combination, we use the GNSS Rapid solutions generated by the CODE IGS Analysis Centre (AC) and the VLBI INT and RAP solutions generated by the BKG IVS AC, respectively. The solutions and normal equations are provided in SINEX format.

The processing is based on datum-free normal equations (NEQs), which allow a rigorous combination on the normal equation level instead of the observation level. The NEQs of

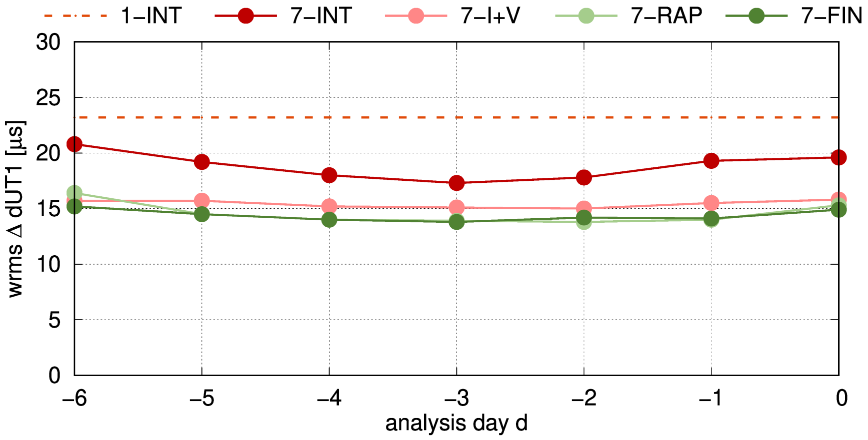


Figure 5: WRMS values of dUT1 estimates resulting from different analysis approaches compared to the IERS Bulletin A series. The analysis epoch is 12 h. Red series: VLBI-only solutions. Green series: Combined VLBI-GNSS solutions.

seven consecutive days are homogenized with respect to parameterization and parameter a priori values and stacked to one NEQ system before applying datum constraints and solving for the parameters. The combination procedure is repeated on a daily basis. The resulting solution, essentially includes EOP and station coordinates.

Two different inter-technique combination solutions are considered:

1. The so-called 7-RAP solution represents the 7-day combination of GNSS with VLBI INT data. This solution has a latency of about one or two days, depending on the latency of the VLBI INT data.

2. The so-called 7-FIN solution additionally contains the VLBI RAP data and therefore has a latency of at least 2 weeks.

Figure 5 gives a brief insight into the different combined 7-day dUT1 solutions. The WRMS values of the dUT1 estimates w.r.t. the IERS Bulletin A series are shown for the 7-RAP and 7-FIN approach. The comparison epoch is 12:00 UTC which is usually not the strongest epoch for VLBI-based parameter estimation. The WRMS values of the single- and 7-day VLBI INT-only solutions (1-INT, 7-INT) and the 7-day intra-technique combined solution of VLBI INT and RAP data (7−I+V) are depicted additionally. The analysis day d ranges from 0 to −6 and represents the analyzed day within the 7-day polygon, 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 (7-RAP) leads to a significant improvement in WRMS values compared to the individual technique-specific solutions (1-INT, 7-INT). 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. The inclusion of the VLBI R1/R4 sessions into the combination (i.e., the 7-FIN solution) additionally stabilizes the dUT1 estimates of the boundary days.

Detailed information about the data processing, the combination strategy, the validation procedure and the different EOP solutions can be found in Lengert et al. (2021, 2022); Klemm et al. (2023a,b)

Based on the improved combination method, we intent to set up a new operational EOP product at BKG with daily and regular resolution and a short latency of 1-2 days with open access for the international community. Its characteristics make it suitable as an input for EOP prediction algorithms.

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

NRCan Analysis Center Technical Report 2022

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1 Introduction

This report provides an overview of the major activities conducted at the NRCan Analysis Center (NRCan-AC) and product changes during the year 2022 (products labelled 'em*'). Furthermore, it includes an outline of the changes to the stations and services managed 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 version 6.4 software until 2022-Nov-26, with no major changes to the processing strategy. Beginning with 2022-Nov-27, the final GPS products are being generated using Gipsy-X (currently in development). The GNSS Rapid and Ultra-Rapid products continued to be generated using the Bernese GNSS Software, Version 5.2 (Dach et al., 2015). IGS20/Repro3 standards for GNSS Rapid and Ultra-Rapid products were implemented for the switchover date.

The products available from the NRCan-AC are summarized in Table 2. 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. Multi-GNSS phase rate measurements are used to investigate the Canadian high latitude ionospheric irregularities Alfonsi et al. (2022); Ghoddousi-Fard (2022); Ghoddousi-Fard et al. (2022) .

4 Real-time correction service

NRCan is moving towards 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 1. Figure 1 shows a map of the NRCan GNSS network as of January 2023. Further details about NRCan stations and access to NRCan public GNSS data and site logs can be found at:

> `https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/data-donnees/cacs-scca.php`

or from the following anonymous ftp sites:

> `ftp://cacsa.nrcan.gc.ca/gps`
> `ftp://cacsb.nrcan.gc.ca/gps`

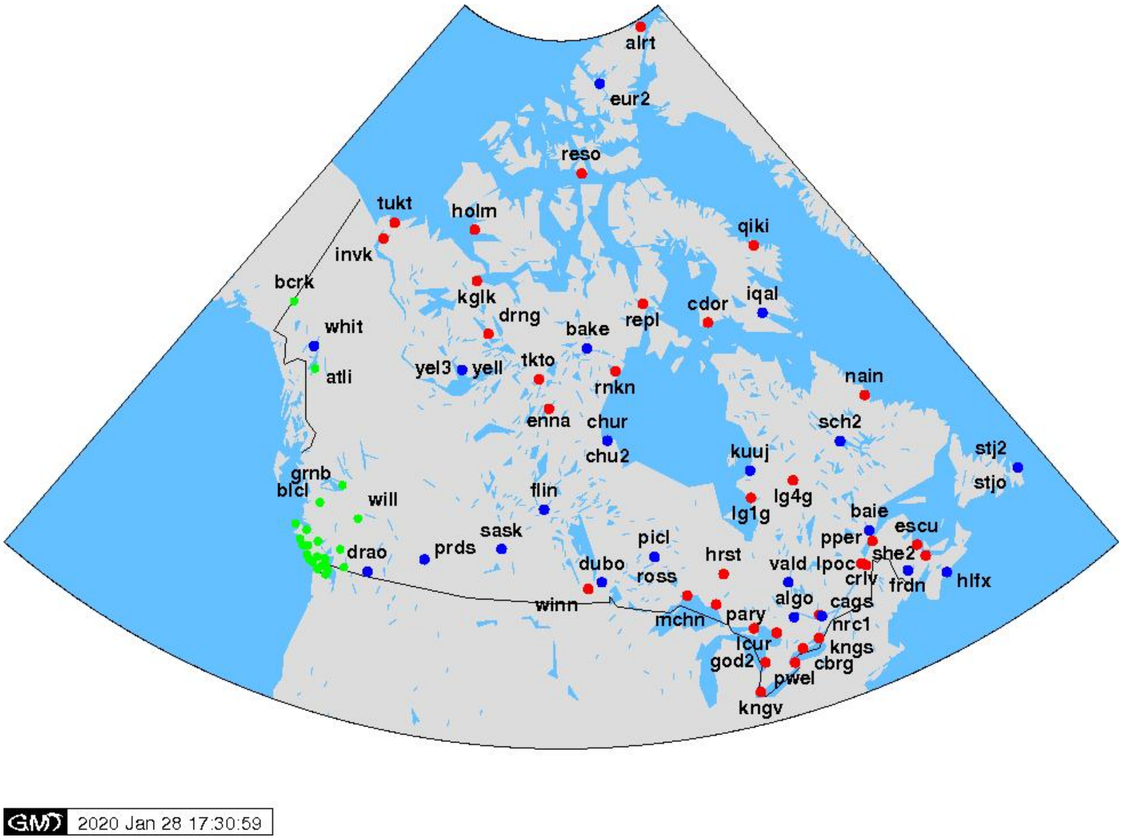

Figure 1: NRCan Public GNSS Stations (CGS-CACS in blue, CGS-RACS in red and CHIS-WCDA in green).

Table 1: NRCan-IGS Station upgrades in 2022.

Station	Date	Remarks
FRDN00CAN	2022-06-20	Station receiver upgraded to SEPT POLARX5
HLFX00CAN	2022-07-15	Station receiver upgraded to SEPT POLARX5

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Table 2: 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

Table 2: NRCan-AC products (continued).

Product	Description
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-01to 2022-Nov-26
	• Use of JPL's GipsyX (mix of v1.3 and 2.0) from 2022-Nov-27 (currently development only)
	• 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 2: 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

GFZ Analysis Center Technical Report 2022

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1 Summary

During 2022, the standard IGS product generation was continued with minor changes in the processing software EPOS.P8. With switching to the new IGS20 reference frame, the GNSS observation modeling was updated from the GFZ repro-2 (2nd IGS Reprocessing campaign) to the repro3 (3rd IGS Reprocessing campaign) settings. While Galileo was added to our ultra-rapid and rapid products in 2021, the constellation was also added to the final products in week 2238. The multi-GNSS processing was continued routinely during 2022 including GPS, GLONASS, BeiDou, Galileo, and QZSS.

2 Products

The list of products provided to the IGS by GFZ is summarized in Table 1. The long naming scheme was introduced for the IGS products in week 2238.

Table 1: List of products provided by GFZ AC to IGS and MGEX; YD = YYYYDDD0000. The long naming scheme was introduced for the IGS products in week 2238.

IGS Final (GLONASS since week 1579, Galileo since week 2238)	
GFZ0OPSFIN_YD_01D_05M_ORB.SP3	Daily orbits for GPS/GLONASS satellites
GFZ0OPSFIN_YD_01D_30S_CLK.CLK	5-min clocks for stations and 30-sec clocks for GPS/GLONASS satellites
GFZ0OPSFIN_YD_01D_01D_SOL.SNX	Daily SINEX files
GFZ0OPSFIN_YD_07D_01D_ERP.ERP	Earth rotation parameters
GFZ0OPSFIN_YD_07D_07D_DSC.SUM	Summary file including Inter-Frequency Code Biases (IFB) for GLONASS
GFZ0OPSFIN_YD_01D_01H_TRO.TRO	1-hour tropospheric Zenith Path Delay (ZPD) estimates
IGS Rapid (GLONASS since week 1579, Galileo since week 2159)	
GFZ0OPSRAP_YD_01D_05M_ORB.SP3	Daily orbits for GPS, GLONASS, Galileo satellites
GFZ0OPSRAP_YD_01D_30S_CLK.CLK	5-min clocks for stations and GPS, GLONASS, Galileo satellites
GFZ0OPSRAP_YD_01D_01D_ERP.ERP	Daily Earth rotation parameters
GFZ0OPSRAP_YD_01D_01D_DSC.SUM	Summary file
IGS Ultra-Rapid (every 3 hours; provided to IGS every 6 hours; GLONASS since week 1603, Galileo since week 2159, YDH = YYYYDDDHH00)	
GFZ0OPSULT_YDH_02D_05M_ORB.SP3	Adjusted and predicted orbits for GPS, GLONASS, Galileo satellites
GFZ0OPSULT_YDH_02D_01D_ERP.ERP	Earth rotation parameters
GFZ0OPSULT_YDH_01D_01D_DSC.SUM	Summary file
MGEX Rapid containing GPS, GLONASS, Galileo, BeiDou, and 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

3 Operational Data Processing and Latest Changes

Our EPOS.P8 processing software is following the IERS Conventions 2010 (Petit and Luzum, 2010). With switching to the new IGS20 reference frame, the processing lines are updated to repro3 standards. This includes:

- IGS20 reference frame (post-seismic deformations applied, seasonal signals not considered as agreed between the ACs),

- igs20.atx (as it is),
- ground antenna misorientations are corrected and reported,
- linear mean pole as adopted by the IERS in 2018,
- FES2014b ocean tide model (Lyard et al., 2021), and
- a new high-frequent EOP model Desai and Sibois (2016).

Moreover, the IGS long naming scheme was adopted and troposphere results are provided in the new trop sinex 2.00 format (including delays and gradients). With switching to repro3 standards, we applied a new network configuration resulting in approximately 140, 120, and 70 sites processed in the IGS final, rapid and ultra-rapid chains, respectively. Incorrect products were submitted for weeks 2238 to 2240 due to wrong usage of the tidal harmonics (i.e., ignore that they are given as *normalized*). The issue was corrected by the end of week 2240 and all products were re-computed and re-submitted. 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

Table 2: Recent processing changes

Date	**IGS**	**IGR/IGU**	Change
2022-11-27	w2238	w2238.0	switch to long naming scheme and repro3 models
2022-12-15	w2240	w2240.5	bug correction related to ocean tide model

4 Multi-GNSS data processing

The rapid multi-GNSS product GBM was continued in 2022. Starting from day 2022/321 and announced in IGSMAIL #8278, we provide daily P1P2 DCB biases for satellites and stations in GFZ0MGXRAP_YYYYDDD0000_01D_01D_REL.BIA.gz. The GFZ rapid ionosphere products are introduced to estimate DCBs (Brack et al., 2021). The observations used in the POD are taken for the DCB estimation using GFZ EPOS8 software, which makes a more consistent solution with our POD products.

The OSBs provided via GFZ0MGXRAP_20223210000_01D_01D_OSB.BIA.gz are converted from UPD and the new DCB product. In the updated DCB and OSB products the PCO/PCV corrections are applied for the satellite and station. We follow the IGS conventions by introducing the "APC_MODEL IGS14_2188" keyword in the BIAS/DESCRIPTION block. Since GPS week 2238 (2022/331) the GFZ MGEX product has been generated in the IGS20 frame. The new reference frame and the associated ANTEX file are applied and are indicated in the product header. The new IGS20 product can be found under the GFZ Ftp server: ftp://ftp.gfz-potsdam.de/pub/GNSS/products/mgex/WWWW_IGS20/. All GFZ MGEX products are available at ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

5 Operational ionosphere products

The rapid and final global ionosphere map (GIM) products were continued in 2022 without changes. 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. The products are provided via https://isdc.gfz-potsdam.de/gnss-products as daily IONEX files following the IGS long-name definition. 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/`). Based on extended processing, the GFZ repro3 solution is extended until week 2237.

In 2022, we pursued our efforts to elaborate an orbit and clock combination strategy compatible with a multi-GNSS environment (Mansur et al., 2022). The modernized clock combination follows a similar scheme for the orbits using the Variance Component Estimation. The alignment used in the process takes one AC as a reference and computes a drift and offset between this reference and the other ACs, which then keeps the clocks consistent among each other to perform the combination. We note that the assumption relies on a linear clock behavior, which is true in most cases. One specific issue for the combination, which involves more than one constellation, refers to the inter-system bias present in the solutions; the satellite clocks absorb the shifts for one constellation. We then compute offsets between a reference and the other constellations, which proved to be effective in removing the existing bias. On average, the agreement of the combined solution compared to the legacy GPS clock combination is around 32 picoseconds. With the combined clocks and orbits a PPP processing was completed, where the ionosphere-free phase residuals are compared between GPS, GLONASS, and Galileo. Generally, the residuals are below 10 mm, with GLONASS being slightly larger than the other two systems.

Based on our contribution to repro3, we performed a small study on the impact of non-tidal surface deformation. To apply related corrections (provided by ESMGFZ) at the observation level, we repeated the repro3 partly – 2012.0 -2016.0 – keeping all models but adding the ESMGFZ non-tidal loading corrections. Applying a time series assessment to the derived coordinates revealed averaged reductions from 1.5 to 0.8 and from 1.1 to 0.8 mm for North and East annual amplitudes, respectively. For the vertical amplitudes, an overall reduction of -1.3 mm from 3.2 to 1.9 mm was observed. Using a linear trajectory model the mean coordinate variability in the original repro3 (2012–2016) solution was determined with 2.1, 2.1, and 5.1 mm in North, East, and Up directions. Correcting for non-tidal loading corrections at the observation level leads to reduced RMS values of 1.8, 2.0, and 4.5 mm. Overall, the variability in North, East, and Up is reduced for 90, 80, and 84 % of the stations. A corresponding publication is in preparation.

7 Operational GFZ Stations

The global GNSS station network operated by GFZ still comprises 24 GNSS stations contributing to the IGS tracking network in 2022. Beside regular F/W updates only minor hardware changes were necessary in 2022. In ACRG (Accra/Ghana) we upgraded the receiver from `JAVAD TR_G3TH` to `JAVAD TRE_3S` and the antenna from `JAV_RINGANT_G3T`

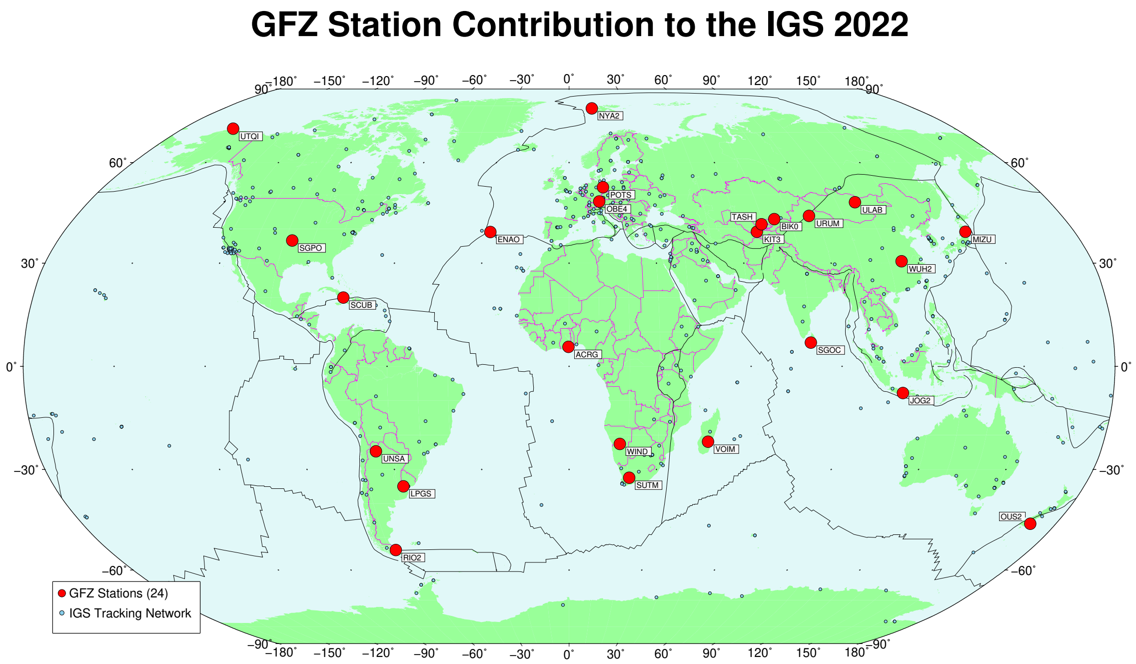

Figure 1: GNSS stations operated by GFZ (as of January 2023)

`NONE` to `SEPCHOKE_B3E6 NONE` after severe damage of the site's hardware due to lightning. JOG2 was suffering from a bad internet connection, but this could be sorted out in the end 2022.

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 also serves as the landing page for our RINEX toolbox **gfzrnx** which was updated to fully support the new RINEX4 formats.

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CNES-CLS
Technical Report 2022

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1 Introduction

The CNES-CLS Analysis Center is providing final products on behalf of the Groupe de Recherches de Géodésie Spatiale (GRGS) since 2010 using the GINS CNES software package.

The year 2022 has been focused on the finalization of our participation to the REPRO3 campaign and the preparation of the post-ITRF 2020 products (see IGSMAIL #8191) that started being delivered on GPS week 2238 (together the others ACs). The main evolutions in the processing in 2022 are summarized in Table 1.

The formal "GRG" GPS-GLONASS-GALILEO products can be downloaded from the gps/products/wwww directory of the IGS archiving centers. Additional information and links to the AC publications can be found at https://igsac-cnes.cls.fr/.

During 2022 we all pursued the efforts to increase our participation toward a full set of products; the rapid and ultra-rapid products and the future inclusion of the Beidou constellation are presented in the following parts.

Table 1: Main processing changes in 2022

Date	GPS week	Change
2022/11/27	2238	New standards corresponding to the post ITRF 2020 switch: • igs20.atx antenna patterns and alignment referring to the IGS20 frame IGSMAIL #8274 • more realistic weights for Galileo observations (that were downweighed before) • vmf1 model for tropospheric correction (Böhm et al., 2006) • DE440 for lunar and planetary ephemeris (Park et al., 2021)
2022/11/27	2238	Start of delivering the APC corrected Observable Specific Biases IGSMAIL #8113, IGSMAIL #8279
2022/11/27	2238	Long names convention for the products files following Guidelines For Long Product Filenames in the IGS v2.0 (see Table 2)
2022/11/27	2238	Start of delivering the Rapid and Ultra GRG products (see Section 3)

2 Finalization of the REPRO3 campaign

The contribution of GRG to the REPRO3 campaign has been filled with our contribution of 2022 data up to the date of the "switch" (GPS week 2238). The complete dataset represents more than 22 years of data for a total of 82 satellites. The orbit 3D-overlaps (see Figure 1) reach the mid-centimeter at the end of 2022. The Galileo satellites (in Green) are now fully included in the AC products. The derived reference frame is shared with the others historical constellations Glonass (in Red) and GPS (in black).

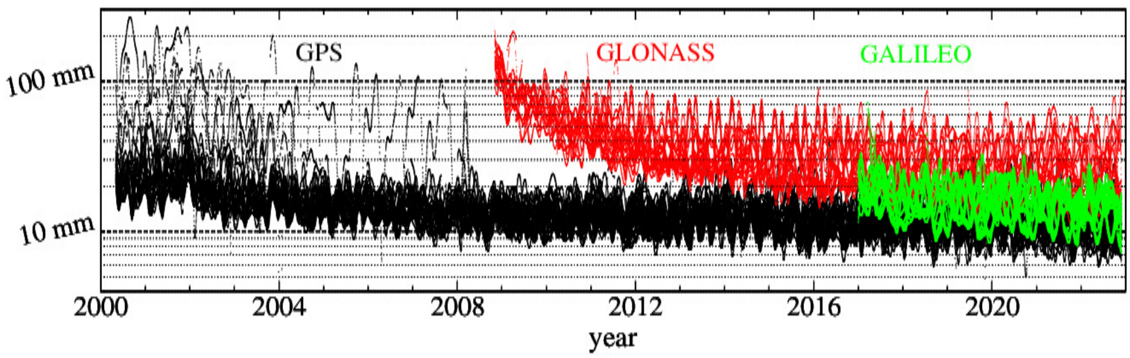

Figure 1: Smoothed orbit 3D-overlaps for the three constellations of satellites included in the GRG contribution to REPRO3.

3 Rapid and Ultra-Rapid products

Since the end of year 2022 we deliver rapid (GRR) and ultra-rapid (GRU) products for GPS and Galileo constellations. This contribution follows a dedicated effort to develop a fast and fully automatic processing chain on a dedicated server. Algorithms have been chosen to accelerate the delays between the recovery of hourly RINEX data and the ultra-rapid products and their predictions delivery. Since the end of 2022 our submissions are evaluated by the ACC coordinator. Figure 2 shows one of the results of the ultra-rapid combination (including GRU products for comparison); EOP estimates & predictions have been improved at the end of GPS week 2243 by adding iterations to be less sensitive to erroneous a priori values. The list of all the GRG products delivered today is summarized in Table 2.

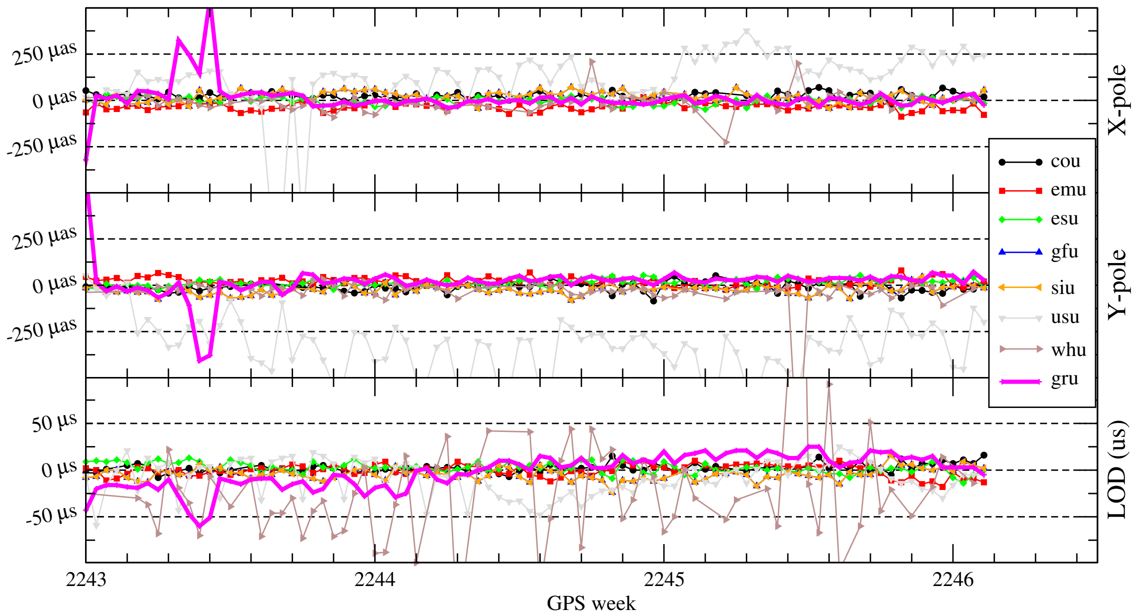

Figure 2: EOP ultra-rapid combination residuals (from the ACC summaries).

Table 2: CNES-CLS products files for IGS (New products in 2022)

File	Type	Sampling
FINAL PRODUCTS: GPS,GLONASS & GALILEO (since week 2238) Updated weekly		
GRG0OPSFIN_YYYYDDD0000_01D_000_SOL.SNX	SINEX solution (station coord./ERP/Satellites PCO)	1/day
GRG0OPSFIN_YYYYDDD0000_01D_30S_ATT.OBX	Satellites attitudes	30 seconds
GRG0OPSFIN_YYYYDDD0000_01D_01D_OSB.BIA	Observable specific biases	1 set/day
GRG0OPSFIN_YYYYDDD0000_01D_05M_ORB.SP3	Satellites ephemeris	5 minutes
GRG0OPSFIN_YYYYDDD0000_01D_30S_CLK.CLK	Satellites clocks	30 seconds
GRG0OPSFIN_YYYYDDD0000_07D_01D_ERP.ERP	Weekly Earth rotation	1/day
RAPID/ULTRA GPS & GALILEO Updated daily (Rapid) / Four times a day (Ultra)		
GRG0OPSRAP_YYYYDDD0000_01D_05M_ATT.OBX GRG0OPSULT_YYYYDDDHH00_01D_05M_ATT.OBX	Satellites attitudes	5 minutes
GRG0OPSRAP_YYYYDDD0000_01D_05M_CLK.CLK GRG0OPSULT_YYYYDDDHH00_01D_05M_CLK.CLK	Satellites clocks	5 minutes
GRG0OPSRAP_YYYYDDD0000_01D_05M_ORB.SP3 GRG0OPSULT_YYYYDDDHH00_01D_05M_ORB.SP3	Satellites ephemeris	5 minutes
GRG0OPSRAP_YYYYDDD0000_07D_01D_ERP.ERP GRG0OPSULT_YYYYDDDHH00_07D_01D_ERP.ERP	Daily Earth rotation	1/day

4 Preliminary results with Beidou satellites

The studies on Beidou satellites started in 2022 with the aim to construct a four-constellation product (receiver clocks, erp and tropospheric parameters being common to all signals). It is a huge task but it will give a homogenous access to the reference frame regardless of the signals or constellations being used.; software's improvements were done, and several studies are still in progress (e.g. relative ponderation of measurements). The preliminary results of GPS+Beidou processing indicate orbits overlaps at the level of few centimeters for the BDS-3 satellites for which we fix the ambiguities to integer values on phase measurements while BDS-2 satellite measurements are left unfixed (see Figure 3). We plan to include the satellites of the Beidou constellation in our final products in 2023.

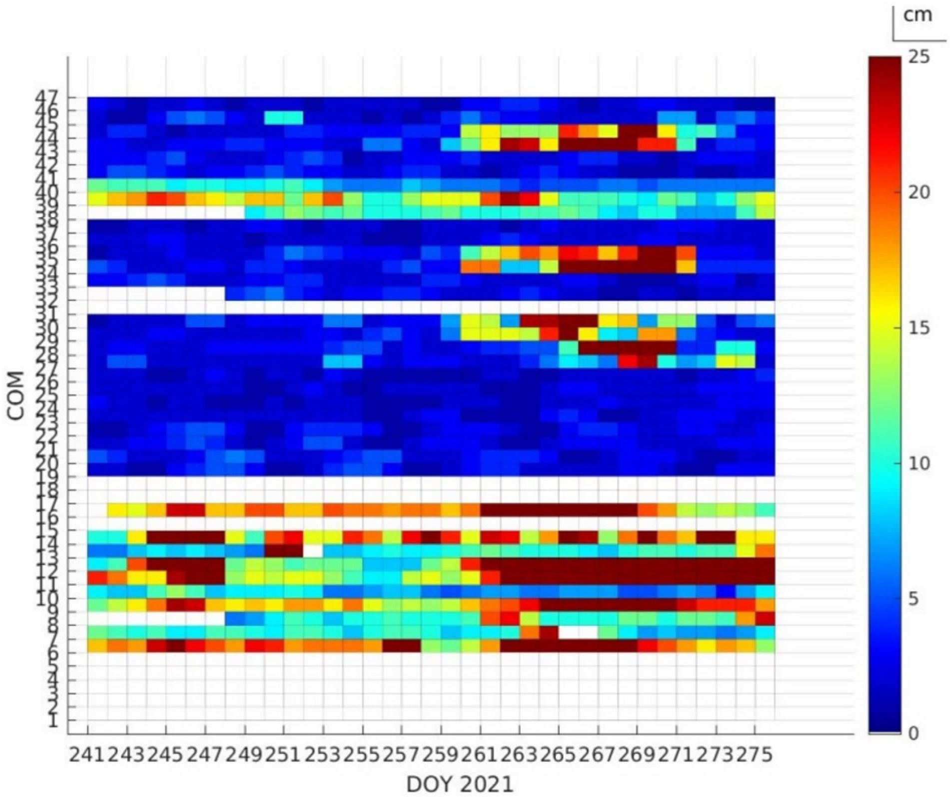

Figure 3: Preliminary internal overlaps of Beidou satellites (by PRN number) over a one-month test period in 2021.

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Jet Propulsion Laboratory Analysis Center Technical Report 2022

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1 Introduction

In 2022, 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 2022.

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

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

- Transitioned JPL Rapid products delivered to IGS to the IGS20 reference frame as of 2022-11-28.

- Transitioned JPL Rapid products to new long product names as of 2023-12-08.
- Conducted analysis of the effect of center-of-figure (CF, i.e. local motions only) vs. center-of-mass (CM, i.e. CF+global periodic geocenter) vs no seasonals in orbits and clocks produced with IGS20 which were presented at the 2022 Unified Analysis Workshop UAW (Ries , 2022) and the AGU (Ries et al., 2022). Results showed that CM seasonals generally produced better results than CF seasonals, which produced better results than ignoring seasonal terms.
- Contributed to research into creating an experimental reference frame using combined SLR and GNSS data at the observation level tied together using spacecraft with both GNSS receivers and SLR reflectors which showed good agreement with ITRF2020 (Haines et al., 2022).
- Continued Multi-GNSS development. Efforts included substantial code refinement, all based around our GipsyX software. Also continued to operationally produce low-rate (5-minute) GPS+GALILEO rapid products in JPL-format:

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

  Remaining development efforts are focused on continuing to ensure that our codebase 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 geodetic data has been added to GipsyX and VLBI is under development and testing.

6 Acknowledgments

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MIT Analysis Center Technical Report 2022

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1 Introduction

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

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 Herring, 2022).

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. Starting in week 2238 (2022/11/27) we switched to the IGS20 system and to long files names as shown in Tables 1 and 2. Our operational processing also moved to a combined GPS+Galileo solution with 5-minute tabular points in the SP3 orbit files to accommodate the high eccentricity Galileo satellites.

The network of stations processed by MIT in 2022 is shown in Figure 1. The figure shows the weighted root-mean-square (WRMS) scatter of the horizontal coordinates of

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)
mitWWWWn.snx.Z	Daily GPS coordinate and EOP SINEX file
After Week 2238. YYYY year, DDS DOY Start, DOE DOY End.	
Long File Name	Description
MIT0OPSFIN_YYYYDDS0000_07D_01D_SUM.SUM	Summary file
MIT0OPSFIN_YYYYDDS0000_07D_01D_ERP.ERP	Earth rotation parameters for 7-days
MIT0OPSFIN_YYYYDDS0000_01D_05M_ORB.SP3	Day 0 satellite orbits to
MIT0OPSFIN_YYYYDDE0000_01D_05M_ORB.SP3	Day 6 satellite orbits
MIT0OPSFIN_YYYYDDS0000_01D_05M_CLK.CLK	Day 0 satellite clocks to
MIT0OPSFIN_YYYYDDE0000_01D_05M_CLK.CLK	Day 6 satellite clocks
MIT0OPSFIN_YYYYDDS0000_01D_01D_SOL.SNX	Day 0 coordinate and EOP sinex file to
MIT0OPSFIN_YYYYDDE0000_01D_01D_SOL.SNX	Day 6 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)
After Week 22238. YYYY year, DDD DOY for each day of week.	
Long File Name	Description
MIT0OPSGLB_YYYYDDD0000_01D_01D_SUM.SUM	Summary file
MIT0OPSGLB_YYYYDDD0000_01D_01D_SOL.SNX	Combined SINEX file from all available analysis centers
MIT0OPSGLB_YYYYDDD0000_01D_01D_RES.SUM	File of the individual AC position estimates residuals to the combined solution for the week

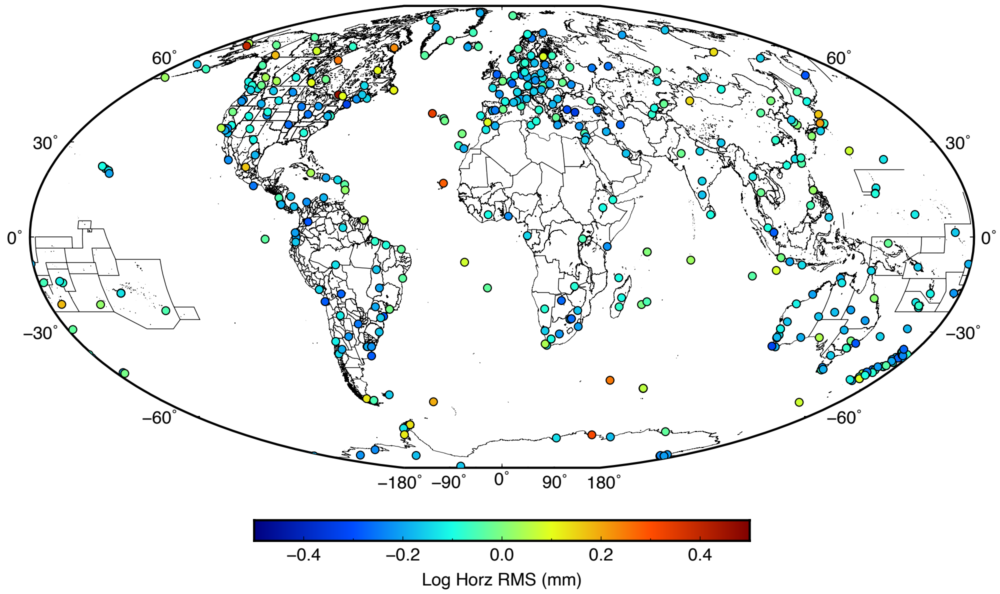

Figure 1: Log (base10) of the RMS scatter of the horizontal position estimates from the network of 481 stations processed more than 5 times by MIT in 2021. Each daily network has 350 station and the networks evolve with time depending on data availability and geometry. The cooler colors are all less 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 CZTG (4.82), URUM (4.90), KETG (4.93), KEPA (5.42), FLRS (5.49), USUD (6.04), AB11 (6.50), ALGO (6.74), (7.00), and TONG (9.36) mm. The sites with the largest height RMS scatters (mm) are NVSK (12.97), URUM (13.22), ANKR (13.64), TONG (13.76), FLIN (14.57), LAMA (15.19), NOT1 (16.53), FAIR (25.58), PARK (31.80), and ADIS (37.15) mm.

nearly all of the stations included in the MIT finals processing. Stations that were used just a few times (15 stations in all) are not included in the plot. Only linear trends were removed from the time series. Figure 2 shows histograms of the WRMS in all three topocentric coordinates after the removal of linear trends from the time series. The median WRMS scatters of the 481 sites, measured more than five times, included in the statistics are 1.5, 1.5 mm in North and East and 5.2 mm in height. No annual signals were removed. The station selection in 2022 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).

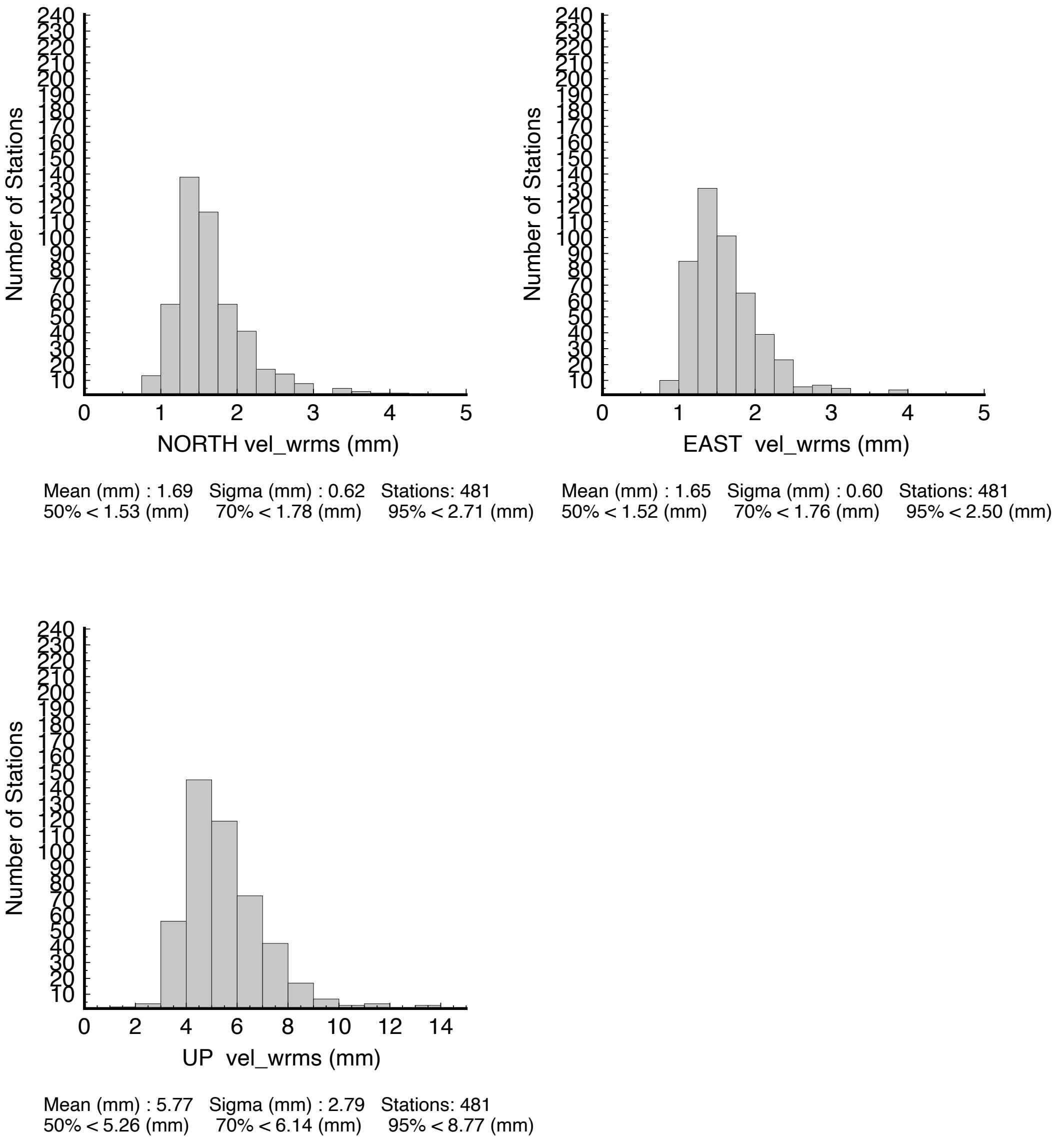

Figure 2: Histogram of the weighted root-mean-square (WRMS) scatter of daily position estimates of site used more than 5 times for 2022 after removal linear trends and elimination of gross outliers (5 times WRMS scatter). The median scatters are similar to last year with 1.5, 1.5 mm horizontal and 5.3 mm vertical.

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). After the switch to long file names, these combinations are call MIT0OPSGLB. 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 IGb14/IGS20 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 IGb14 (until week 2137) or IGS20 (after 2138). The transition to IGS20 does not show major changes although 2 ACs are not submitting IGS20 results and are not included in the combination. While the AC results look similar, there are differences in the mean of the RMS differences. Table 3 gives the mean RMS differences for each AC with respect IGb14/IGS20 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.

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	2.79	3.14	7.55	0.85	0.85	2.80
COD	2.88	3.23	7.98	1.40	1.32	3.95
EMR	2.80	3.04	7.31	1.04	1.02	3.25
ESA	2.61	2.95	8.52	1.03	0.90	3.74
GFZ	2.62	2.82	8.17	1.05	1.10	3.31
GRG	2.33	3.01	6.96	1.20	0.99	3.64
JPL	2.91	3.50	7.93	1.07	1.25	3.65
NGS	2.97	3.13	8.35	1.34	1.55	3.83
SIO	3.12	3.46	8.85	1.74	1.77	5.16

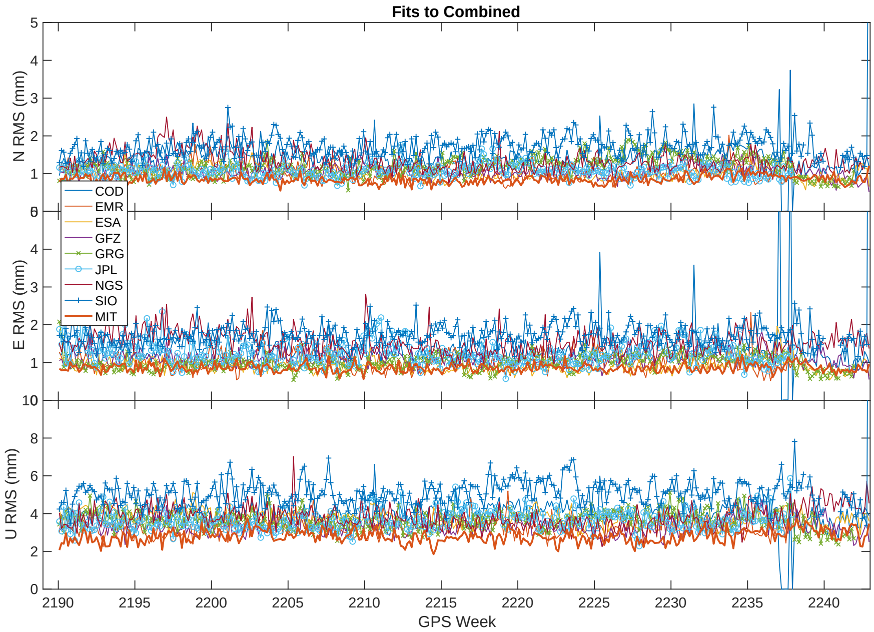

Figure 3: RMS scatters of the fits of the different IGS ACs to the MIG/MIT0OPSGLB combined solution for 2022.

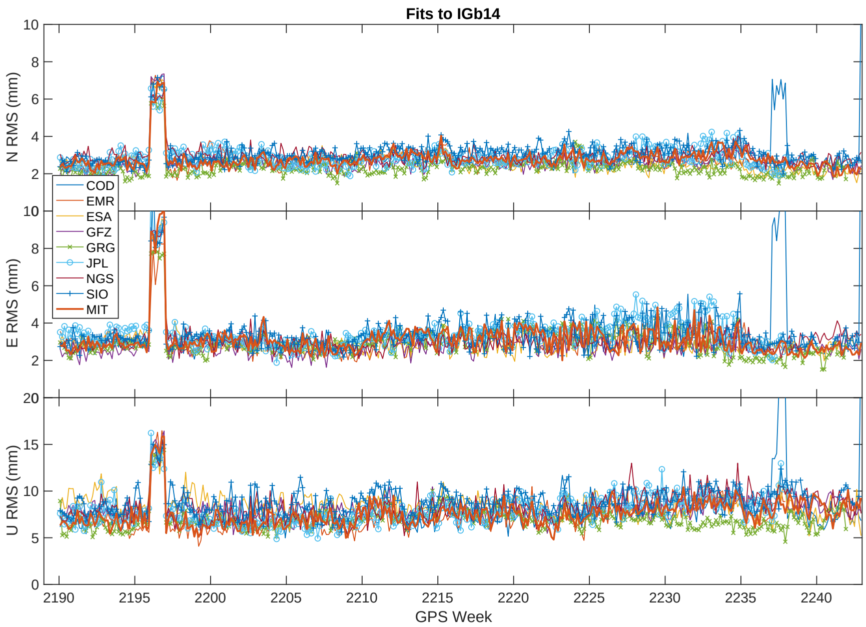

Figure 4: RMS scatters of the fits to IGb14 prior to week 2238 and IGS20 after that week. The series from JPL and EMR end at week 2238. The increased scatter in week 2196 is due to a processing error and reflect the results submitted to CDDIS at that time.

4 Completion of Third Reprocessing Campaign

MIT submitted the 2021-2022/11/27 Repro3 results to complete the reprocessing up to the start of the operational IGS processing. Only the combined GPS-Galileo results were submitted with the FIN label.

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USNO Analysis Center Technical Report 2022

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1 Introduction

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

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

The USNO AC is hosted in the GPS Analysis Division (GPSAD) of the USNO Earth Orientation Department. USNO AC activities, chairing the IGS TWG, and serving on the IGS Governing Board are overseen by Dr. Sharyl Byram who also oversees production of the IGS Final Troposphere Estimates. All GPSAD members, including Mr. Jeffrey Crefton, Dr. Elizabeth Lovegrove, 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 UT1-UTC measurements. The IERS (International Earth Rotation and Reference Systems Service) Rapid Combination/Prediction Service uses UTGPS to in their combined daily processing of UT1-UTC. Mr. Crefton oversees UTGPS.

More information about USNO Rapid, Ultra-rapid, Troposphere, and UTGPS products can be found at the USNO website: https://maia.usno.navy.mil/products/gps-analysis. The IGS Final Troposphere Estimates can also be downloaded at https://cddis.nasa.gov/archive/gnss/products/troposphere/zpd/.

2 Product Performance, 2022

Figures 1-4 show the 2022 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 29 mm with respect to (wrt) the IGS rapid combined orbits. The USNO Ultra-rapid orbits had median WRMSs of 26 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 224 ps and 929 ps RMSs wrt IGS combined rapid clocks.

USNO rapid polar motion estimates had (x, y) 25 and 25 microarcsec RMS differences wrt IGS rapid combined values, respectively. USNO Ultra-rapid polar motion estimates differed (RMS of x, y) from IGS rapid combined values by 482 and 272 microarcsec for the 24-h post-processed segment, respectively. The USNO Ultra-rapid 24-h predict-segment values differed (RMS of x, y) from the IGS rapid combined values by 552 and 362 microarcsec, respectively.

All USNO AC official products were generated with the Bernese GNSS Software, Version 5.2 in 2022 and were produced using the IGS20 reference frame starting GPS week 2238.

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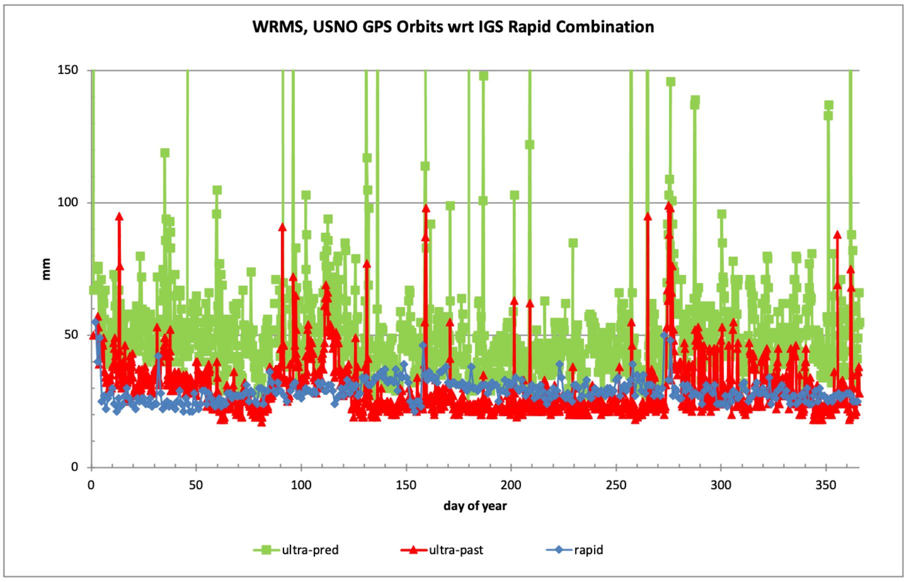

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2022. "Ultra-past" refers to 24-hour post-processed section of USNO Ultra-rapid orbits. "Ultra-pred" refers to first six hours of Ultra-rapid orbit prediction.

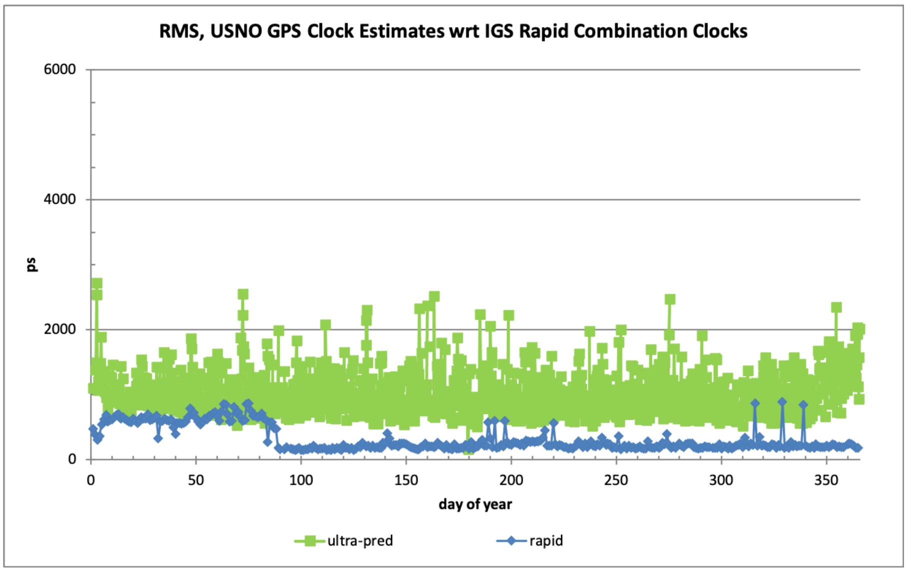

Figure 2: RMS of USNO GPS Rapid clock estimates and Ultra-rapid clock predictions with respect to IGS Rapid Combination, 2022.

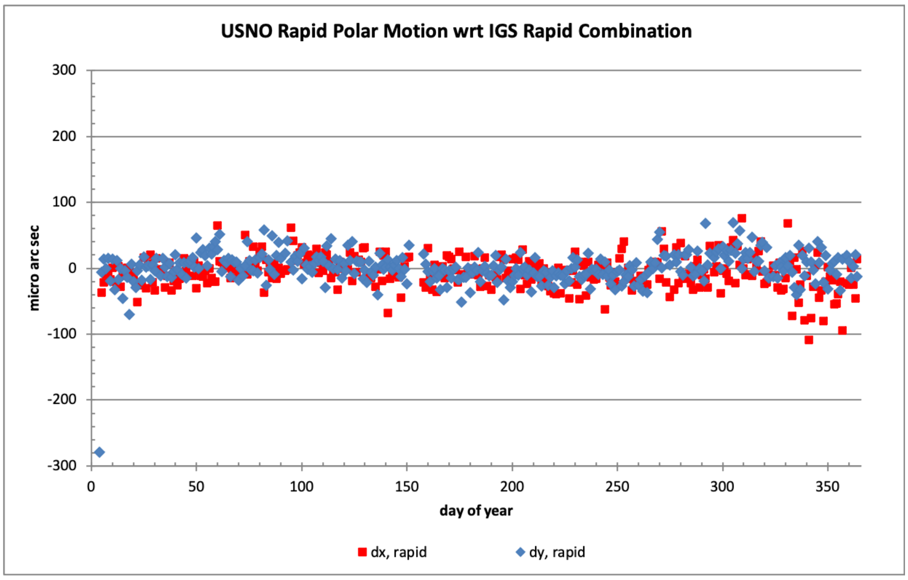

Figure 3: USNO Rapid Polar Motion estimates differenced with IGS Rapid Combination values, 2022.

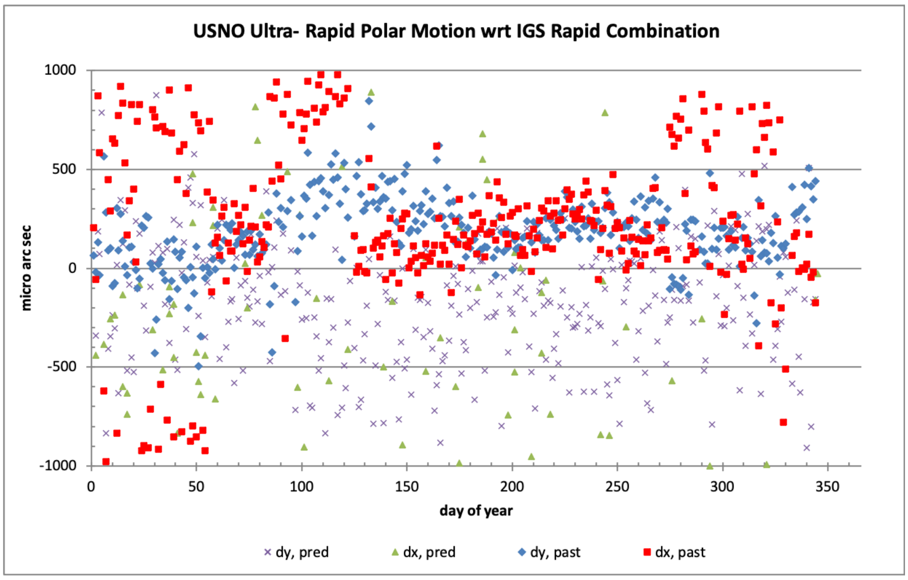

Figure 4: USNO Ultra-rapid Polar Motion estimates differenced IGS Rapid Combination values, 2022. “pred” denotes predicted and “past” denotes post processed.

Table 1: Precision of USNO Rapid and Ultra-Rapid Products, 2020. All statistics computed with respect to IGS Combined Rapid Products.

USNO GPS satellite orbits				USNO GPS–based polar motion estimates							USNO GPS–based clock estimates	
Statistic: median weighted RMS difference units: mm				Statistic: RMS difference units: 10^{-6} arc sec							Statistic: median RMS difference units: ps	
dates	rapid	ultra–rapid		rapid		ultra–rapid					rapid	ultra–rapid
		past 24 h	6-h predict			past 24 4		24-h predict			past 24 h	6-h predict
				x	y	x	y	x	y			
1/1/2022 – 12/31/2022	29	26	47	25	25	482	272	552	362		224	929

Wuhan University Analysis Center Technical Report 2022

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1 Introduction

The IGS Analysis Center of Wuhan University (WHU) has contributed to the International GNSS Service (IGS) since 2012 with a regular determination of the precise ultra–rapid products, rapid products and MGEX 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).

There are some important development steps in the year 2022, WHU products updated to Long Product Filenames and switch to IGS20/igs20.atx, and the processing scheme for multi-GNSS analyses is constantly subject to updates and improvements. Further, WHU organized the 4th stop of the IGS roving seminar, which focused on the latest progress of the BDS constellation.

2 WHU Analysis Products

The products provided by WHU are summarized in Table 1.

3 Multi-GNSS data processing

In 2022, the hourly updated ultra-rapid as well as final multi-GNSS product WUM was continually provided. For the final products, all five constellations were included, whereas only four global constellations were analyzed in the ultra-rapid solution. The WUM product are available at IGN data center (ftp://igs.ensg.ign.fr/pub/igs/products/mgex) as well as WHU data center (ftp://igs.gnsswhu.cn/pub/gps/products/mgex).

Table 1: List of products provided by WHU.

WHU rapid GNSS products	
WHU00PSRAP_YYYYDDDHH00_01D_15M_ORB.SP3	Orbits for GPS/GLONASS/Galileo satellites
WHU00PSRAP_YYYYDDDHH00_01D_05M_CLK.CLK	5-min clocks for stations and GPS/GLONASS/Galileo satellites
WHU00PSRAP_YYYYDDDHH00_01D_01D_ERP.ERP	ERPs
WHU ultra-rapid GNSS products	
WHU00PSULT_YYYYDDDHH00_02D_15M_ORB.SP3	Orbits for GPS/GLONASS/Galileo satellites, provided to IGS every 6 hours
WHU00PSULT_YYYYDDDHH00_02D_01D_ERP.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
WUM0MGXRAP_YYYYDDD0000_01D_01D_ABS.BIA	Rapid OSB with 1-d multi-GNSS observations
IONO00WHU0	Real time GIM with 5-min GPS observations

The processing scheme for multi-GNSS analyses is constantly subject to updates and improvements. There are some important development steps in the year 2022 for the final products. The first one is that the ITRF 2020 frame has been adopted since GPS week 2238. At the same time, the recommendation for the third reprocess of IGS have been implemented, including the long-term mean pole, high-frequency EOP, ocean tidal loading corrections for station deformation and gravitational effect on satellite orbits based on FES 2014b, and more. Besides the model updates, the undifferenced ambiguity resolution was implemented for orbit and clock determination instead of the double-difference ambiguity resolution used previously. The following figure show the workflow. Generally, the processing is accomplished in two analysis steps. First, the orbit and clock are estimated based on zero-difference measurements with the double-difference ambiguity resolution. Subsequently, the undifferenced ambiguities are fixed based on the daily wide-lane and 15 min narrow-lane FCB. Finally, the satellite orbit and clock corrections are re-estimated based on a zero-difference analysis including undifferenced ambiguity resolution for GPS, Galileo, and BDS. As the improvement of successful ambiguity fixing rate, the orbit quality has been improved. All of the updates have been active since GPS week 2238.

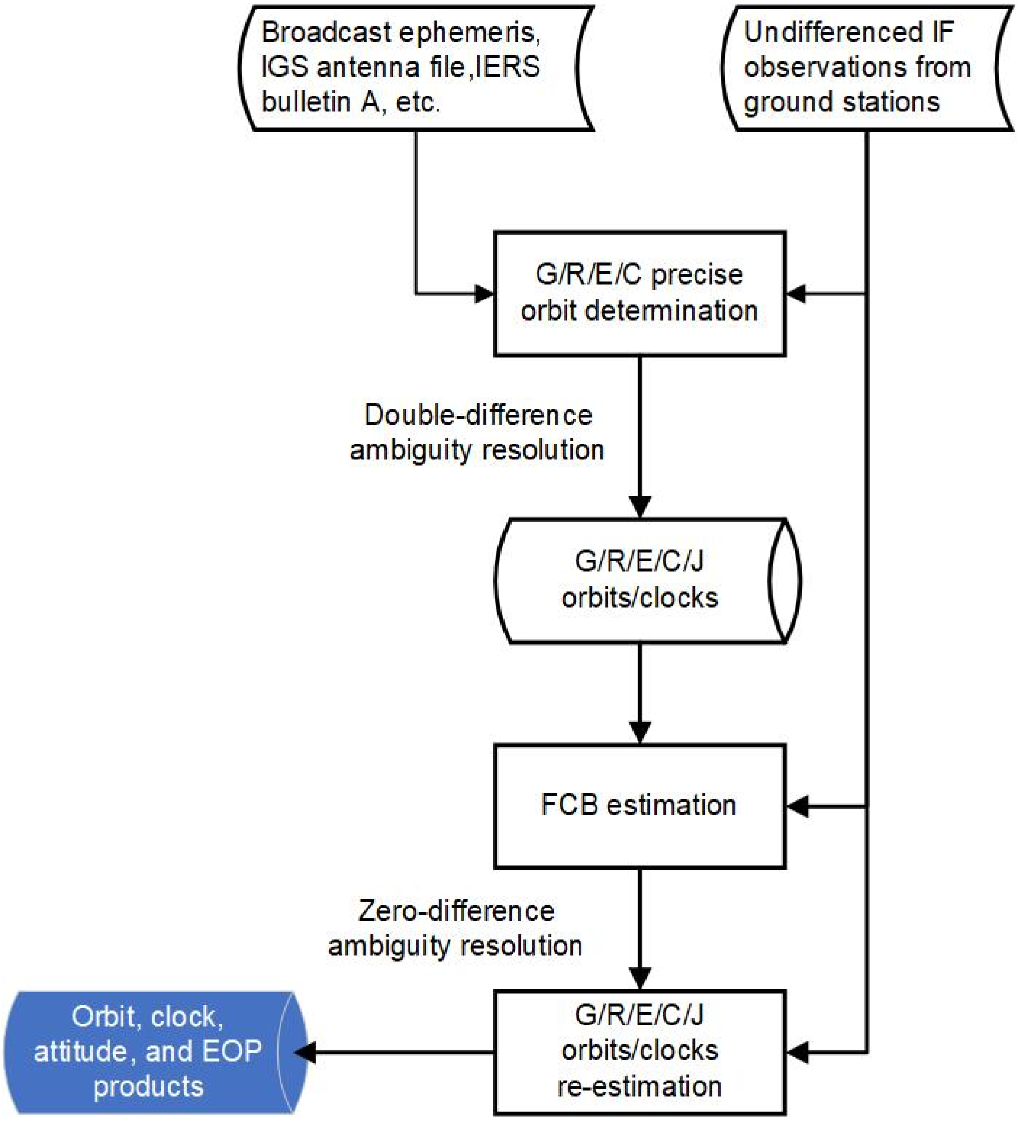

Figure 1: The workflow for generation of WUM final products since GPS week 2238.

4 IGS Repro3 activities

In the IGS Repro3 Campaign, WHU has submitted GPS/GLONASS solutions spanning from 2008 to 2019, including orbits, clocks, and SINEX. Besides, cooperating with IGS ACC, WHU has computed the clock/bias combination products starting from 1994. The combined products include GPS, GLONASS, and Galileo systems, uploaded to the IGS repository together with the associated consistency statistics.

5 The 4th stop of the IGS roving seminar

Researchers in WHU gave four talks at IGS Workshop 2022, with topics on iGMAS orbit combination, clock/bias combination, antenna phase center impact on phase biases, and PPP validation of repro3. Moreover, PPP-AR/Bias session was chaired by Prof. Jianghui Geng, who is a member of WHU AC.

Later, WHU organized the 4th stop of the IGS roving seminar, which focused on the latest progress of the BDS constellation. Prof. Jianghui Geng and Prof. Qile Zhao take the main responsibilities for the organization, inviting global scientists on BDS featured services, BDS data usage, and performance of BDS data processing. The seminar was held online successfully, chaired by Prof. Jianghui Geng and Dr. Leo Martire.

Figure 2: Organized the 4th stop of the IGS roving seminar.

The new IGS Working Group, PPP-AR Working Group was led by Prof. Jianghui Geng in 2022. He found the non-negligible impact of PCO on the interoperability of products from different ACs. All ACs have agreed to add a new keyword "APC_MODEL" into Bias-SINEX after a discussion presided over by Prof. Geng.

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EUREF Permanent Network Regional Network Associate Analysis Centre Technical Report 2022

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1 Introduction

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

This paper provides an overview of the main changes in the EPN during the year 2022.

2 EPN Central Bureau

The EPN Central Bureau (CB, managed by the Royal Observatory of Belgium, Bruyninx et al., 2019) continued to monitor operationally EPN station performance in terms of data

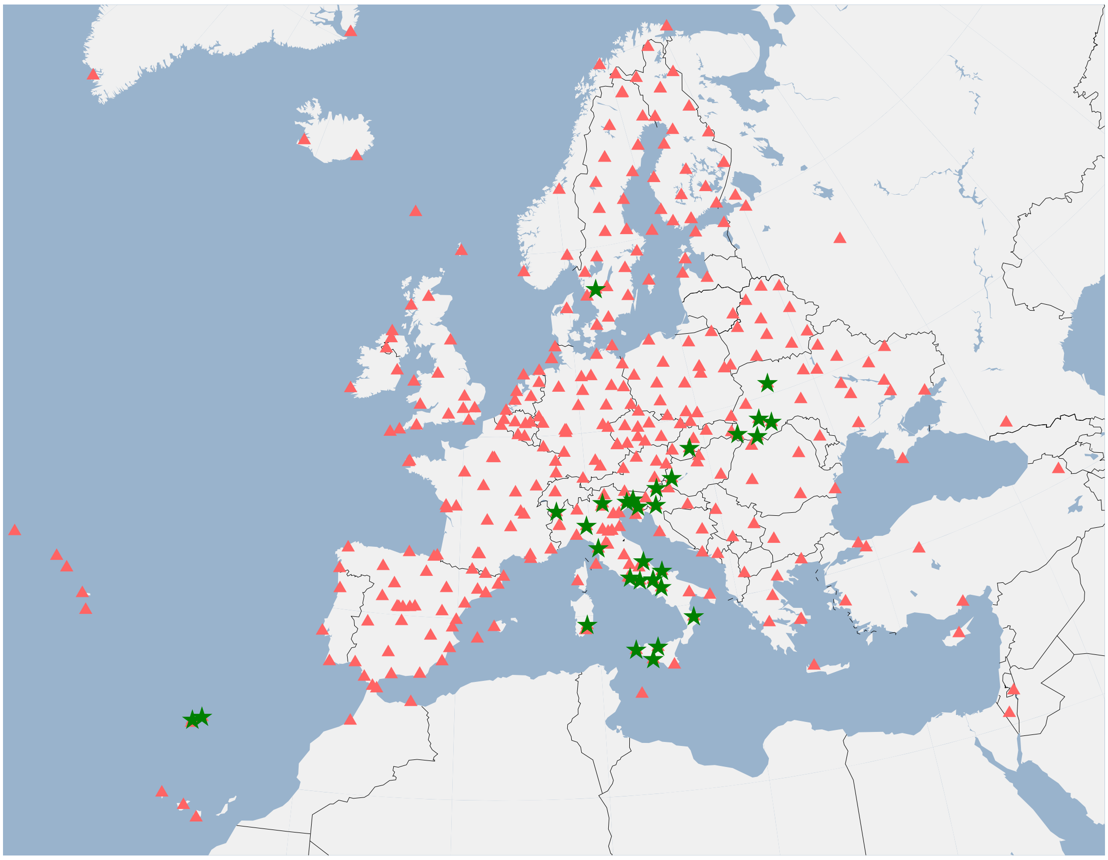

Figure 1: New GNSS stations (in green) integrated in the EPN in 2022.

availability, correctness of metadata, and data quality. In 2022, the EPN Central Bureau (CB) added 32 new stations to the EPN (indicated in green in Figure 1).

The effort to move towards FAIR-aligned GNSS data continues with 94% of the EPN stations that have assigned a data license to their RINEX data in M^{3}G (Fabian et al., 2021).

In order to comply with EU General Data Protection Regulation (GDPR), from Oct. 24 2022 on, all EPN site logs and GeodesyML files that can be retrieved from M3G (and EPN CB) have been stripped from any personal contact information coming from persons who have not given M3G the explicit permission to publish their personal information. Moreover, from that date on, M3G only allows to upload site logs that use non-personal contact information in the "Prepared by" field (section 0) and the "Primary contact" of the "On-Site, Point of Contact Agency Information"/"Responsible Agency" fields (sections 11 and 12).

The EPN CB released version 2.0 of the ETRF/ITRF Coordinate Transformation Tool

(ECTT) available from https://epncb.oma.be/_productsservices/coord_trans/. It now allows transforming coordinates from and to ITRF2020.

Encouraged by Resolution No 2 of the 2019 EUREF symposium in Tallinn, more than 67% 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 (https://epncb.oma.be/ftp/obs/) managed by the EPN CB.

In March 2022, the EUREF Governing Board also updated the "Guidelines for EPN stations and Operational Centres" making the submission of RINEX 3 data mandatory for EPN stations and encouraging the submission of high-rate RINEX data files.

3 Data Products

3.1 Availability

Likewise the EPN data, the EPN data products should be available from all EPN data centers. First steps to improve the flow were made early this year, as announced in last year's report. End of March 2022 the EPN data center at BKG was affected by an outage, which lasted over several weeks. It turned out that the flow scheme for data, as described in the "Guidelines for EPN Stations and Operational Centres", as well as for data products was not fully redundantly established. Some station and products provider did not upload the data/products in parallel to both EPN DCs. Moreover, some station provider of IGS stations used BKG as single source for uploading their RINEX data. Station providers as well as EPN Analysis Centres and Combination Coordinators were contacted and encouraged to strictly upload their data and data products to both EPN Data Centres.

3.2 Positions

The EPN Analysis Centers (ACs) operationally process GNSS observations collected at EPN stations. In 2022, all 16 ACs (Table 1) were providing final daily coordinate solutions of their subnetworks. Thirteen ACs were providing also rapid daily solutions, and four ACs were providing near real-time 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 2022, all 32 new stations in the EPN have been included in AC and combined coordinate solutions.

A new EPN analysis centre was established at the GeoForschungsZentrum (GFZ), Potsdam, Germany. GFZ AC will use the EPOS.P8 software, developed at the GFZ, to process GNSS data. The GFZ AC will process GNSS data from 114 EPN GNSS stations with the

Table 1: EPN Analysis Centres characteristics: provided solutions (W – final weekly, D – final daily, R – rapid daily, N – near real-time), 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	WDRN	98(20/0)	GipsyX 1.6	GRE
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	133(22/1)	BSW 5.2	GRE
BEV	Federal Office of Metrology and Surveying, Austria	WD	177(46/1)	BSW 5.2	GRE
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRN	153(16/3)	BSW 5.2	GRE
COE	Center for Orbit Determination in Europe, Switzerland	WD	39(0/1)	BSW 5.3	GR
IGE	Instituto Geografico Nacional, Spain	WDR	99(9/1)	BSW 5.2	GRE
IGN	Institut Géographique National de L'information Geographique et Forestiére, France	WDR	62(0/1)	BSW 5.2	GR
LPT	Federal Office of Topography swisstopo, Switzerland	WDRN	59(0/2)	BSW 5.3	GRE
MUT	Military University of Technology, Poland	WDR	159(13/2)	GG 10.71	GE
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WDR	104(3/3)	BSW 5.2	GRE
RGA	Republic Geodetic Authority, Serbia	WD	64(0/9)	BSW 5.2	GRE
ROB	Royal Observatory of Belgium, Belgium	DR	113(4/2)	BSW 5.2	GRE
SGO	Lechner Knowledge Center, Hungary	WDR	64(17/1)	BSW 5.2	GRE
SUT	Slovak University of Technology, Slovakia	WDRN	81(23/0)	BSW 5.2	GRE
UPA	University of Padova, Italy	WDR	101(31/1)	BSW 5.2	GRE
WUT	Warsaw University of Technology, Poland	WDR	153(17/3)	BSW 5.2	GRE

final solutions expected from GPS week 2238 onwards.

In 2022, the Federal Office of Metrology and Surveying (BEV), Austria, became the new EPN product centre (in addition to BKG). Since March 2022, all EPN analysis centers and combined products (final, rapid and near real-time) can be downloaded from both BEV and BKG servers.

The activities of the ACC and the EPN ACs included also preparations for the switch to the IGS20/igs20.atx reference frame (published in July 2022) and IGS repro3 standards in operational EPN analysis. The IGS switched to the new reference frame for the generation of its operational products on November 27, 2022 (with the start of GPS week 2238). To discuss the details regarding the switch to the IGS20 in EPN analysis, the EPN Analysis Centres Workshop was organized on November 3, 2022. Presentations and minutes from the workshop are available at the EPN CB webpage at: https://epncb.oma.be/_newseventslinks/workshops/EPNLACWS_2022/. Changes in the EPN analysis after the switch to IGS20 will include, e.g.: the usage of consistent three-system IGS AC final products (e.g., CODE or GFZ), the usage of the new EPN antenna model (based almost exclusively on the IGS type-mean model with some additional calibrations for antenna-radome pairs not included in the IGS model), the correction of antennas not oriented to true north, the switch to FES2014b ocean tide model, the usage of the VMF3 for troposphere modelling, the new long filenames for the EPN products. It was also recommended that ACs upgrade the GNSS software packages they use to the recently released versions (Bernese GNSS Software version 5.4, GipsyX-2.1) for the complete consistency with the new standards. First AC (LPT) final solutions according to the IGS20 standards were provided in December 2022. It is expected that all ACs will be ready to start providing their solutions in IGS20 by the end of February 2023.

3.3 Troposphere

Besides station coordinates, the 16 EPN ACs operationally submit Zenith Total Delay (ZTD) parameters and horizontal gradients in the SINEX_TRO format. The ZTDs and horizontal gradients are delivered with a sampling rate of one hour, on a weekly basis, but in daily files. The status of the EPN operational tropospheric product has been reported to the community during the EPN Analysis Centres Workshop. In 2022, the 32 new EPN stations were successfully included in the tropospheric combined solution. ZTD combined estimates are available, on average, for 368 EPN stations (compared to the 355 in 2021). For each combined EPN station Integrated Water Vapour (IWV) is provided along with ZTD. Tropospheric products are disseminated in SINEX_TRO v2.0 format and are available in the EUREF product directory at the BKG and BEV data centre.

https://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.

The EPN multi-year tropospheric solution has been released twice: T2195 (in April 2022) and T2227 (in November 2022). T2227 covers the period 1996-09/2022. For each EPN station, ZTD time series, ZTD monthly mean (period 1996-2021) and inter-technique comparison with radiosonde data (if collocated) plots are available at the EPN CB https://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 Bruyninx, , 2019). The Reference Frame Coordinator (RFC) computes these EPN multi-year solutions with the CATREF software (Altamimi et al., 2007). In 2022, four solutions expressed in IGb14 have been released: C2190 (in April 2022, Legrand , 2022b) and C2205 (in July 2022, Legrand , 2022c), C2220 (in October 2022, Legrand , 2022d).

The latest 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 `https://epncb.oma.be/ftp/product/cumulative/latest/`. Archives of the previous EPN multi-year product can be found at `https://epncb.oma.be/ftp/product/cumulative/`. 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. 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 new IGS20 solution contains 74 EPN stations. In comparison, the IGb14 contains 61 EPN stations. In total, we have 21 new stations compared to IGb14 and 8 stations have been removed. This is a nice improvement especially when considering the repartition of the EPN stations in the IGS20.

4 Working Groups

4.1 EPN Densification

The EPN Densification (EPND) is a collaborative effort of 30 European GNSS Analysis Centres providing series of daily or weekly station position estimates of the dense national and regional GNSS networks in SINEX format (Kenyeres et al., 2019). These are combined into one homogenized set of weekly SINEX series, then adjusted with the CATREF software to derive a regional station position and velocity product.

The most recent combination (D2200) covers the period from October 2008 to March 2022 (GPS week 1500-2200) using inputs expressed in IGS14. 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 removed. 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). The EPND velocities are used as part of the EPOS GNSS products and for the generation of the European Velocity Model (Steffen et al., 2022). EPND is extended with the European part of the NGL (Nevada Geodetic Laboratory) global processing results in order to generate a unique reference velocity model for referencing the EGMS (European Ground Motion Service) InSAR ground motion model.

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, about 7900 individual station velocities are available for Europe.

In 2022, several additional data sets were included, such as a dense velocity data set from INGV consisting of more than 2500 sites. As shown in Figure 2, this big amount of stations did not increase the total number of stations, even not the number of stations, which are already observed by two analysis centres. Additional solutions mainly improve the reliability of the velocity product.

Also, a campaign data set from Saudi Arabia or the velocities of ITRF2020 were included. The website of the project gives feedback to the providers and was moved from http to https: `https://pnac.swisstopo.admin.ch/divers/dens_vel/index.html`.

In parallel, an OGC working group met almost every 2 weeks in 2022 to work on standardizations on a deformation model which will be derived from this data set.

In the framework of an interdisciplinary project a student at ETH Zurich investigated several possibilities to fit a deformation model through the data using classical kriging methods, but also using machine learning algorithms.

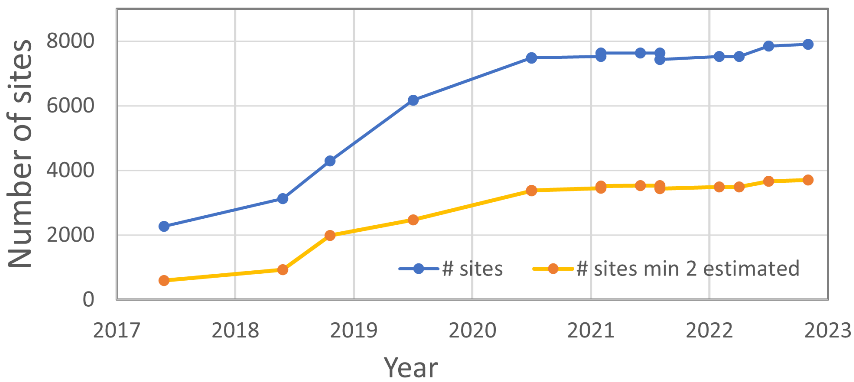

Figure 2: Number of sites included in database of EG on Dense Velocities.

4.3 Multi-GNSS

A discussion on the implementation of the EPN Repro3 campaign has been initiated within the EPN Analysis. 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 change of the reference frame from IGb14 to IGS20 end of 2022 will keep the ACs busy till beginning 2023 because also various model changes are necessary. Some of the changes require updating to the newest analysis software tools. Analysis Centers using the Bernese software are asked to switch to the version 5.4, which was released in autumn 2022.

Almost all EPN stations deliver its data in RINEX 3, only few submissions of RINEX 2. In 2022, the RINEX 4 format version was confirmed by RTCM. The biggest changes occur for the RINEX navigation files. File naming is identical to RINEX 3 and the content of the observation files includes some minor changes. Therefore, the version change from 3 to 4 is not comparable with the version change from 2 to 3. Several vendors already implemented the new standard in their firmware versions. It is expected that in spring 2023 several EPN stations may provide their GNSS data in RINEX 4 and make them also available at the various data centers.

4.4 EPN reprocessing

Starting in the last quarter of 2022, the EPN Reprocessing Working Group has been preparing the third reprocessing campaign of the entire EPN. Currently, data analysis strategies are being fine-tuned to ensure the best possible agreement between the IGS reprocessed and the upcoming EPN operational solutions. These tunings include the choice of antenna corrections models, the use of tropospheric mapping function, and many other issues. Compared to previous EPN reprocessing campaigns, this time we will dispense the use of individual calibrations and only use type mean calibration for ground antennas. Since only 12 of the total 17 ACs can participate in EPN reprocessing, the subnetworks had to be reordered to meet the important criterion that a single GNSS station is present in at least three subnetworks of the participating ACs. It is expected that the reprocessing of the EPN will start early 2023.

5 Stream and Product Dissemination

End of 2022, 219 EPN stations (i.e., mount-points) provided real-time data (198 end of 2021) which corresponds to 55% (same percentage as in 2021) of the EPN stations. Almost all varieties of RTCM 3.x messages are available from the EPN broadcasters, plus three 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 MSM4 messages (message types 1074 etc.) remains at 8 stations, MSM5 (message types 1075 etc.) decreased from 73 to 66 whereas the MSM7 (message types 1077 etc.) increased significantly from 97 to 127 data streams. Hence, the stations providing the old "legacy" messages 1004 (GPS) and 1012 (GLONASS) further reduced from 26 to 20. All streams are coming (directly) from the receiver.

The visibility, in particular availability and latency, of the real-time data streams and the monitoring of the three EPN broadcasters is maintained at the EPN CB (https://epncb.oma.be/_networkdata/data_access/real_time/status.php) as well as the meta-data monitoring (https://epncb.oma.be/_networkdata/data_access/real_time/metadata_monitoring.php). More than 96% of the real-time data is available at all three EPN casters at ASI, BKG and ROB.

Concerning real-time products, the EPN continues to follow the activities in the IGS and the standardization efforts in RTCM and in the IGS. The long product and broadcast ephemerides mount-point names have been completely introduced within the IGS, and consequently also the EUREF products were adapted: SSRA02IGS0_EUREF and SSRA03IGS0_EUREF for the RTCM SSR representation and SSRA02IGS1_EUREF and SSRA03IGS1_EUREF for the slightly different IGS SSR representation.

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SIRGAS Regional Network Associate Analysis Centre Technical Report 2022

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1 Introduction

SIRGAS is the Geodetic Reference System for the Americas. The current objectives of SIRGAS include the establishment and maintenance of a geometric reference frame as a regional densification of the ITRF and a unified physical reference frame for physical height determination, geoid modelling and gravimetry (see https://sirgas.ipgh.org/ for more details). This report focuses on the geometric reference frame component. The SIRGAS reference frame (Figure 1) currently consists of 480 operational continuously operating GNSS stations (another 160 stations are decommissioned). 104 operational (and 34 decommissioned) stations belong to the International GNSS Service (IGS) global network (Johnston et al., 2017), and 376 operational (and 130 decommissioned) stations belong to the Latin American national reference frames. Approximately 40 of the 105 operational IGS stations are located in North America and were added to the SIRGAS routine processing in 2021 to provide support (i.e. common stations) for a future combination of the North American national reference frames with SIRGAS. 86% of the SIRGAS stations track GLONASS, 31% Galileo and 20% Beidou.

The operational performance of the SIRGAS network is based on the contribution of more than 50 organisations that 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 consists of

- A core network (SIRGAS-C), the primary densification of ITRF in Latin America, with a good continental coverage and stable site locations to ensure high long-term stability of the reference frame.

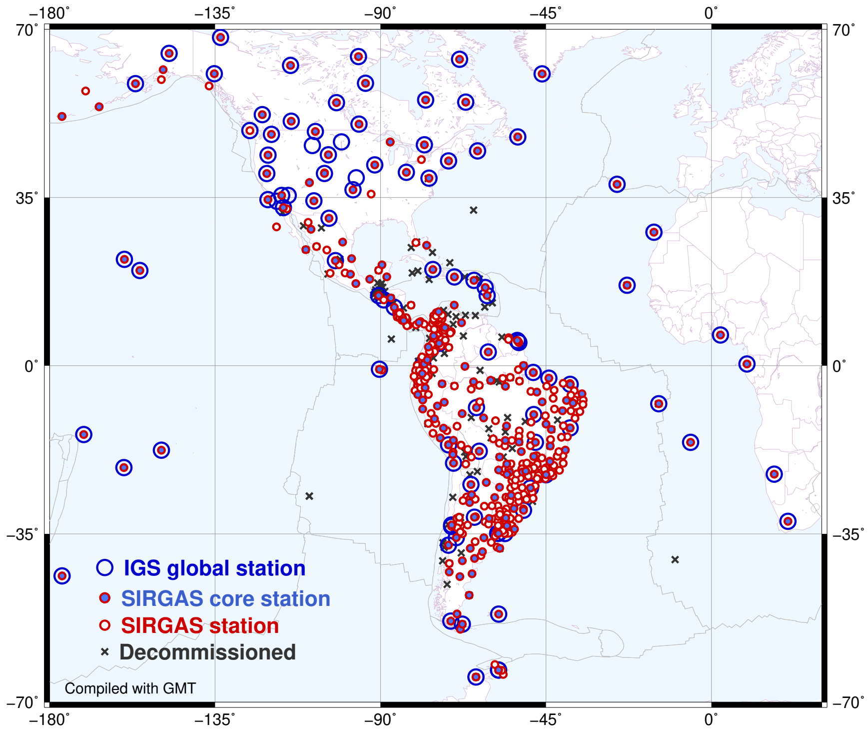

Figure 1: SIRGAS reference network (as of December 2022).

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

The SIRGAS reference network is processed on a weekly basis to generate instantaneous weekly station positions aligned with the ITRF and multi-year (cumulative) reference frame solutions (Bruini et al., 2012a; Cioce et al., 2020; Tarrío et al., 2021; Costa et al., 2022; Sánchez et al., 2022). The instantaneous weekly positions are particularly useful when strong earthquakes cause co-seismic displacements or strong relaxation motions at the SIRGAS stations, making it impossible to use the 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 to realise and maintain the SIRGAS reference frame between two releases of the ITRF. While a new ITRF release is published more or less every five years, the multi-year solutions of the SIRGAS reference are updated every one or two years (see e.g., Sánchez and Drewes, 2016, 2020; Sánchez and Seitz, 2011; Sánchez et al., 2016, 2022).

2 Operational analysis of the SIRGAS reference frame

Eleven SIRGAS analysis centres (Table 1) process GPS and GLONASS observations to produce daily and weekly position solutions for a given set of SIRGAS stations. Three analysis centres use GAMIT/GLOBK (Herring et al., 2015, 2018); the others use the Bernese GNSS Software, version 5.2 (Dach et al., 2015). Currently, most of these analysis centres are adapting their analysis procedures to the version 5.4 of the Bernese GNSS Software (Dach et al., 2022). The SIRGAS-C network is analysed by DGFI-TUM as the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS, Sánchez et al., 2022). The SIRGAS-N networks are computed by the SIRGAS Local Processing Centres, which operate under the responsibility of national Latin American organisations. The SIRGAS analysis centres follow common standards for the computation of weekly loosely constrained solutions. These standards are 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). An exception is that in the SIRGAS individual solutions the satellite orbits and clocks as well as the Earth orientation parameters are fixed to the final weekly IGS values (SIRGAS does not compute these parameters), and the positions for all stations are constrained to ±1 m to produce loosely constrained position solutions in SINEX format.

The individual solutions are combined by the SIRGAS combination centres currently operated by DGFI-TUM (Sánchez et al., 2012, 2022) and IBGE (Costa et al., 2012). For the combination, the constraints contained in the individual solutions are removed and the sub-networks are individually aligned to the IGS reference frame using a set of selected reference stations. The 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 individual normal equations. Scaling factors for the relative weighting of the individual solutions are derived from the variances obtained after the alignment of the individual sub-networks to the IGS reference frame. The datum realisation in the final SIRGAS combination is achieved through the IGS weekly coordinates of the IGS reference stations. In addition to the loosely constrained position solutions, the SIRGAS processing centres also provide station tropospheric Zenith Path Delays (ZPD) with an hourly sampling rate. The SIRGAS analysis centre for the Neutral Atmosphere (CIMA) combines the individual ZPD estimates to generate consistent troposphere solutions over the entire SIRGAS region and to provide reliable time series of troposphere parameters, see Mackern et al. (2020). Figure 2 summarises the data flow within the SIRGAS routine analysis.

Table 1: SIRGAS analysis centres

ID	Agency/University	Software	Operative From	to
DGF	DGFI-TUM: Deutsches Geodätisches Forschungsinstitut at the Technical University of Munich, Germany (Sánchez and Seitz, 2011; Sánchez et al., 2012)	BSW52[2]	1996-06-30	present
CHL	IGM-CL: Instituto Geográfico Militar, Chile (Rozas et al., 2019)	BSW52[2]	2013-01-01	present
CIM	CIMA: Centro de Ingeniería in Mendoza, Argentina[1] (Mackern et al., 2012)	BSW52[2]	2008-08-31	2012-12-31
CRI	IGN-CR: Instituto Georáfico Nacional, Costa Rica (Álvarez et al., 2022)	BSW52[2]	2023-01-01	present
ECU	IGM-EC: Instituto Geográfico Militar, Ecuador (Cisneros et al., 2013)	BSW52[2]	2010-01-01	present
GNA	IGN-AR: Instituto Geográfico Nacional, Argentina (Gómez et al., 2018)	GG[3]	2011-01-01	present
IBG	IBGE: Instituto Brasileiro de Geografia e Estatistica, Brazil (Costa et al., 2018)	BSW52[2]	2008-08-31	present
IGA	IGAC: Instituto Geográfico Agustín Codazzi, Colombia (IGAC , 2021)	BSW52[2]	2008-08-31	present
INE	INEGI: Instituto Nacional de Estadística y Geografía, Mexico (Gasca, 2018)	GG[3]	2011-01-01	present
LUZ	CPAGS-LUZ: Centro de Procesamiento y Análisis GNSS de la Universidad del Zulia, Venezuela (Cioce et al., 2017)	BSW52[2]	2010-01-01	2019-02-09
PER	IGN-PE: Instituto Geográfico Nacional, Peru (Rodríguez Rocca, 2021)	GG[3]	2022-01-01	present
UNA	CNPDG-UNA: Centro Nacional de Procesamiento de Datos GNSS, Universidad Nacional, Costa Rica (Moya Zamora et al., 2018)	BSW52[2]	2014-01-01	2018-12-31
URY	IGM-UY: Instituto Geográfico Militar, Uruguay (Caubarrère , 2018)	BSW52[2]	2010-01-01	present
USC	USCH: Centro de Procesamiento y Análisis Geodésico, Universidad de Santiago de Chile (Tarrío et al., 2020)	BSW52[2]	2019-09-15	present

[1] CIMA acts as the SIRGAS Analysis Centre for the Neutral Atmosphere since Nov. 2019 (Mackern et al., 2020)
[2] BSW52: Bernese GNSS Software, version 5.2 (Dach et al., 2015)
[3] GG: GAMIT/GLOBK: GNSS at MIT/Global Kalman filter (Herring et al., 2015, 2018)

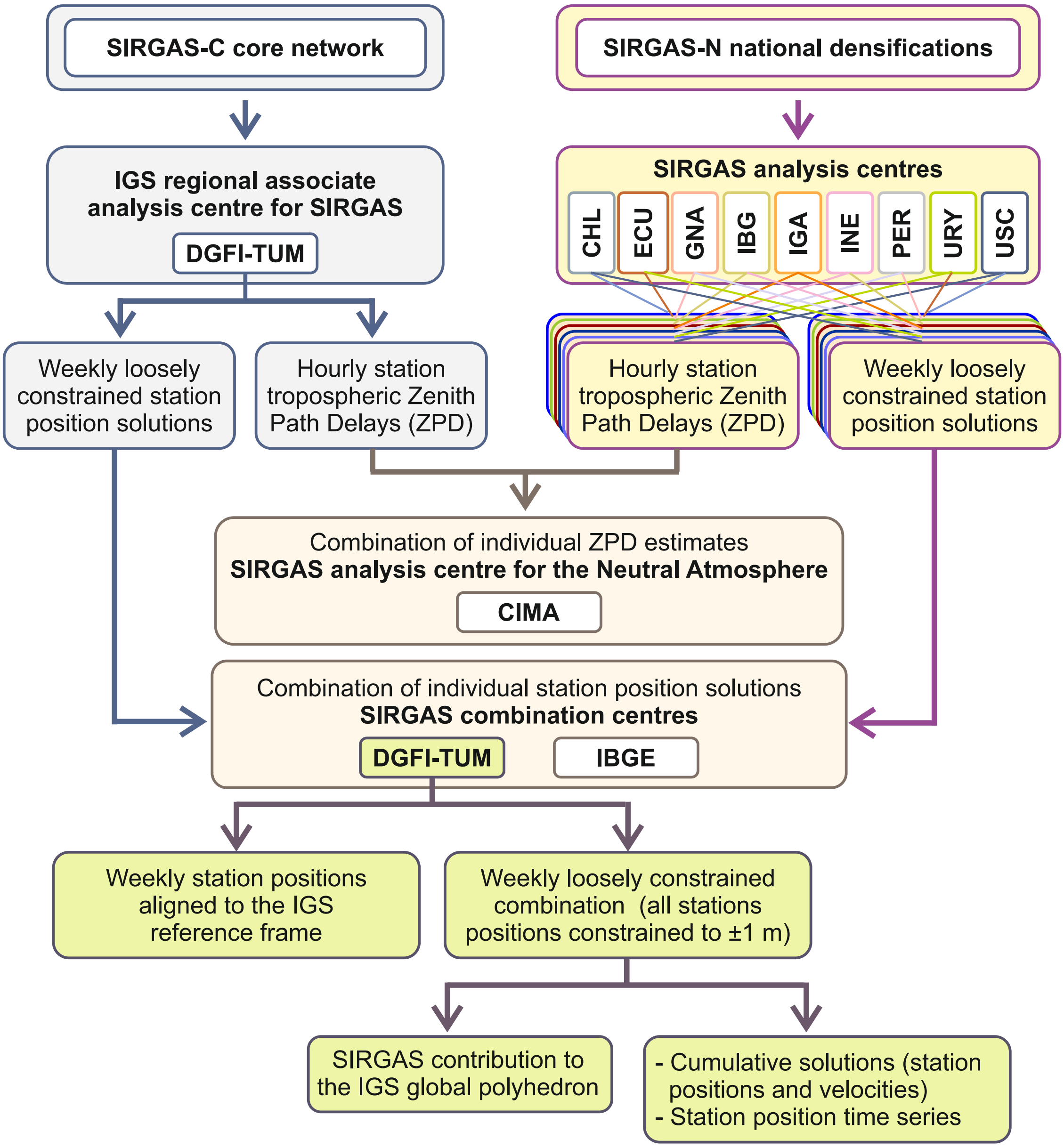

Figure 2: Data flow within the weekly analysis of the SIRGAS reference frame (see Table 1 for more details about the SIRGAS analysis centres).

3 Second reprocessing of the SIRGAS reference frame

The operational SIRGAS products refer to the IGS reference frame valid at the time of routine processing of the GNSS data. A first reprocessing campaign of the SIRGAS reference network was carried out 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 with respect to the IGS08/IGb08 frame was not performed. Thus, the SIRGAS weekly normal equations currently refer to different reference frames: IGS05 (from January 2000 to April 2011), IGS08/IGb08 (from April 2011 to January 2017), IGS14/IGb14 (from January 2017 to November 2022), and IGS20 (since November 2022). 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 performed by DGFI-TUM, hereafter referred to as SIRGAS-Repro2 (Sánchez et al., 2022).

For the entire period covered by SIRGAS-Repro2 (January 2000 to December 2021), 537 SIRGAS regional stations plus 128 IGS global stations (88 of which belong to the IGS14/IGb14 reference frame) were reanalysed. Nearly 2.6 million daily RINEX files were processed. The rejection rate for low quality RINEX files is only 0.2%. Figure 3 shows the number of years processed per station. The GNSS observations were analysed according to the standards described in Section 2, except that for the weeks prior to January 29 2017 (when the IGS14 was adopted as the reference frame), the orbits, satellite clocks and EOPs based on the IGS-Repro2 (hereafter referred to as IG2 products) were used (Griffiths, 2019). From January 30 2017, the operational and SIRGAS-Repro2 solutions are virtually the same, as both series are based on the IGS14/IGb14 and the IGS operational products. According to Figure 4, the consistency of the SIRGAS-Repro2 stations positions

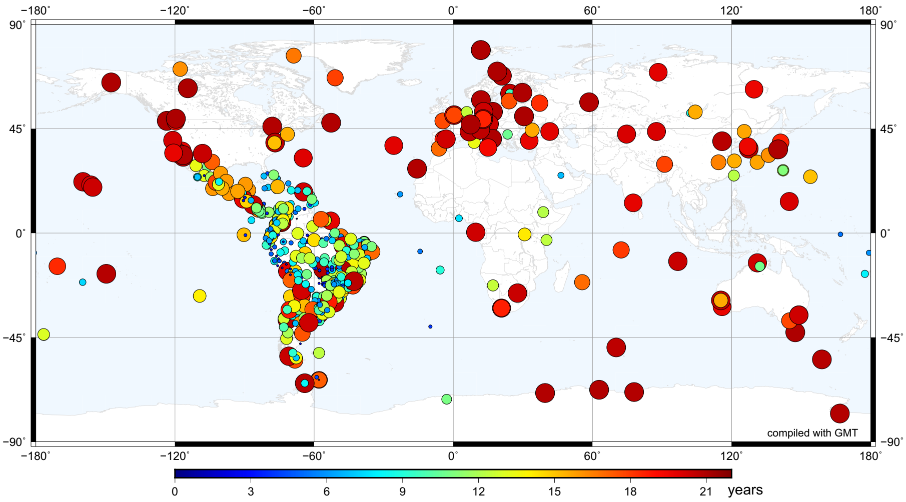

Figure 3: Time span of GNSS data included in SIRGAS-Repro2 per station.

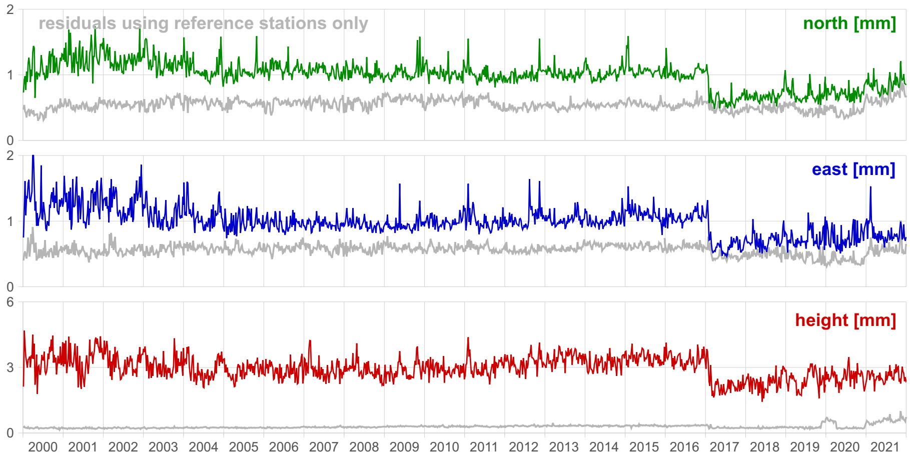

Figure 4: Mean RMS values of the station position residuals obtained after comparing the SIRGAS-Repro2 station positions and the weekly coordinates of the IGS stations in IGS14/IGb14. Grey lines represent the values obtained when comparing SIRGAS with the IGS fiducial stations only; coloured lines represent the values obtained when comparing all SIRGAS/IGS common stations.

with the IGS14/IGb14 reference frame is about ±1.0 mm in N/E and ±3.0 in U before January 2017. Afterwards, this consistency improves reaching values around ±0.8 mm in N/E and ±2.6 in U. The jump observed at the end of January 2017 is due to the fact that the IG2 products (generated within the second IGS reprocessing campaign and used for the SIRGAS-Repro2 analysis) are computed using a different antenna phase centre correction model than the operational IGS products based on the IGS14/IGb14.

4 SIRGAS2022: the latest SIRGAS reference frame solution

SIRGAS2022 is based on the SIRGAS-Repro2 SINEX product series and includes the weekly normal equations between January 2000 (GPS week 1043) and March 2022 (GPS week 2200). Figure 5 summarises the procedure use to determine SIRGAS2022. SIRGAS2022 (Figures 6 and 7) contains 573 stations with 1302 occupations. It includes post-seismic approximations for the first time in a SIRGAS reference frame solution. The SIRGAS2022 station positions refer to the IGb14 reference frame and are given at the epoch 2010.0. Their accuracy is estimated to be ±0.8 mm in N/E and ±1.8 mm in h at the reference epoch. The accuracy of the velocities is estimated to be ±0.6 mm/year in N/E and ±1.0 mm/year in U.

The modelling and assimilation of seismic events remains a major challenge in the determination of the SIRGAS reference frame. In the determination of SIRGAS2022, 793 discontinuities were detected: 69% are caused by antenna changes, 21% correspond to co-seismic displacements and 10% have unexplained causes. In addition, 75% of the co-seismic dis-

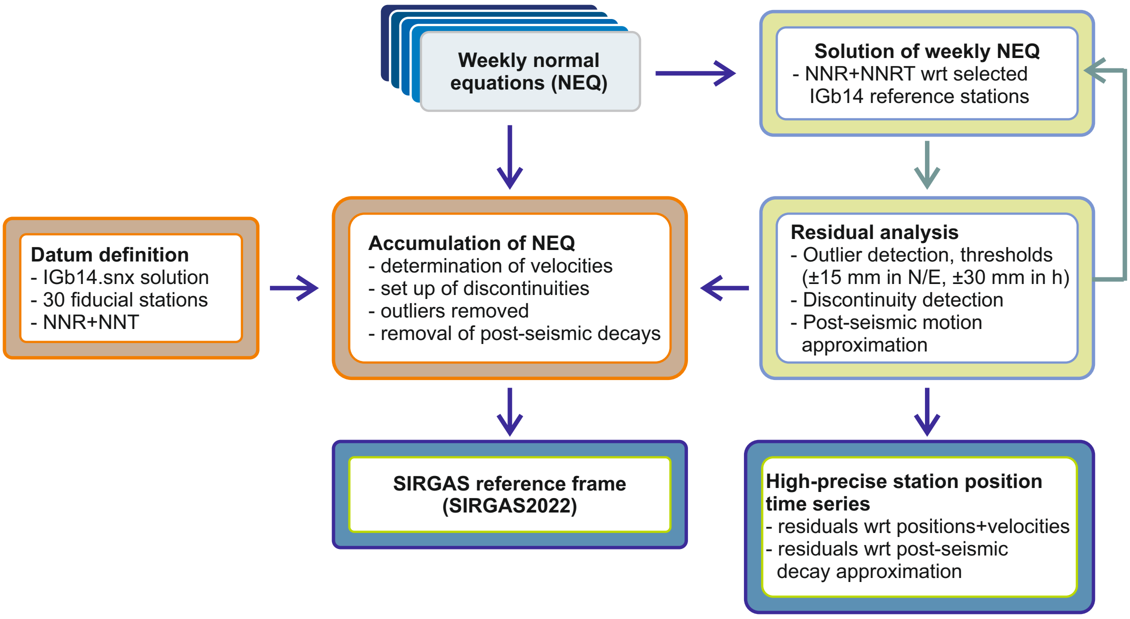

Figure 5: SIRGAS reference frame determination procedure.

placements are followed by strong post-seismic decay. In many cases (especially for stations in Argentina, Chile, Ecuador and Costa Rica), the post-seismic effects of different earthquakes overlap, making it difficult to approximate these effects by a single logarithmic or exponential function. The situation is further complicated by the lack of data and the malfunctioning or dismantling of earthquake-damaged stations, as these factors reduce the reliability and availability of station position time series. In some cases, the entire reference frame of a country is affected by a single earthquake, which means that for a certain period after the earthquake there is no reliable reference frame for practical or scientific applications. The reduced reliability of regional reference frames in regions with these extreme conditions is addressed with the approach developed by DGFI-TUM for a direct geocentric datum realisation of regional epoch reference frames based on global networks; for more details see Kehm (2022) and Kehm et al. (2022).

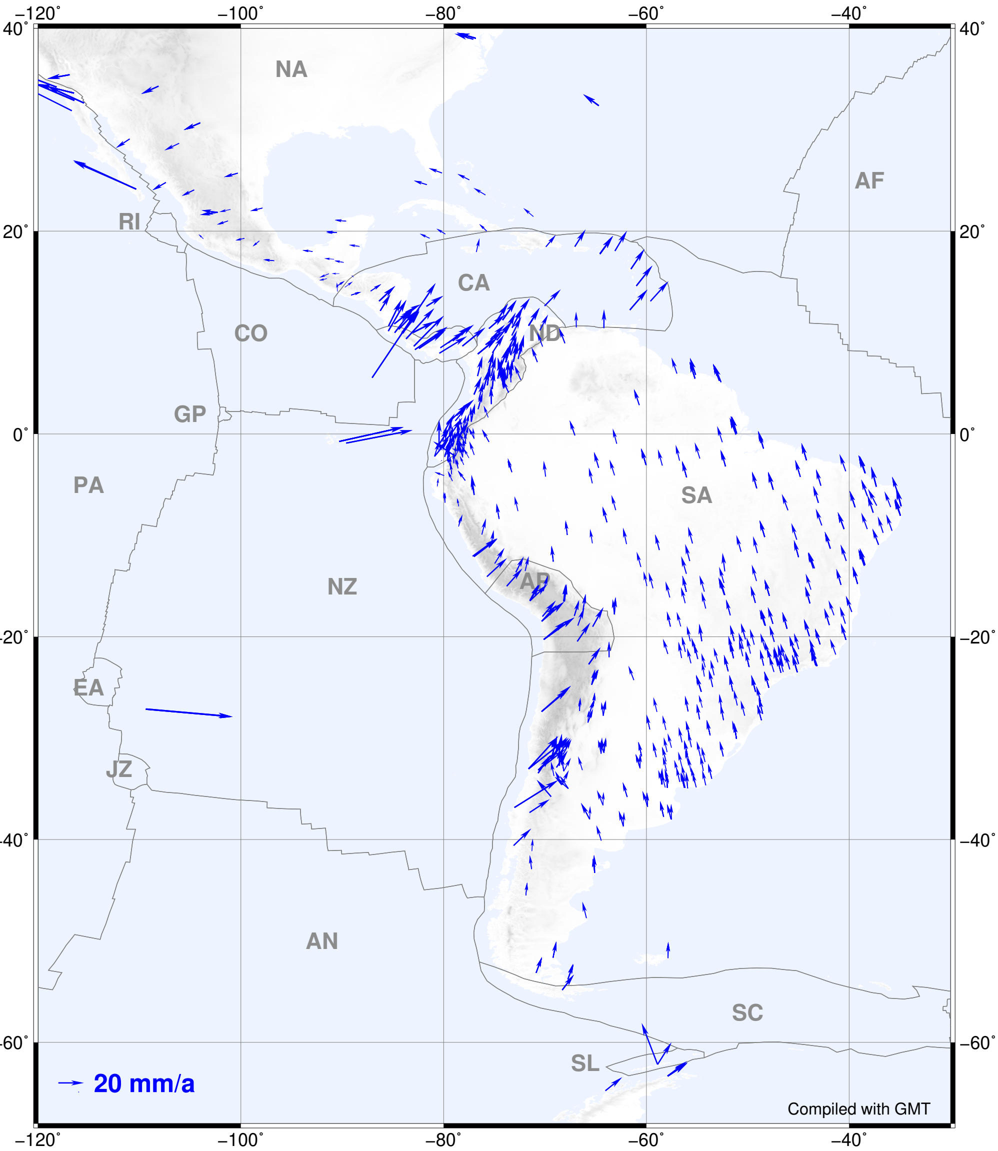

Figure 6: SIRGAS2022 horizontal velocities.

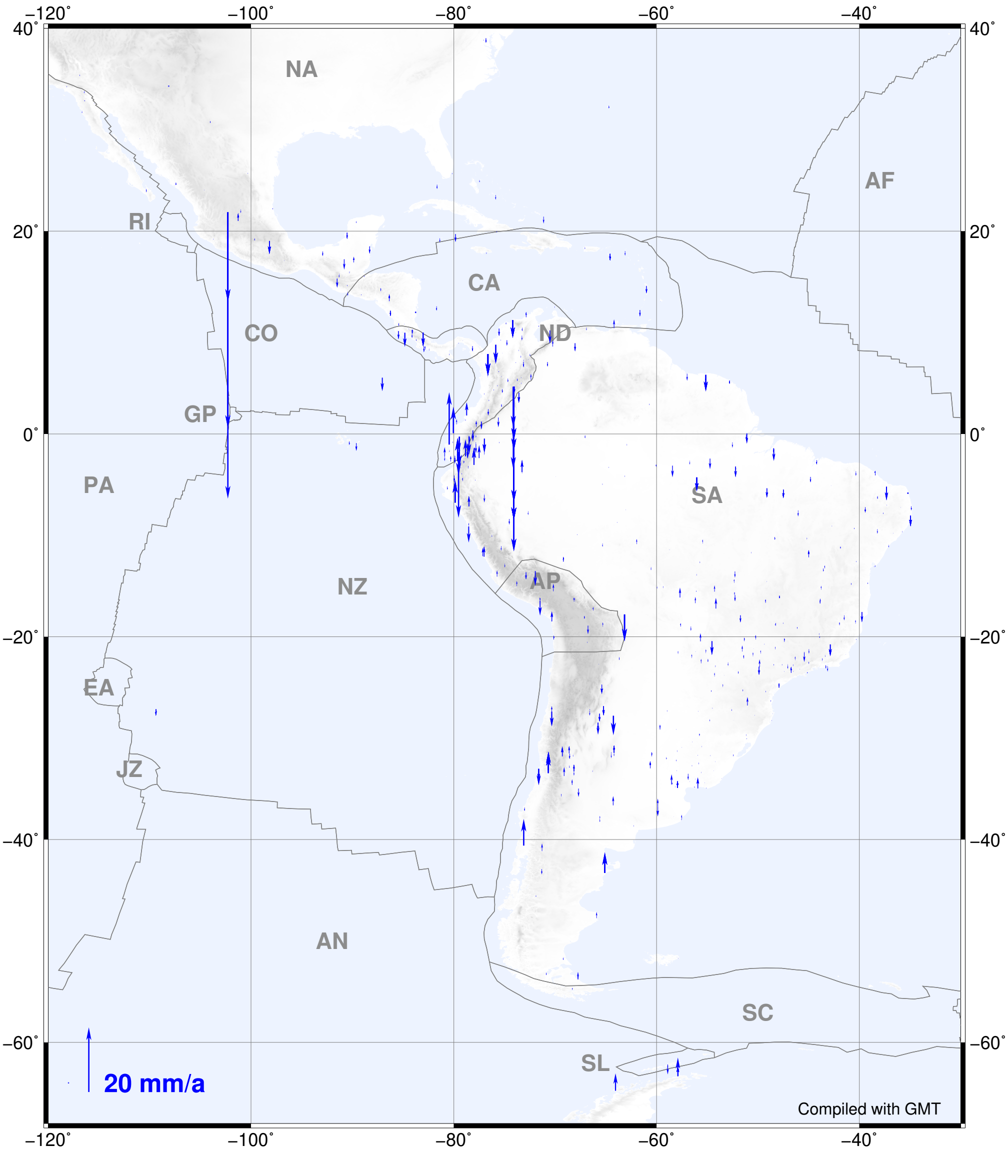

Figure 7: SIRGAS2022 vertical velocities.

5 SIRGAS data availability

The data recorded by the SIRGAS stations are made available in RINEX format by the station owners at the SIRGAS National Data Centres, see https://sirgas.ipgh.org/en/gnss-network/data-centres/. The individual and combined weekly solutions are available via ftp at ftp.sirgas.org/pub/gps/SIRGAS or via https at https://www.sirgas.org/archive/gps/SIRGAS. The latest multi-year solutions and VEMOS models are available at https://www.sirgas.org. Absolute and residual time series as well as post-seismic approximation functions of the SIRGAS stations included in SIRGAS-Repro2 can be downloaded from the same site https://www.sirgas.org.

Please note that DGFI-TUM hosted the SIRGAS portal https://www.sirgas.org between July 2007 and July 2021, when the SIRGAS website was moved to https://sirgas.ipgh.org/. All official matters related to SIRGAS are available at the new site. The site https://www.sirgas.org continues providing research results and data products generated by the DGFI-TUM as the IGS RNAAC SIRGAS. The server ftp.sirgas.org/pub/gps/SIRGAS or https://www.sirgas.org/archive/gps/SIRGAS is maintained by DGFI-TUM.

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Part III

Data Centers

Infrastructure Committee Technical Report 2022

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1 Introduction

The IGS Infrastructure Committee (IC) is a permanent body established to ensure that the data requirements for the highest quality GNSS products are fully satisfied while also anticipating future needs and evolving circumstances. Its principal objective is to ensure that the IGS infrastructure components that collect and distribute the IGS tracking data and information are sustained to meet the needs of main stakeholders, 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 members) and a representative from each of the active global data centres.

Table 1 shows the current membership as of December 31, 2022.

Table 1: List of IGS Infrastructure Committee Members (as of December 31, 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
Fernandes, Rui	UBI/SEGAL	IGS Network Representative
Ruddick, Ryan	GA	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
Martire, Léo	JPL	IGS Central Bureau (CB) Deputy Director
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	

3 Summary of Activities in 2022

Over 2022 the IC has supported the Network Coordinator on answering questions from IGS product and data users. The newly formed station approval committee (SAC) added 15 multi-GNSS stations to the network and removed 6 long-term absent stations from the network as stated in Table 2. The SAC consists of the IC Coordinator, the IGS Network Coordinator, the Reference Frame Coordinator, as well as the three network representatives and selected network representatives from international networks.

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.

The IC assembled a comprehensive program for the plenary infrastructure session of the fully virtual IGS Workshop 2022. The session included an interactive polling to receive heterogenic and unbiased user input to determine the program direction of the IC for

Table 2: List of approved and decommissioned Stations in the IGS Network in 2022

Station	Location	Systems	Real-Time	Agency
Approved Stations (15):				
AC2300USA	Soldotna, AK, USA	GRECJ	Yes	UNAVCO
AC2400USA	King Salmon, AK, USA	GRECJ	Yes	UNAVCO
ACSO00USA	Delaware, OH, USA	GREC	Yes	UNAVCO
ANK200TUR	Ankara, Turkey	GREC	No	MGDT
ANTF00CHL	Antofagasta, Chile	GRECS	Yes	USACH
IITK00IND	Kanpur, India	GRECJI	Yes	IITK
KSU100USA	Manhattan, KS, USA	GREC	Yes	UNAVCO
P04300USA	Newcastle, WY, USA	GRECJ	Yes	UNAVCO
P05100USA	Billings, MT, USA	GRECJ	Yes	UNAVCO
P05300USA	Whitewater, MT, USA	GRECJ	Yes	UNAVCO
P38900USA	Brothers, OR, USA	GRECJ	Yes	UNAVCO
P77900USA	Rosman, NC, USA	GRECS	Yes	UNAVCO
P80200USA	Mandan, ND, USA	GRECJ	Yes	UNAVCO
PBR400IND	Port Blair, India	GRECJI	No	ISRO
SHLG00IND	Shillong, India	GRECJIS	No	ISRO
Decommissioned Stations (5):				
ANKR00TUR	Ankara, Turkey	GRECJS	No	MGDT
BRMU00GBR	Bermuda, United Kingdom	GR	No	NGS
FALE00WSM	Faleolo Upolo Island, Samoa	G	No	GNS
KGNI00JPN	Koganei, Japan	GREJS	Yes	NICT
UNX200AUS	Sydney, Australia	GREJIS	Yes	DLR

Legend for system IDs
G: GPS, R: GLONASS, E: Galileo, C: BeiDou, J: QZSS, I: IRNSS/NavIC, S: SBAS

the upcoming years[1] . The outcome of this session led to the following five recommendations[2].

R1 Following input from the community at the 2022 workshop, develop a roadmap to enhance the IGS tracking network to meet the shifting user needs.

R2 Advocate for the importance of information security across the IGS to improve the resilience of the infrastructure and increase trust and confidence in our data and products.

R3 Explore modern standards, data storage and access methodologies to improve the FAIR[3]ness of the IGS data and metadata.

R4 Develop a proposal to investigate a higher tier of data centre (global archive) which would set mandatory requirements such as quality control, data synchronization and some form of service level agreement with the IGS.

R5 Actively engage with all working groups to support them in accessing the data and products needed to succeed in their objectives.

The IC started to actively work on Recommendation 1 by preparing a position paper titled "The Future of the IGS Network". This paper aims to be the basis for decision-making and to develop guidelines, knowledge bases, and monitoring solutions. The work on the updated "Guidelines for IGS Continuously Operating Reference Stations (CORS)" have been put on hold until the position paper is finished and has been acknowledged by the IGS Governing Board. We aim to publish it in Q2/2023.

Since the end of 2021, another task team within the IC is working on the promotion of GeodesyML[4] as recognised standard to maintain the metadata of GNSS stations in our community (see recommendation 3). The team further works on the development of new features to be implemented into the current standard. The new features mostly address the need for FAIR data principles (e.g., data license, file provenance information, file access, etc.) in the geodetic community. In addition, members of this task team actively contribute with their expertise to the GGOS Working Group on Digital Object Identifiers (DOIs) for Geodetic Data Sets[5].

Furthermore, the IC supported the IGS with a smooth switch to IGS20 and repro3 standards[6]. The "Guidelines for Long Product Filenames in the IGS"[7] have been updated under the lead of the ICC to reflect the whole portfolio of IGS products.

[1] https://files.igs.org/pub/resource/pubs/workshop/2022/IGSWS2022_S01_01_Bradke.pdf

[2] https://files.igs.org/pub/resource/pubs/workshop/2022/IGSWS2022_S01_Recommendations_Bradke.pdf

[3] Acronym for Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016, https://doi.org/10.1038/sdata.2016.18)

[4] http://geodesyml.org

[5] https://ggos.org/about/org/co/dois-geodetic-data-sets

[6] https://igs.org/news/igs20

[7] https://files.igs.org/pub/resource/guidelines/Guidelines_For_Long_Product_Filenames_in_the_IGS_v2.0.pdf

Last but not least, the IC initiated the transition to RINEX 4.00 by setting up campaign directories at CDDIS and BKG data centres. The directories contain observation, navigation, and meteorological RINEX 4.00 files provided by GFZ and DLR. In December 2022, we reached the end of this trial period and we aim to integrate RINEX 4.00 data in the first quarter of 2023.

4 Current and planned Activities

In 2023, the Committee aims to work on all recommendations from the IGS Workshop listed in section 3 .

The IC 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) to build capacity and capability. The committee will work on the development of guidelines, knowledge bases and set up connections to other groups, e.g., FIG[8] commission 5 .

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 and in a test and validation phase by the IC. Once established, the IC will work on solutions for an automated exchange of metadata between different IT systems. Additionally, a dedicated trial project will focus on the feasibility of using modern database engines to store GNSS observations and provide APIs (Application Programming Interface) to access data in a customised way.

Two key topics from the workshop recommendations that we would like to address in 2023 are: Global Archive and Information Security. The idea of a Global Archive emerged from the diversity of data centres in terms of handling data storage, data access, metadata collection, quality checks, security standards, and the lack of synchronisation methods between data centres.

In the first phase, we need to develop a concept, gather requirements, and prepare a feasibility analysis. A dedicated task team will be implemented for this topic. Once acknowledged, the task team can continue with a call for interested data centres and a design phase. Information Security is part of this plan but not limited to data centres. In general, this topic is still underestimated but it affects everyone starting from the receiver infrastructure going down to analysis and data centres. We therefore aim to provide promotion material to advocate the importance of Information Security amongst all components of the IGS.

[8] InternationalFederationofSurveyors,https://www.fig.net

Acronyms

BKG	Bundesamt für Kartographie und Geodäsie
CDDIS	Crustal Dynamics Data Information System
DLR	Deutsches Zentrum für Luft- und Raumfahrt
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
IGN	Institut national de l'information géographique et forestiére
IITK	Indian Institute of Technology Kanpur
ISRO	Indian Space Research Organisation
JPL	Jet Propulsion Laboratory
KASI	Korea Astronomy and Space Science Institute
MGDT	Map General Directorate of Turkey
MIT	Massachusetts Institute of Technology
NGS	National Geodetic Survey of the National Oceanic and Atmospheric Administration
NICT	National Institute of Information and Communications Technology
NRCan	Natural Resources Canada
NRL	United States Naval Research Laboratory
ROB	Royal Observatory of Belgium
SEGAL	Space & Earth Geodetic Analysis Laboratory
SIO	Scripps Institution of Oceanography
UBI	University of Beira Interior
USACH	Universidad de Santiago de Chile
WHU	Wuhan University

GSSC Global Data Center Technical Report 2022

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1 Introduction

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

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

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 (ESOC) 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 2022 Developments

In 2022, the focus of GSSC developments was to release the first public version of the GNSS Science Exploitation Platform “GSSC Now” in March 2022 (see Figure 1). This release introduced ESA’s innovative proposal for collaboration, exploration, and analysis, unlocking the full potential of ESA GNSS archives. Over the course of the rest of 2022, the indexed datasets have been continuously expanded and enriched to include an even wider variety of assets and scientific tools, called datalabs.

This platform, released as public beta, provides advanced search and scientific analysis services on top of GSSC’s repository (including IGS assets). These services allow users to search IGS data using keywords, worldwide maps or filters (see Figure 2 as an example).

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

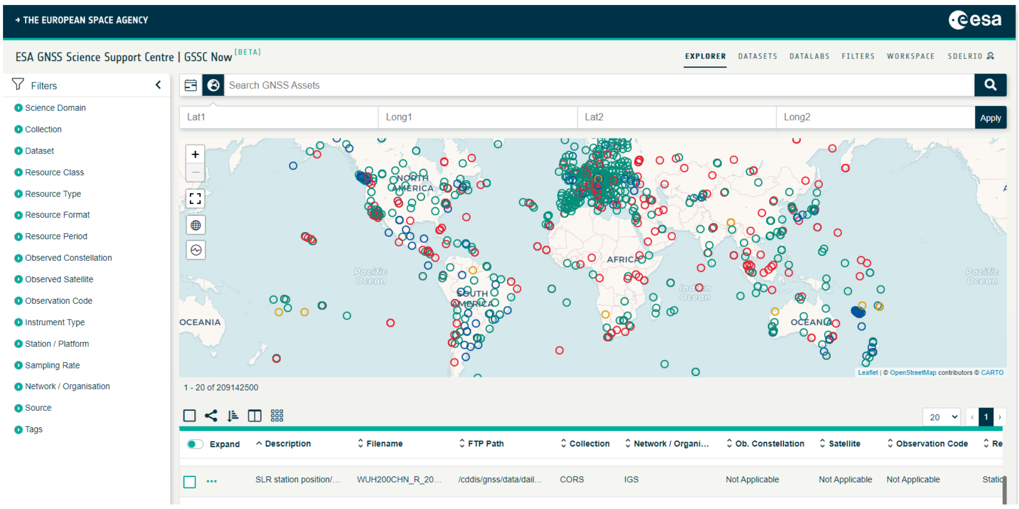


Figure 2: GSSC Now – Explorer View

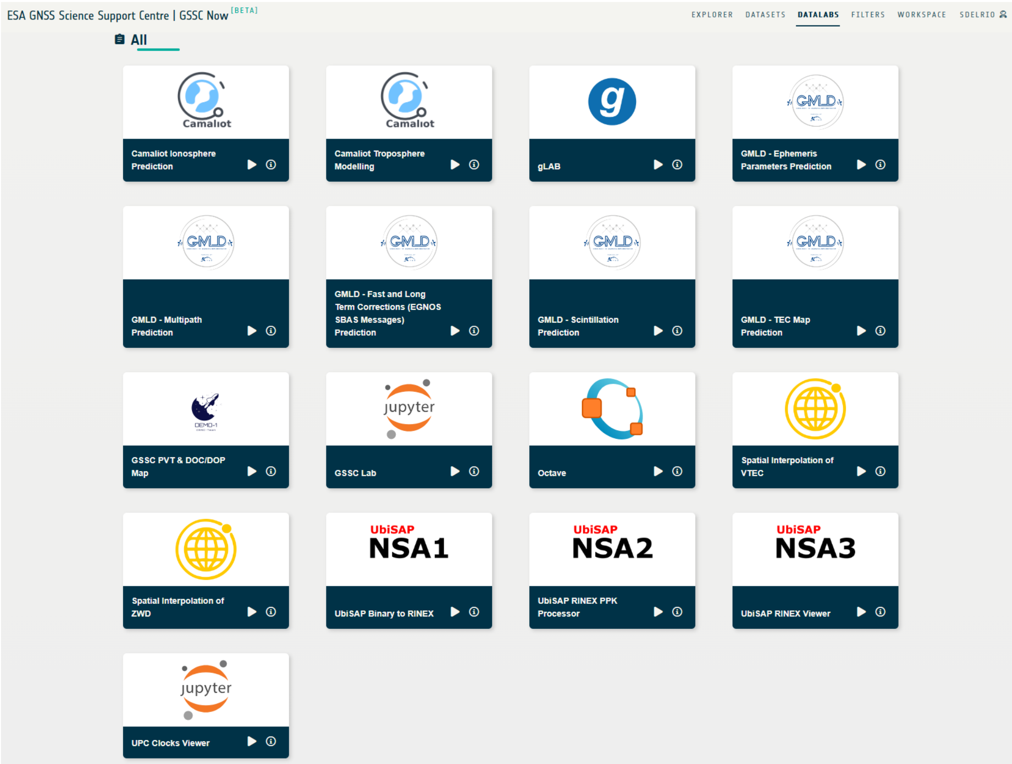


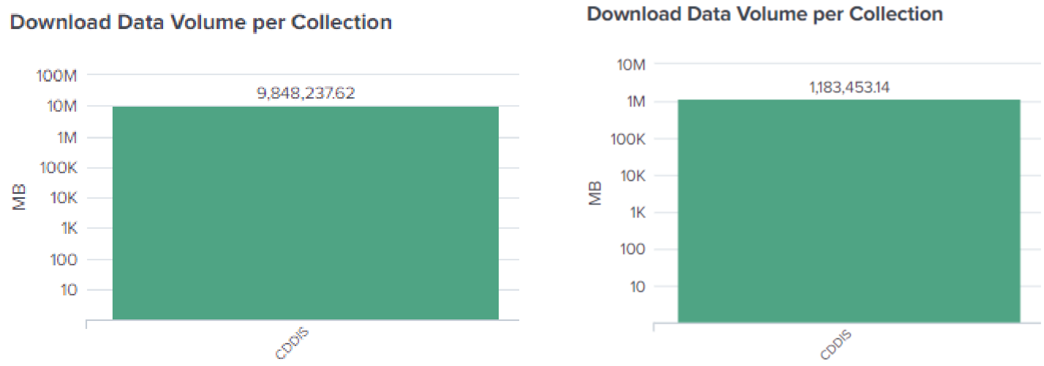
Figure 3: GSSC Now – Datalabs View

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 (see Figure 3).

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.

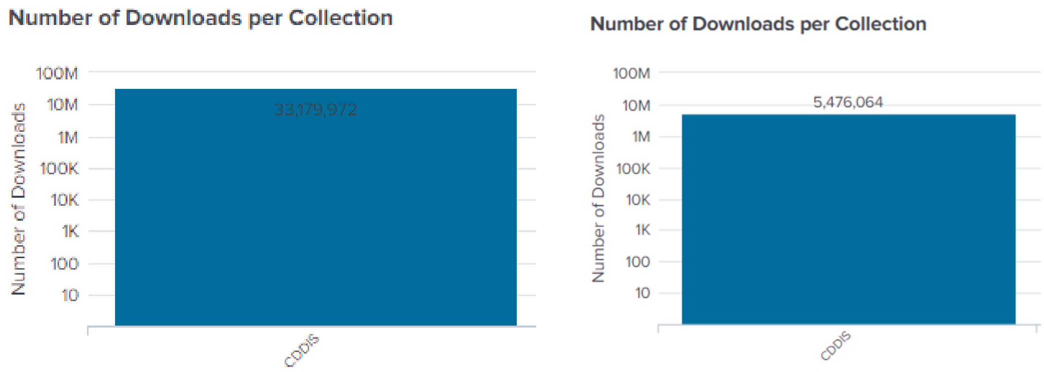
Additionally, 2022 has continued with the steady evolution of GSSC (`gssc.esa.int`) repository and ingestion and analysis services supported by following developments:

- Support for the IGS switch to IGS20/igs20.atx reference frame and repro3 standards.
- Incorporated support for the latest GNSS RINEX V4 format.
- Assessment of additional GNSS datasets for integration into the repository extension with new data collections for ESA projects.
- Integration of new Jupyter Notebooks and on-demand scientific tools in the form of GSSC Now datalabs.



(a) year 2022 (b) year 2021

Figure 4: Download Data Volume per Collection – IGS

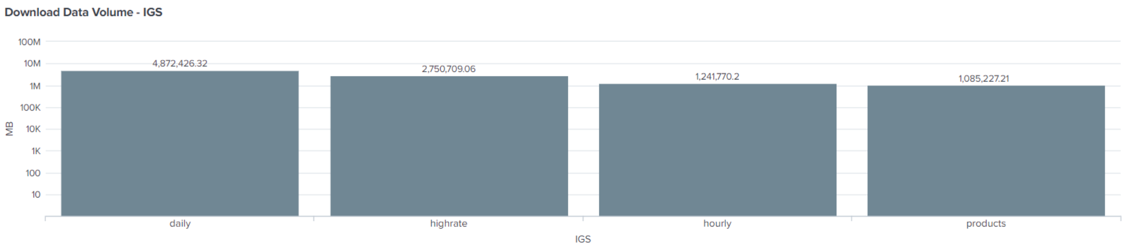


(a) year 2022 (b) year 2021

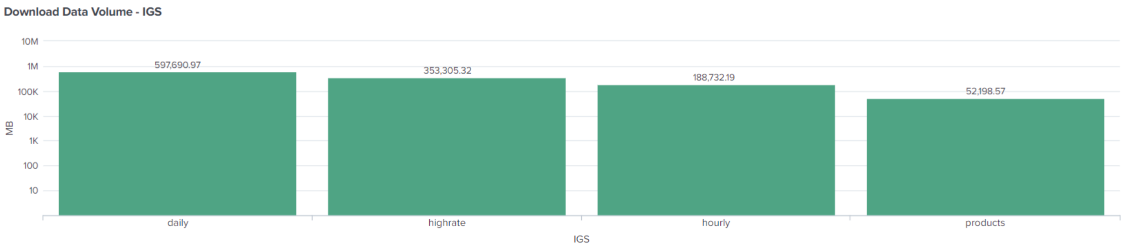
Figure 5: Number of Downloads per Collection – IGS

- GSSC Now user interface improvements to enhance the overall user experience.
- Performance optimizations, bug fixes, and security, stability, and accessibility improvements.

As shown in Figures 4 to 7, it can be observed that the number of accesses to the IGS GDC hosted at GSSC has significantly increased in the past year compared to previous years (e.g., with repsct to 2021).

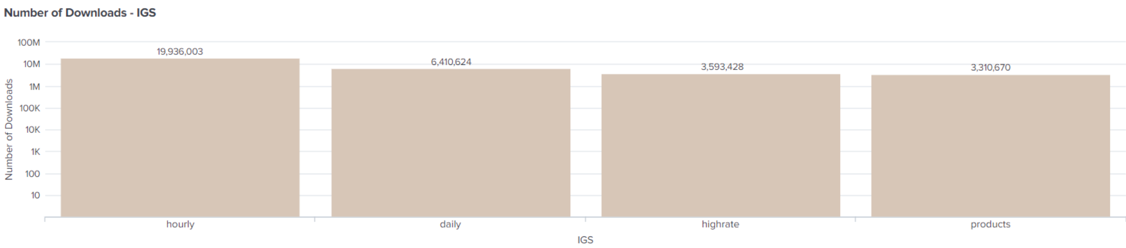


(a) year 2022

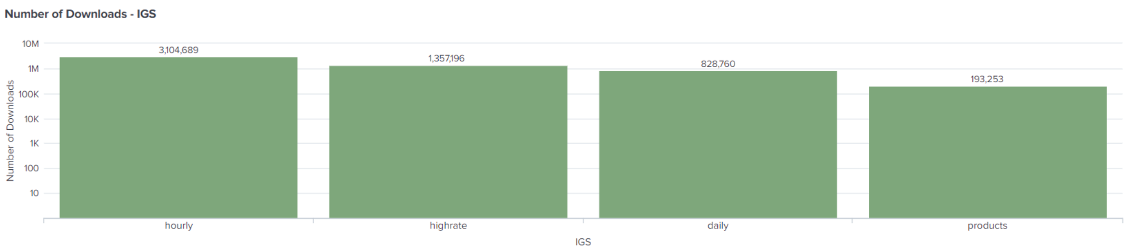


(b) year 2021

Figure 6: Download Data Volume – IGS



(a) year 2022



(b) year 2021

Figure 7: Number of Downloads – IGS

4 Planned 2023 Activities

Planned 2023 activities will include:

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

Wuhan University Data Center Technical Report 2022

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1 Introduction

Wuhan University has joined as an IGS Global Data Center since 2015. The IGS Data Center from WHU has been established with the aim of providing services to global and especially Chinese users, for both post–processing and real-time applications. The GNSS observations of both IGS and MGEX from all the IGS network stations, as well as the IGS products are archived and accessible at WHU Data Center (WHU DC).

The activities of WHU DC within the IGS during 2022 are summarized in this report, which also includes recent changes or improvements 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/).

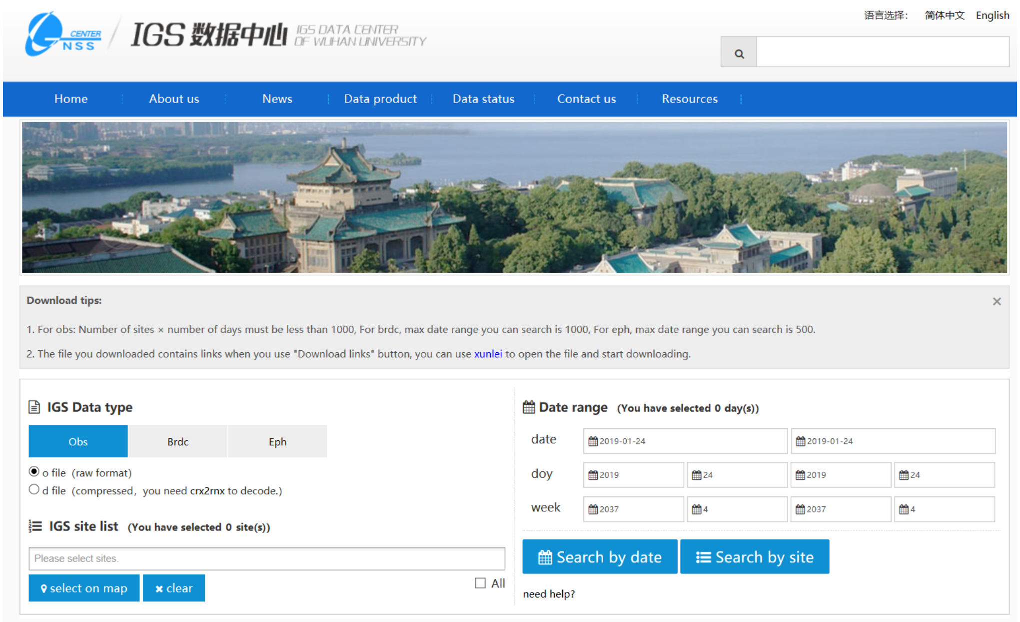

Figure 1: A snapshot of the website of WHU data center for data and products provision.

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, ready to accept GNSS data in the RINEX 4.00 format and Long Name 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 and QZSS.

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.

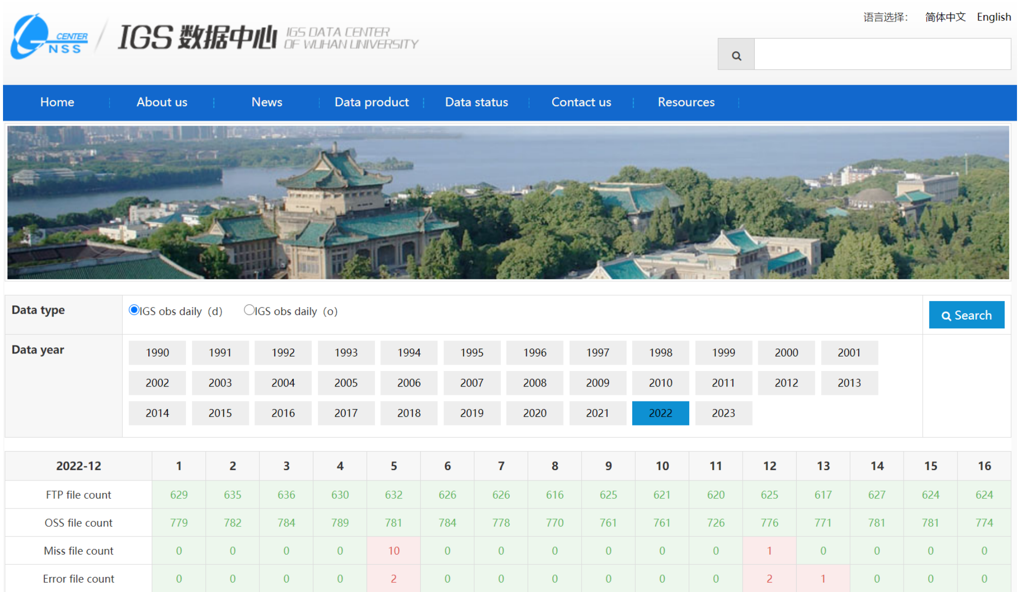

Figure 2: Data and products monitoring of WHU data center.

BKG Regional Data Center Technical Report 2022

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1 Introduction

Since more than 25 years BKG is contributing to the IGS data center infrastructure operating a regional GNSS Data Center (GDC). BKG's GDC is also serving as a data center for the regional infrastructure of EUREF as well as for national infrastructure or for specific projects. Two types of data are handled in the GDC: file-based (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. The core real-time infrastructure is running independently from the file-based infrastructure. 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.

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. 1 Hz) RINEX files
- Interactive map allowing condensed information about each station

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

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 to use the HTTPS protocol for downloading files. Support for FTP uploads was already switched off. GNSS station operators and product managers are asked to use SFTP for uploading files. Support for downloading files via FTP will be turned off within the next year or years.

2.3 GNSS Data & Products

The BKG GDC contains all the regular GNSS data, as there are navigational data, meteorological data, observational data, in RINEX v2 (Rx2) and RINEX v3 (Rx3), daily, hourly and high-rate data of approximately 864 (with national stations 991) 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 navigational data,
- `highrate` for sub-hourly 1Hz data,
- `nrt` (near real-time) for 30 seconds hourly data,
- `obs` for 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.

During 2022, BKG started to store RINEX v4 (Rx4) files. For a test phase, the files were stored in a separate directory, obs_v4. The files were mainly coming from DLR and GFZ. In early 2023, BKG will follow the IGS guidelines for finally storing the Rx4 files.

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 Usage Statistics

At the end of 2022 19.4 million files are stored in the GDC with an overall archive size of 17.0 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 2021. Approximately 1000 different users did visit the GDC websites per day.

2.6 2022 incident

At the end of March 2022 BKG GDC had to be shutdown on a very short note, for technical reasons. Immediately after, it turned out that several station data providers obviously used BKG as the first and in some cases single Data Centre for their upload. During BKG's outage several station data providers began to upload directly to CDDIS. But this single point of failure, which also affects BKG as one of the DCs of the EUREF Permanent Network (EPN), has to be solved in collaboration with the IGS Data Centre Coordinator and CDDIS.

BKG returned to normal work several weeks later, after careful restoring of the data archive and downloading the missing files from, e.g., CDDIS.

2.7 Policy

BKG GDC has to strictly follow the European Union's General Data Protection Regulation (GDPR). As a consequence, it was agreed in the wider GNSS community to introduce, if not already applied, generic names and emails in the publicly available files. These changes are ongoing in cooperation with, e.g. the EPN Central Bureau. Another consequence is that each data provider explicitly has to agree with BKG's data policy by writing ("active consent"). By the end of 2022, 89% of the data provider sent back their feedback and accepted the data policy.

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 2022):

- On the MGEX caster (http://mgex.igs-ip.net) are real-time data of approx. 56 streams provided (compared to 57 a year before). 50 streams are received in raw data format. Only one stream is still converted with the EuroNet software (Horváth , 2016) from receiver raw data into RTCM 3.2/3.3 Multiple Signal Message (MSM) format, one with NRCanRTCM software. On the MGEX caster, only three 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. 229 data streams in RTCM3.0/1/2/3 format provided (compared to 210 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. 339 data streams (compared to 275 one year before) in RTCM3.0/1/2/3 format provided. Meanwhile, 307 MSM streams are coming directly from the receiver. 20 streams are generated from EuroNet, three 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. 42 data streams in RTCM3.0/1/2- and 34 in the IGS-SSR format provided. These streams divide in 73 clock & orbit correction streams from various organizations, six 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 more than 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 5000 from approx. 200 different users during a typical day (compared to 4500 connections from 150 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. 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.

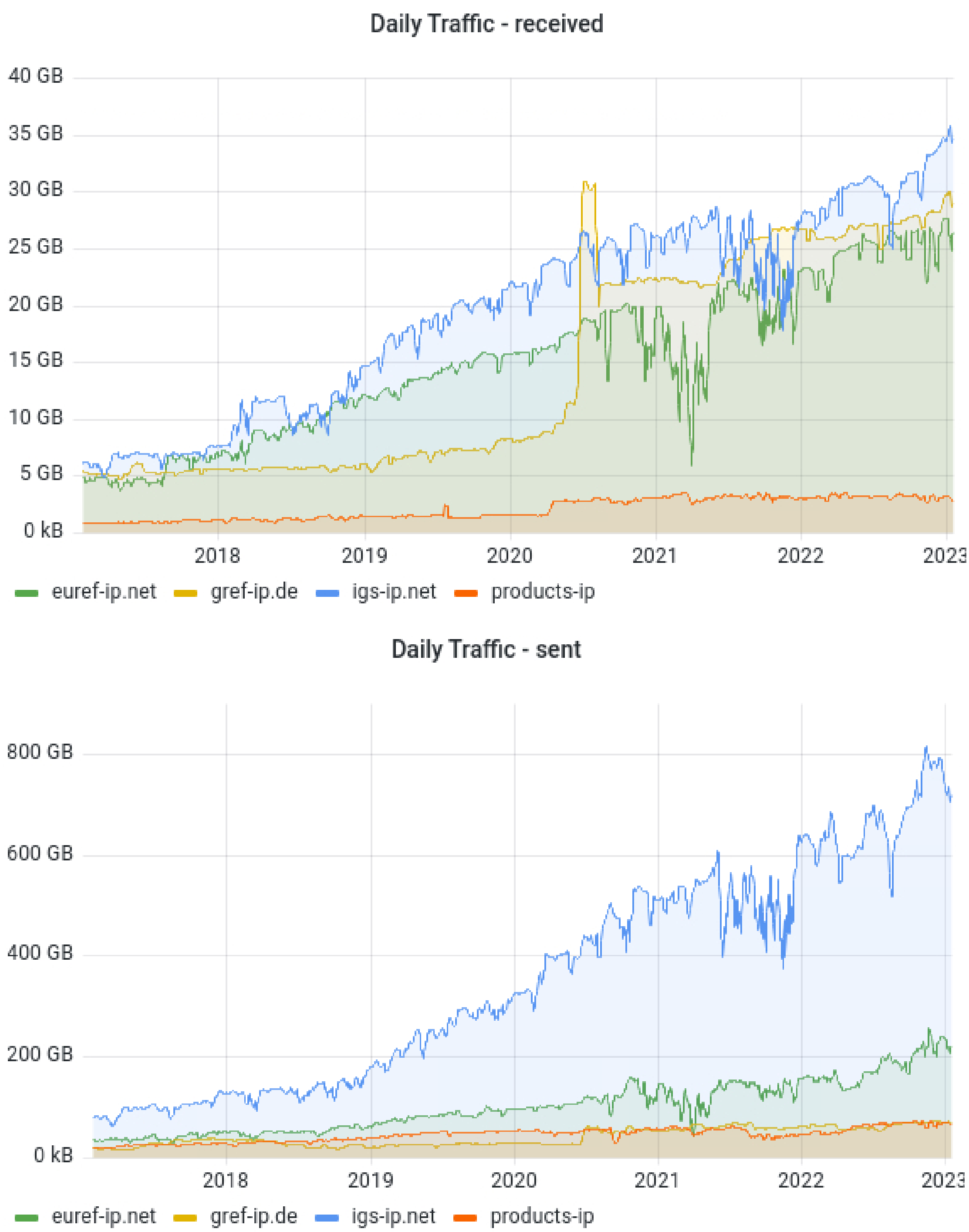

Figure 1: Daily received (i.e., upload to BKG, top) and sent (download from BKG) data volume at the BKG Broadcasters from 2017 to the end of 2022.

References

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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

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2022

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1 Introduction

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

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

2 Transition from IGS14 to IGS20

Starting from GPS week 2238 the IGS switched from IGS14 to IGS20. In this context the used satellite and receiver antenna calibrations have been updated. The major changes w.r.t. the IGS14 antenna model file (`igs14_ wwww.atx`) are:

2.1 satellite antenna calibrations

The satellite antenna pattern have been revised. For Galileo and GPS BLOCK IIIA chamber calibrated antenna pattern have been disclosed and integrated into the IGS20 ANTEX file. For the other satellites the phase center offset (PCO) have been re-estimated and the phase variation patterns checked. Another major change was the introduction of time dependent X- and Y-PCO values for GLONASS satellites.

2.1.1 Scale adjustments w.r.t. ITRF2020:

The z-PCO have been re-estimated for:

- GPS
  - one common offset for BLOCK IIIA satellites (+89.34)
  - re-estimated for other satellites
  - BLOCK I satellites SVN 1-8 set to block average 1775.00 (not used in Repro3)
- **GLONASS**
  - re-estimated
  - GLONASS satellites 758,760-767,770,775-778,780-782,785 set to block average 1940.00 (not used in Repro3)
- **Galileo**
  - one common offset for all GALILEO FOC/IOV satellites (+155.73)
  - one individual offset for E102

2.1.2 Time dependent X- and Z-PCO

For a subset of the GLONASS satellites time dependent X- and Y-PCO have been introduced (Dach et al., 2019):

```
R701, R714, R723, R725, R734, R736, R737
```

2.2 satellite antenna calibrations

On the receiver antenna side several calibration pattern have been replaced by newer multi-GNSS pattern including Galileo.

1. Updated antenna calibrations (multi-GNSS)

AERAT1675_120	SPKE	ASH700936D_M	SCIS
ASH701945B_M	NONE	ASH701945B_M	SCIS
ASH701945C_M	NONE	ASH701945E_M	NONE
ASH701945E_M	SCIS	ASH701945E_M	SCIT
CHCC220GR2	CHCD	HITAT45101CP	HITZ
HXCCGX601A	HXCS	JAVRINGANT_DM	NONE
JAVRINGANT_DM	SCIS	JAVRINGANT_G5T	JAVC
JAVRINGANT_G5T	NONE	JAVTRIUMPH_3A	NONE
JAV_GRANT-G3T	NONE	JAV_RINGANT_G3T	NONE
LEIAR10	NONE	LEIAR20	LEIM
LEIAR20	NONE	LEIAR25.R3	LEIT
LEIAR25.R3	NONE	LEIAR25.R4	LEIT
LEIAR25.R4	NONE	LEIAT504	NONE
LEIAT504GG	NONE	NAX3G+C	NONE
NOV703GGG.R2	NONE	NOV850	NONE
RNG80971.00	NONE	SEPCHOKE_B3E6	NONE
SEPCHOKE_B3E6	SPKE	STHCR3-G3	STHC
STXSA1200	STXR	TPSCR.G3	NONE
TPSCR.G3	SCIS	TPSCR.G3	TPSH
TPSCR.G5	TPSH	TPSCR.G5C	NONE
TPSCR3_GGD	CONE	TRM115000.00	NONE
TRM29659.00	NONE	TRM55971.00	NONE
TRM55971.00	TZGD	TRM57971.00	NONE
TRM57971.00	TZGD	TRM59800.00	NONE
TRM59800.00	SCIS	TRM59800.00	SCIT
TRM59800.80	NONE	TRM59800.80	SCIS
TRM59800.80	SCIT	TRM59900.00	SCIS
TWIVC6150	SCIS	TWIVP6050_CONE	NONE

3 Updates and content of the antenna phase center model

Table 1 lists all updates of the igs20_wwww.atx in 2022. 12 new antenna/radom combinations have been added. Since GPS week 2238 the IGS switched from the IGS14 to the IGS20 reference frame. In this context the new igs20.atx antenna calibration file was introduced.

Table 2: Calibration status of 509 stations in the IGS network (`logsum.txt` vs. `igs20_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%
JAN 2023	**igs20.atx:**	**93.8%**	**1.0%**	**4.3%**

Table 1: Updates of the phase center model `igs20_wwww.atx` in 2022 (`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`	
2239	9. Dec 2022	`Added`	`EML_REACH_RX NONE`
2233	16. Nov 2022	`Added`	`ESVUA92 NONE`
2223	26. Aug 2022	`Added`	`EML_REACH_RS2+ NONE`
			`GING20M NONE`
			`GING30 NONE`
2218	14. Jul 2022	`Added`	`TRMR780 NONE`
2215	23. Jun 2022	`Added`	`GMXZENITH06 NONE`
			`TRM59800.99 SCIS`
2194	42. Jan 2022	`Added`	`HXCCGX611A HXCM`
			`TXSA1000 NONE`
			`TIAPENG7N NONE`

4 Calibration status of the IGS network

Table 2 shows the percentage of IGS tracking stations with respect to certain calibration types. For this analysis, 508 IGS stations as contained in the file `logsum.txt` (available at

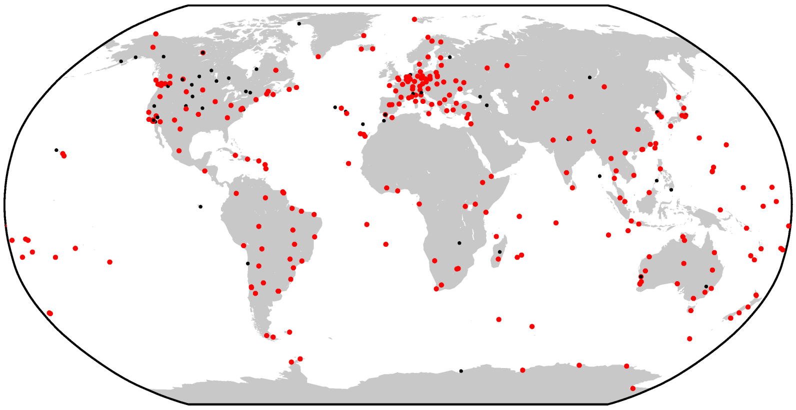

Figure 1: IGS stations tracking Galileo. Red dots: antennas with Galileo calibrations; Black dots: antennas without Galileo calibrations.

`ftp://igs.org/pub/station/general/`) were considered. At that time, 107 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 `igs20_wwww.atx` that were released in December 2022. The overall situation regarding the stations with state-of-the-art robot-based calibrations is similar to the one from 2021. While for the igs08 84.9% and for the igs14 93.5% of the IGS stations are covered by robot calibration the situation is slightly better of the new igs20 with a coverage of 93.8%.

The IGS20 is based on three GNSS systems (GPS, GLONASS, Galileo) while the predecessor IGS14 relied on GPS and GLONASS only. The inclusion of Galileo in the IGS20 was possible due to the release of updated receiver antenna calibrations covering the corresponding frequencies. Currently the `igs20.atx` covers 384 out of 508 sites with antennas for which multi-GNSS calibrations are available. 377 IGS sites are currently tracking Galileo out of which 84% are antennas with available mutli-GNSS calibrations. Figure 1 shows stations which are tracking Galileo (according to https://network.igs.org/. Stations using antennas with according Galileo antenna pattern are represented as red dots while the black dots are antennas without Galileo calibration patterns.

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

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

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Improving GLONASS Orbit Quality by Re-estimating Satellite Antenna Offsets, Advances in Space Research, doi: 10.1016/j.asr.2019.02.031

GPS BLOCK IIIA satellite antenna calibrations URL https://www.navcen.uscg.gov/sites/default/files/pdf/gps/GPSIII_APCs_SVNs_74_78_ISC_SVN78_Dec2021.pdf

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

Bias and Calibration Working Group Technical Report 2022

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1 Introduction

The IGS Bias and Calibration Working Group (BCWG) coordinates research in the field of GNSS bias retrieval and monitoring. It defines rules for appropriate, consistent handling of biases which are crucial for a "model-mixed" GNSS receiver network and satellite constellation, respectively. At present, we consider: GPS C1W–C1C, C2W–C2C, and C1W–C2W differential code biases (DCB). Potential quarter-cycle biases between different GPS phase observables (specifically L2P and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and other 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 2022

- 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,

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. Starting with GPS week 2238, an identical extension (to three GNSS) was made in the CODE final analysis line. From the latter point in time, the results of the rapid analysis line are no longer included in the long-term history of 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) product provided by CODE (specifically in the Bernese DCB format) corresponds to a converted extract from our new OSB final/rapid product line.

- Our new bias implementation allows to combine bias results at normal-equation (NEQ) level. We are thus able to combine bias results obtained from both clock and ionosphere analysis, and, moreover, to compute coherent long-term OSB solutions. This could be already achieved for the period starting with epoch 2016:136 up to now. Corresponding long-term OSB solutions are updated daily.

- The use of the RINEX2-based tool for *direct* estimation of GPS and GLONASS P1–C1 and P2–C2 DCB values has been discontinued in February 2022. In its place, a newly developed, RINEX3-driven tool for *direct* estimation of all determinable intra-frequency code biases is now applied. This tool is declared to be multi-GNSS capable, treats the generated information at OSB level and further allows to export this information (at NEQ level) for later parameter stacking operations. It is intended that corresponding bias estimates will eventually be used to complement the CODE.BIA 30-day and long-term product. They are currently being substituted (down-converted) for the GPS/GLONASS DCB legacy product files and are already being used to augment CODE'a daily bias product files, in particular with regard to the GPS satellit constellation, now covering all sampled code signals of L1

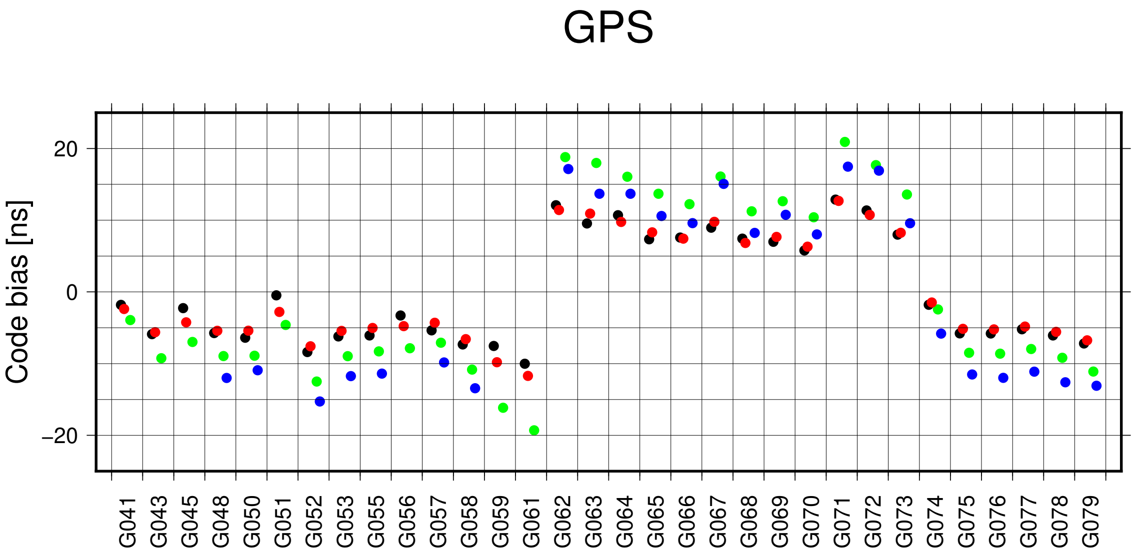

Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2023. Note that G041–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations and G074–G079 corresponds to Block IIIA. Legend: C1C (black), C1W (red), C2W (green), C2L/C2S (blue).

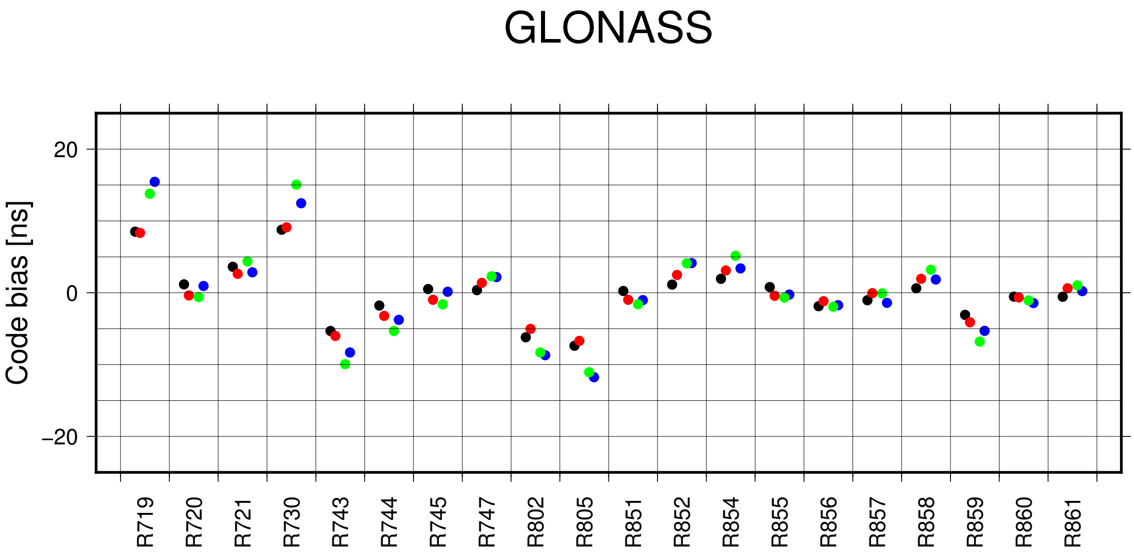

Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2023. Note that R719–R747 and R851–R861 correspond to GLONASS-M; R802–R805 correspond to GLONASS-K1 satellite generations. Legend: C1C (black), C1P (red), C2P (green), C2C (blue).

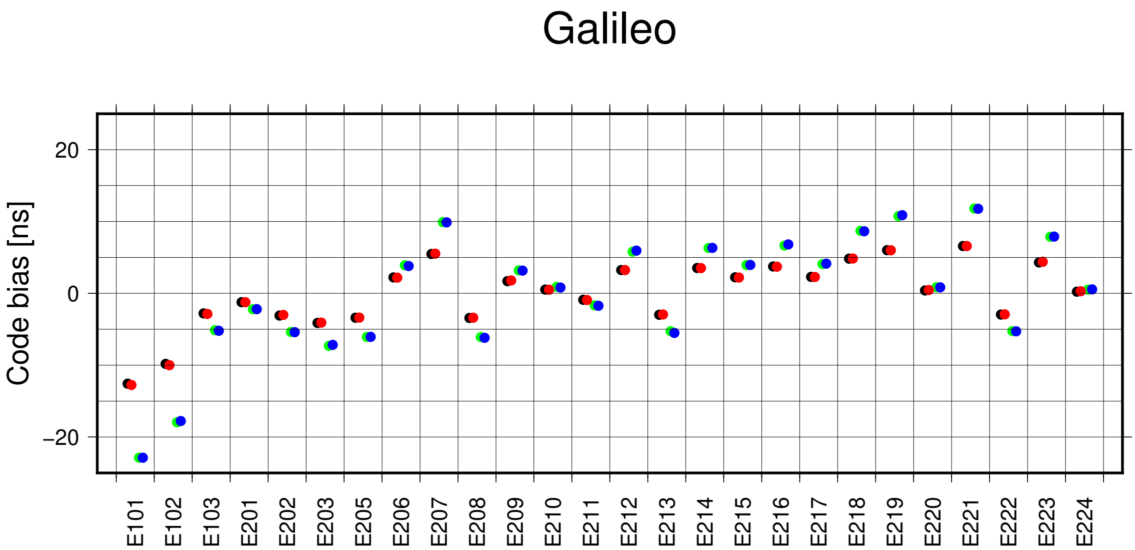

Figure 3: Observable-specific code bias (OSB) estimates for Galileo code observable types (using the RINEX3 nomenclature) and Galileo SV numbers, computed at CODE, for January 2023. Legend: C1X (black), C1C (red), C5Q (green), C5X (blue).

and L2 (specifically since GPS week 2210). It should be noted that the GPS DCB values declared as P1–C1 and P2–C2 are now strictly equivalent to C1W–C1C and C1W–C2L.

- The new bias convention concerning satellite antenna corrections was implemented according to the IGS guidelines, both in relation to the Melbourne-Wübbena LC and in relation to the geometry-free LC (see also section 4). This means that inter-frequency code bias determinations generated by CODE are also affected by this model change (effective from start of GPS week 2238). However, it should be pointed out that this only affects all bias products in the OSB representation. **Caution:** Inter-frequency DCB legacy products in the Bernese DCB format are explicitly corrected to the old, simplifying bias convention. This means that this particular legacy product (which will be obsolete in the foreseeable future) will no longer experience this model change (also to allow long-standing users to make this model change when switching to a contemporary OSB product).
- 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/y2022/odata2_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata2_d335_sat.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata3_gnss_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata3_gps_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata3_glonass_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata3_galileo_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata3_beidou_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/odata3_qzss_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2022/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.

In 2022: RINEX3 observation data covering well over one calendar year (back to January 1, 2021) was reprocessed for testing and validation purposes using the newly developed multi-GNSS-capable tool for direct code bias estimation. Corresponding intra-frequency biases could be retrieved between:
GPS C1C/C1L/C1W/C1X and C2L/C2S/C2W/C2X,
GLONASS C1C/C1P and C2C/C2P,
BeiDou C2D/C2I/C2P/C2X,
QZSS C1C/C1L/C1X/C1Z and C5P/C5Q.
With regard to Galileo, the available tracking data does not allow a direct determination of intra-frequency differential code biases.

4 New Bias Convention for Melbourne-Wübbena LC and Geometry-Free LC

It was agreed in the IGS that, at the same time as the model switch to IGS20 (specifically from the start of GPS week 2238), a new bias convention for the Melbourne-Wübbena LC should also be applied. Satellite antenna corrections (especially concerning antenna phase center offsets), which were usually ignored until now, shall now be taken into account. This change of convention affects in particular phase biases as they are needed in the PPP-AR application.

An analogous adjustment is in principle also necessary withn respect to the geometry-free LC as used for ionosphere analysis. In this application, one expects different estimates for inter-frequency code biases, namely for all satellites with deviating L1 and L2 PCO values, i.e., in particular for all Block IIIA satellites of the GPS constellation (currently G04/G074, G11/G078, G14/G077, G18/G075, G23/G076). Such GPS C1W–C2W DCB values conforming with the new convention are about 0.492 m or 1.64 ns larger than those following the old convention (where until recently it was not necessary to consider satellite PCO). Conversely, this means that new GPS Block III DCB estimates would have to be corrected by −1.64 ns in order to obtain old determinations.

It is therefore important to clearly state the bias convention to be applied in Bias-SINEX product files. The `BIAS/DESCRIPTION` sequence is suitable for this. We apply the following declaration when relying on the new bias convention:

```
 APC_MODEL                                IGS20
*SATELLITE_ANTENNA_PCC_APPLIED_TO_MW_LC   YES
*SATELLITE_ANTENNA_PCC_APPLIED_TO_GF_LC   YES
```

If none of the above records or one of the following records can be found, then the old convention is assumed:

```
*SATELLITE_ANTENNA_PCC_APPLIED_TO_MW_LC   NO
*SATELLITE_ANTENNA_PCC_APPLIED_TO_GF_LC   NO
```

Note that MW and GF denote the respective linear combinations (where exactly this bias convention is supposed to apply).

5 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

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

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Clock Products Working Group Technical Report 2022

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The Clock Products (CP) Working Group (WG) consists of IGS members who are: involved with the production of the IGS's GNSS clock solutions, researchers and/or operators at prominent IGS sites serving at UTC(k) sites, or key users and stakeholders of clock products from the IGS. This report contains a summary of the current products as well as items under review in this WG for future IGS products and file standards.

1 Current Product Operations

The IGS final and rapid clock products are combinations of solutions from contributing IGS Analysis Centers (ACs). The combination software makes daily evaluations of each solution and weights each AC contribution based upon the solution precision. The RMS and standard deviation statistics as well as weight of each of AC solution is contained in Table 1. These figures comprise a median of the daily statistics taken over the calendar years 2020 through 2022.

Corresponding plots of the standard deviations are shown in Figure 1 for both rapid and final clocks but only for those ACs contributing weight. The points shown are decimated on 20 days for clarity. Note that the precision level of each AC generally holds around the same level with the exception of rare dates where an outlier in the solution precision is found.

The current core rapid and final products contain a subset of the IGS network station clocks as well as all GPS satellite clocks. While some ACs generate solutions for GLONASS, Galileo and/or Beidou, those clocks are not yet part of the main core products. On-going work for the multi-GNSS clock products aims to bring these towards production as soon as possible. See Section 2.1 for more details.

Table 1: Quality of clock solution contributions from IGS Analysis Centers. Median RMS and Standard Deviation statistics over the 2020 – 2022 calendar years.

AC	**Rapid Clock Product**			**Final Clock Product**		
	Med Daily RMS (ps)	Med Daily StDev (ps)	Med Daily Weight	Med Daily RMS (ps)	Med Daily StDev (ps)	Med Daily Weight
COD	157.0	11.8	21.0 %	91.4	5.2	24.2 %
EMR	97.5	20.0	10.1 %	116.1	14.4	9.5 %
ESA	83.7	10.9	21.3 %	73.4	6.5	21.4 %
GFZ	98.7	12.0	18.4 %	78.7	11.8	11.8 %
GRG				129.5	8.7	15.4 %
JPL	88.0	9.8	21.2 %	85.2	7.6	17.7 %
MIT				1325.2	26.0	0.0 %
NGS	1826.5	822.8	0.0 %	1837.7	830.0	0.0 %
USN	211.3	131.6	0.0 %			
WHU	91.6	23.8	8.0 %			

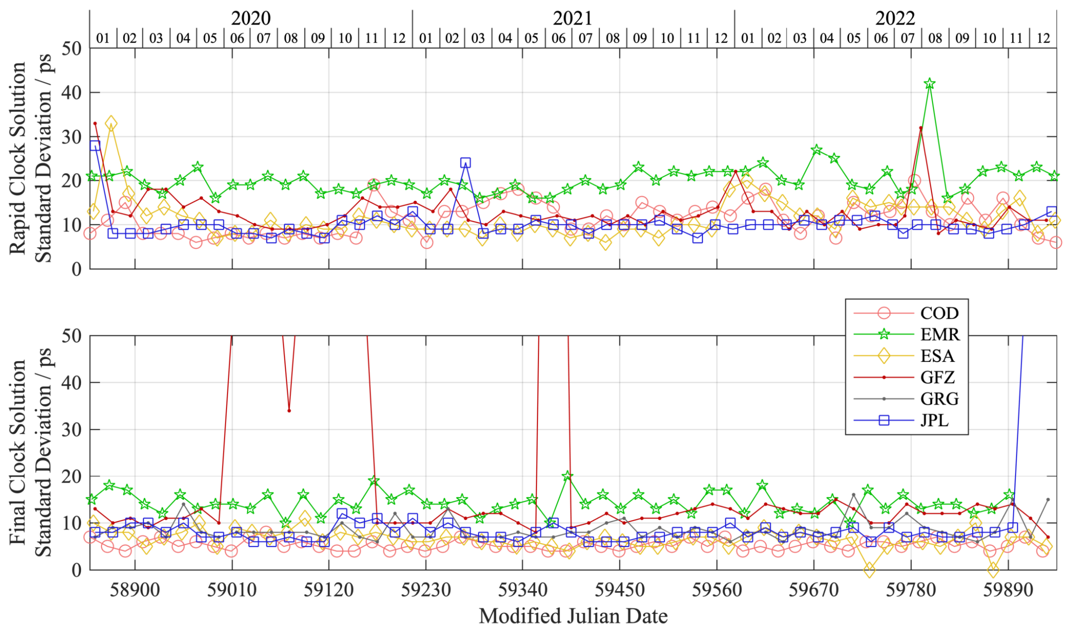

Figure 1: Time series of clock solution precision for weighted AC contributions.

1.1 Reference Time

The reference timescale for the IGS's core products is a clock ensemble consisting of common clock members appearing in the clock combination each day. Since satellite clocks are always part of the combination and since on–orbit clocks are some of the most stable, their contribution in weight to the ensemble has grown over the years.

There are two separate reference timescales, one for the rapid clock products (IGRT) and one for the final clock products (IGST)– we often use the notation IGS(R)T for a general reference to either of these timescales. These reference times are computed on a daily (IGRT) or weekly (IGST) basis by a Kalman Filter based algorithm whose data inputs are the daily combination of the IGS AC solutions. The filter, based on work presented in Coleman and Beard (2020), generates estimates of each clock member using a quadratic clock model and process noise parameters consistent with the type of clock used in each component (satellite or station). Further, GPS clocks are modeled with two periodic components superimposed to the clock phase to account for such observed effects for those clocks Senior et al. (2008).

The two resulting reference times, IGRT and IGST are independently steered to their best internal realizations of UTC each day. The UTC offset from each depends on that day's availability of IGS sites serving as UTC(k) laboratories. Generally, a median computation among available members is chosen, although better stability has recently been found when fixing the weight to the most commonly available site(s). Accuracy of the UTC offset, however, is strongly dependent upon accurate calibration values for the UTC(k) as the IGS clock solution produces the clock offset as observed at the site's antenna phase center.

Table 2 shows the selection of stations that are regularly used for this purpose and the current calibration value between the antenna phase center and on-time point of the external UTC(k). These calibrations are generally updated when a change in that station's solution value is noticed.

Table 2: IGS Sites serving as UTC(k) references for IGS(R)T reference.

Station ID		Calibration Value		No. Days in Combination	
IGS	BIPM	z_k / ns	BIPM CAL ID	2022 Rapids	2022 Finals
BRUX00BEL	OR5Z	203.46	1011 – 2020	365	337
IENG00ITA	IT10	−299.88	1018 – 2022	252	335
NIST00USA	NIST	134.41	1001 – 2020	325	312
OPMT00FRA	OP02	309.72	1001 – 2020	0	318
PTBB00DEU	PT13	184.64	1001 – 2020	36	102
TWTF00TWN	TLT0	18.76	1001 – 2020	363	347
USN700USA	US07	210.96	1001 – 2018	10	291
WAB200CHE	CH05	238.05	1012 – 2016	308	271

These calibration values are confirmed with the database of the BIPM (Bureau International des Poids et Mesures) to ensure that the correct value is logged. All those shown in Table 2 have been validated by some calibration report as cited there. The database for calibration values of UTC laboratories, in general, can be found at:

https://webtai.bipm.org/database

Figure 2 shows the estimated offset of the IGRT timescale with respect to UTC. Earlier plots of this timescale comparison utilized GPST as a pivot timescale and required the assumption that the estimation of GPST in the BIPM's CircularT matched the IGS's clock combination reference. This was never validated, so a new approach to this estimation is taken here where the laboratories of Table 2 serve as pivots.

Each line of the figure is an estimate of IGRT versus UTC as viewed through a particular laboratory, k. We denote this: $\widehat{x}_{\rm I}^{\rm U}[\,k\,]$ and compute

$$\widehat{x}_{\rm I}^{\rm U}[\,k\,] \;=\; \widehat{x}_k^{\rm I} + \widehat{x}_{\rm U}^k - z_k \tag{1}$$

where $\widehat{x}_k^{\rm I}$ is the estimate of the clock at site k versus IGRT at the antenna phase center; $\widehat{x}_k^{\rm I}$ is the BIPM's estimated offset of UTC versus this on-time point of the clock at lab k (as reported in Section 1 of CircularT); and z_k is the calibration value at site k as documented in Table 2.

The cluster of offset estimates in Figure 2 demonstrates that there is consistency among the estimates and measurements applied to Equation (1). The second term on the right side, $\widehat{x}_{\rm U}^k$, is only available in the month following the epoch of data as the BIPM computes UTC on a monthly basis. While the approach of Equation (1) is therefore sound for a post-processing analysis, a daily realization of UTC for the steering operation of IGS(R)T favors only sites that maintain a low offset for $\widehat{x}_{\rm U}^k$.

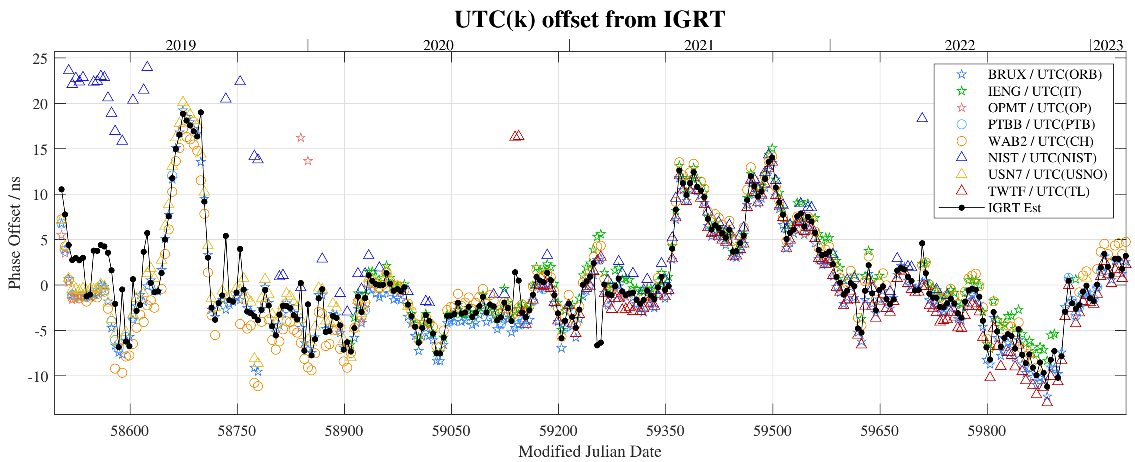

Figure 2: Estimated offset of IGRT from UTC using a subset of UTC(k) stations as pivots.

1.2 Product Files

As of GPS week 2238 (starting 27 November 2022), the published IGS product solutions are named with the long file name format. Table 3 shows the new names convention in the IGS databases compared to the legacy file names for key clock product files. Users should look to these names moving forward but should note the comparison in case solutions from recent history must be obtained. An original plan for the file naming convention is found at lon (2019) and guidelines for the transition are found in detail at lon (2023).

Table 3: Mapping between old and new file name conventions. We use a sample date of 01 July 2022, which is GPS week/day 2216/5 (old files) and day of year 182 (new files).

New File Name	Old File Name
xxx0OPSRAP_20221820000_01D_05M_CLK.CLK.gz Rapid 5 minute clock solution from xxx analysis center.	xxx22165.clk.Z
IGS0OPSRAP_20221820000_01D_05M_CLK.CLK.gz Rapid 5 minute clock combination for satellites and stations; re-referenced to IGRT timescale.	igr22165.clk.Z
IGS0OPSFIN_20221820000_01D_05M_CLK.CLK.gz Final 5 minute clock combination for satellites and stations; re-referenced to IGST timescale.	igs22165.clk.Z
IGS0OPSFIN_20221820000_01D_30S_CLK.CLK.gz Final 30 second clock combination for satellites only; no timescale re-reference.	igs22165.clk_30s.Z
IGS0OPSRAP_20221820000_01D_01D_CLS.SUM.gz Clock combination summary file for 5 minute rapid clock product.	igr22165.cls.Z
IGS0OPSFIN_20221820000_01D_01D_CLS.SUM.gz Clock combination summary file for 5 minute rapid clock product.	igs22165.cls.Z

2 Current Activities and Future Products

The main work continuing in the CPWG is: establishing multi–GNSS products for the core IGS rapid and final clocks and releasing the Clock Exchange file format for use in the community.

2.1 Multi GNSS Clock Products

The re-development of the IGS clock combination utilizes some work done in the PPP-AR WG as a foundation. That work has focused on the combination of satellite clock and bias products together for improved consistency and robustness; see Banville et al. (2020). Some preliminary results of clock combinations (for GPS, GAL, BDS and GLO independently) using the PPP-AR software were presented at the CPWG Meeting in 2019.

Further work has been completed since then at Wuhan University in conjunction with the PPP-AR and has lead to a new multi-GNSS combination for both clocks and signal biases. Relevant background on the approach to estimate these biases can be found in Geng et al. (2019). A reprocessing of historical data (Repro 3 campaign) has been completed on the reprocessed AC clock solutions into a multi–GNSS clock combination. Continued work will be done to address the reference time for this clock data set and mitigation of day boundary jumps.

2.2 Clock Exchange Format

At the request of the IGS Infrastructure Committee, the existing Clock Rinex format should be phased out since it does not contain Receiver Independent Exchange records or data as its key subject. Indeed, timing data observed through a GNSS reception chain is often quite dependent the resident receiver. For this reason, a new format name such as Clock Exchange is being favored to replace this older format. The existing clock data records will not change, but the group is looking at the possibility of promoting records containing other information including:

- calibration records for station clocks;
- frequency estimates for satellite clocks (and possibly predictions);
- day boundary jumps values for all clocks in the combination.

While each of these record types has an existing definition in Clock Rinex, these are almost never utilized. Further, the new file name convention would allow a separate case file for each data type. More details on this format will be made available once this WG has finalized the format and documentation.

2.3 Clock Rinex 3.04

Until the Clock Exchange format is finalized by the working group and approved by the Governing Board, providers and users of the IGS clock products are all encouraged to utilize the Clock Rinex 3.04 format. This format was adopted by the IGS governing board at the 2017 Workshop in Paris.

3 Developments in Critical Timing Issues

Several important developments have taken place in the timing community over the past several years that impact timing and its associated products across GNSS. This WG and some of its members have been involved with these developments in a variety of capacities. While the full effects may not be realized for several years to come, each should be considered now as the impacts may be wide reaching and may have effects on the IGS products in the future.

The BIPM has invested considerable work and research by way of its participating members to four “hot topics" in timing over the past several years. Two of these topics that concern the IGS are: the mutual benefit of GNSS and UTC, and leap seconds in UTC. Each is discussed in more detail in the following subsections.

3.1 Continuous UTC

Since 1972, UTC takes a scheduled insertion of one leap second whenever necessary to maintain the tolerance

$$\mid \mathrm{UTC} - \mathrm{UT1} \mid < 0.9 \text{ sec.}$$

Since this induces a discontinuity in UTC, efforts to end this practice have been ongoing at the ITU-R. This issue has a wide influence and involves many nations, scientific disciplines and operational outfits; see Levine et al. (2023) and Beard (2011). Hence, converging upon an agreed approach has been challenging.

Following a survey from the BIPM's CCTF (Consultative Committee on Time and Frequency) to scientific stakeholders on the use of leap seconds, the IGS formed a position on this issue that was ultimately adopted by the GB in May 2022 lea (2022). This statement emphasized points pertaining to IGS operations including that:

- several files maintained by the IGS (Clock Rinex, Rinex, Sinex) have fields that are impacted by the number of leap seconds or the $\mid \mathrm{UTC} - \mathrm{UT1} \mid$ offset;
- some GNSS providers have not chosen a common number of leap seconds for their system times, leaving several un-aligned system times requiring careful documentation in product files; see rin (2021) and clo (2017) for examples;

- further leap second introductions separate the IGS product timestamps from UTC more and more over time; and,
- discontinuities in UTC have the ability to negatively affect GNSS and timing hardware.

For these reasons, the IGS recommends no additional leap seconds for UTC.

Another approach to handling UTC discontinuities has emerged, however. At the 27th meeting of the General Conference on Weights and Measures (CGPM), Resolution 4 was passed which directs the Comité International des Poids et Mesures (CIPM) to work with relevant organizations and strive for an agreement on a new tolerance level between UTC and UT1. This approach would extend the amount of time between UTC discontinuities but still ensure that these two reference times remain tethered. Among the text of the resolution are a number of key points including that:

- insertion of leap seconds adds discontinuities that risk malfunctions in critical digital infrastructure;
- operators of various networks (including GNSS providers) have taken different approaches to including leap seconds, and there is no existing standard to follow;
- implementation of uncoordinated methods for inserting leap seconds leads to potential problems with synchronization capabilities; and,
- the possibility of a negative leap second is emerging with unknown consequences as such an insertion has been neither considered nor tested.

Continuing discussions will take place moving forward, but a date of 2035 has been identified as a time by which some agreement should be made. Additional notations and details stated by the CGPM can be found in the resolution text at cgp (2022).

3.2 Realization of UTC by GNSS

Another hot topic covered at the CCTF was: Promoting the Mutual Benefit of UTC and GNSS. The production of UTC is facilitated, in part, by links between the scores of time laboratories around the globe. At present, all time labs are connected via GNSS and some 87% of labs are only connected by that method. Other additional methods such as as two–way time transfer are used for some sites.

Among this effort was a subgroup on Traceability to UTC from GNSS Measurements which aimed to formulate how UTC could be available and possibly traceable to end users of GNSS. The findings of this group are applicable to the general accuracy of UTC dissemination using GNSS and any associated receiving equipment. Extensive research was made into each GNSS, their timing components and messages, and the certainty of the time and frequency made available by their signals. Further, different components contributing biases, or needing calibration were also discussed.

The accuracy to which UTC is realized by a typical GNSS user with a receiving system (such as any among the hundreds of IGS sites) is among the cases analyzed by this effort. An analysis regarding this and another relevant points can be found in Defraigne et al. (2022).

4 Charter and Membership

There have been no amendments or changes to the charter since its 2019 update. This WG consists of ex–officio members (those holding other roles within the IGS); representative members (specifically from Analysis Centers or IGS Timing Sites); and at-large members. Representative members are often appointed by the Analysis Center or IGS site to be representatives to the working group. The collection of at–large members is intended to fill or expand the expertise base of the group based on current or on-going activities. The group also strives to maintain a diverse membership both academically and geopolitically. Table 4 shows the current membership as of December 2022. here are a few important points to note.

Table 4: CPWG membership as of December 2022.

Member	Representing	Affiliation
Michael Coleman	Chair	US Naval Research Laboratory
Ken Senior	Previous Chair	US Naval Research Laboratory
Salim Masoumi	IGS ACC	Geoscience Australia
Patrizia Tavella	BIPM Rep to GB	BIPM Time Department
Allison Craddock	IGS Central Bureau Rep	Jet Propulsion Laboratory
Rolf Dach	AC Rep COD	Astronomical Institute, Univ of Bern (AIUB)
Vacant	AC Rep EMR	Natural Resources Canada
Vacant	AC Rep ESA	ESA / European Space Operations Center
Flavien Mercier	AC Rep GRG	Centre National D'Etudes Spatiales (CNES)
Paul Ries	AC Rep JPL	Jet Propulsion Laboratory
Thomas Herring	AC Rep MIT	Massachusetts Institute of Technology
Sharyl Byram	AC Rep USN	US Naval Observatory
Li Min	AC Rep WHU	Wuhan University
Pascale Defraigne	IGS Site Rep BRUX	Royal Observatory of Belgium
Ilaria Sesia	IGS Site Rep IENG	INRiM
Shinn Yan Lin	IGS Site Rep TWTF	Chungwa Telecommunications
Ignacio Romero	At Large Member	Canary Space Consulting (ESA/ESOC)
Giulio Tagliaferro[1]	At Large Member	BIPM Time Department
Jian Yao[1]	At Large Member	UCAR

[1] represents new member

- Salim Masmoumi replaces Michael Moore as the ACC and therefore ex–officio member to this group.
- Ignacio Romero is stepping down as the ESA AC representative, but will remain a working group member.
- Gérard Petit recently retired from the BIPM after a long career in service to the timing community. Patrizia Tavella, the current Head of the BIPM Time Department, now fills that representative role.
- Giulio Tagliaferro, a new member of the BIPM Time Department, has joined the group.
- Jian Yao, a researcher at UCAR has requested to participate in this group as a user of IGS clocks.

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Ionosphere Working Group Technical Report 2022

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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. Claudio Cesaroni (INGV)
4. M. Codrescu (SEC)
5. Anthea Coster (MIT)
6. Joachim Feltens, Telespazio (ESA/ESOC)
7. Mariusz Figurski (TU Gdansk)
8. Pawel Flisek (UWM)
9. Adam Froń (UWM)
10. Alberto Garcia-Rigo (UPC)
11. Reza Ghoddousi-Fard (NRCan)
12. Manuel Hernandez-Pajares (UPC)
13. Pierre Heroux (NRCan)
14. Norbert Jakowski (DLR)
15. Attila Komjathy (JPL)
16. Andrzej Krankowski (UWM)
17. Kacper Kotulak (UWM)
18. Richard B. Langley (UNB)
19. Zishen Li (CAS)
20. Léo Martire (JPL)
21. Angelyn Moore (JPL)
22. Raul Orus (ESTEC)
23. Michiel Otten, PosiTim (SA/ESOC)
24. Ola Ovstedal (UMB)
25. Vergados Panagiotis (JPL)
26. Ignacio Romero, CSC (ESA/ESOC)
27. Stefan Schaer (CODE)
28. Michael Schmidt (DGFI-TUM)
29. Tim Springer, PosiTim (ESA/ESOC)
30. David R. Themens (University of Birmingham)
31. Ningbo Wang (CAS)
32. Rene Warnant (ULiège)
33. Robert Weber (TU Wien)
34. Pawel Wielgosz (UWM)
35. Brian Wilson (JPL)
36. Yunbin Yuan (CAS)
37. Qile Zhao (WHU)

3 Key Issues

a Activities of eight IGS ionosphere Associated Analysis Centres regarding GIMs: CODE, UPC, ESA, JPL, NRCan, CAS, WHU, OPTIMAP (GIMs).

b Activities of UWM IAAC regarding ROTI maps.

c Operation of combined real-time IGS Global Ionospheric Maps (GIMs).

4 Key accomplishments

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

b IGS TEC fluctuation product generated by UWM (ROTI polar maps) – already present in CDDIS and its extension towards low latitudes and Southern Hemisphere.

5 Current IGS ionosphere products

5.1 IGS combined global ionospheric maps (GIM)

Currently the VTEC combined maps in the IONEX format include:

- Final solution with ≈11 days latency and weekly updates
- Rapid solution with less than 24-hour latency and daily updates

Both products are arranged in grid maps with resolution of 5 deg (longitude) by 2.5 deg (latitude) and 2 hours in time. However the products elaborated by different IAACs may have different temporal resolution — from 15 minutes up to 2 hours.

Currently, in cooperation with the Real-Time IGS WG, the Real-Time combined product based on the four IAACs is also provided (Li et al., 2020; Liu et al., 2021).

Combination of the VTEC maps provided by the IACC: The combined IGS maps are obtained as a simple weighted mean of the available IAAC VTEC maps, by using the values obtained during evaluation process.

Evaluation of the VTEC maps provided by the analysis centers: for the evaluation process the STEC variation values, directly obtained from carrier phase observations from a certain subset of test stations, are used. Based on that the root mean square errors are calculated for each IAAC products (i.e. by using the "Self-Consistency Test", see Orus et al., 2007). The weights for combination are the inverse of obtained squared RMS.

Validation of the combined IGS VTEC products is done time to time by comparison with the reference VTEC values provided by dual frequency altimeters on board JASON satellites. Because the altimeters are working over Oceans, where the number of stations is limited and maps are mostly based on interpolation, this comparison can be considered as a pessimistic determination of the global VTEC map actual errors.

The combination methodology and the results of validation are described in detail by Hernández-Pajares et al. (2009, 2017) and Roma-Dollase et al. (2018).

5.2 IGS ROTI fluctuation maps for the Northern hemisphere

Since 2014 UWM provides the IGS diurnal ROTI maps to characterize ionospheric irregularities occurrence over the Northern hemisphere.

The product is based on raw GNSS observations from ≈700 ground-based GNSS stations. The resulted maps show spatial variations of the GNSS-based index ROTI (Rate of TEC Index) that are plotted in a polar view projection within a range of 50° – 90° N in geomagnetic latitude (MLAT) and 00–24 magnetic local time with resolution of 2 deg × 2 deg. The polar ROTI fluctuation maps are available as a daily solution with 11 days latency and weekly updates.

Table 1: Available products with their old and new filenames.

File type	Old short name	New long name
Final combined IONEX	`igsgddd0.yyi.Z`	`IGS0OPSFIN_yyyyddd0000_01D_02H_GIM.INX.gz`
Rapid combined IONEX	`igrgddd0.yyi.Z`	`IGS0OPSRAP_yyyyddd0000_01D_02H_GIM.INX.gz`
ROTI (Northern hemisphere)	`rotiddd0.yyf.Z`	`IGS0OPSFIN_yyyyddd0000_01D_01D_ROT.INX.gz`

`ddd`: day of year [001…366] `yy`: 2-digit year `yyyy`: 4-digit

ROTI index is calculated as a standard deviation of the the time-derivative of the TEC estimation obtained from the frequency-differenced GNSS phase delay.

Methodology and results of the ROTI fluctuation products were presented by Cherniak et al. (2014, 2018, 2022). Currently the ROTI fluctuation product is being expanded to cover also the Southern hemisphere and equatorial region with use of over 1200 ground-based GNSS permanent stations.

Ionospheric products are available through CDDIS:
`https://cddis.nasa.gov/archive/gnss/products/ionex/YYYY/DDD/`
where `YYYY` is the year and `DDD` – the day of the year identification
product's visualisation, WG publications and membership are available at `https://igsiono.uwm.edu.pl/` .

The ionospheric products since GPS week 2238 (November 26, 2022), are in transition to the IGS long product filename convention. The available products are listed in Table 1 together with their previous short names and new long names.

6 Webpage development

A new dedicated IGS Iono Working Group webpage established at University of Warmia and Mazury in Olsztyn, Poland server is meant to allow users to quickly access detailed information regarding:

- IGS Iono WG combined final and rapid GIM products and their quality (RMS maps) – the current visualisations and database cover the period since the beginning of the year 2022.
- IGS ROTI fluctuation maps for northern hemisphere since the beginning of the year 2022.
- Details of combination and validation process used to generate combined Global Ionospheric Maps.
- List of the most impactful papers published by the members of Iono WG.

- Membership of Iono WG.
- IGS Iono WG mailing lists addresses.

The webpage is already fully functional, yet its functionality is planned to be extended over time, according to the user's needs and new products being introduced. Particularly, information about IAACs, the methodology they incorporate and contact persons will be added shortly. The igsiono.uwm.edu.pl webpage is to become the main knowledge base for Iono WG members and product's users regarding crucial information about publications, methodology and products.

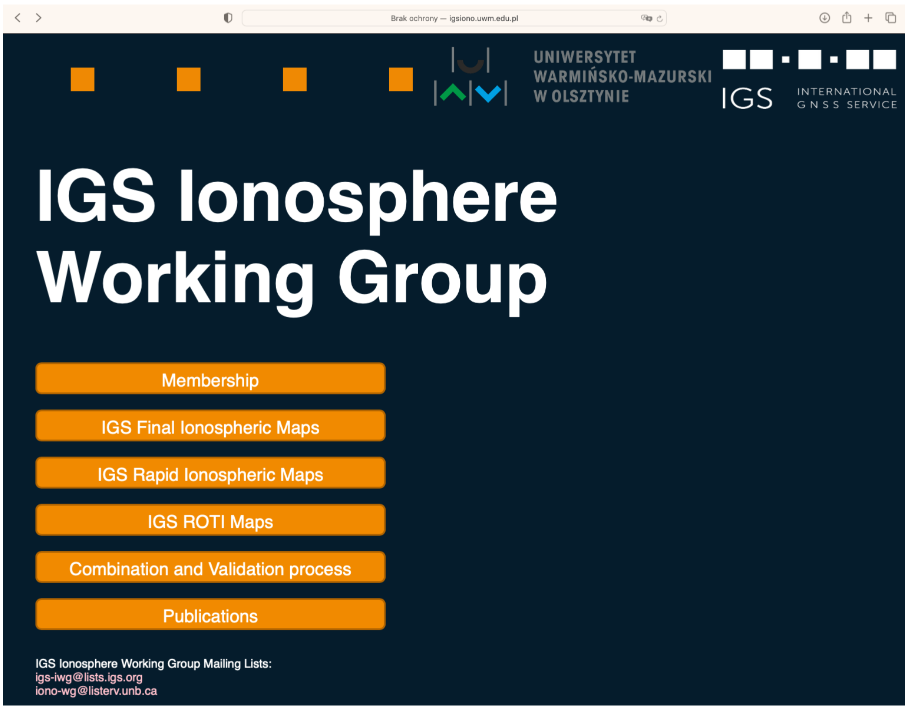

Figure 1: The main page of igsiono.uwm.edu.pl

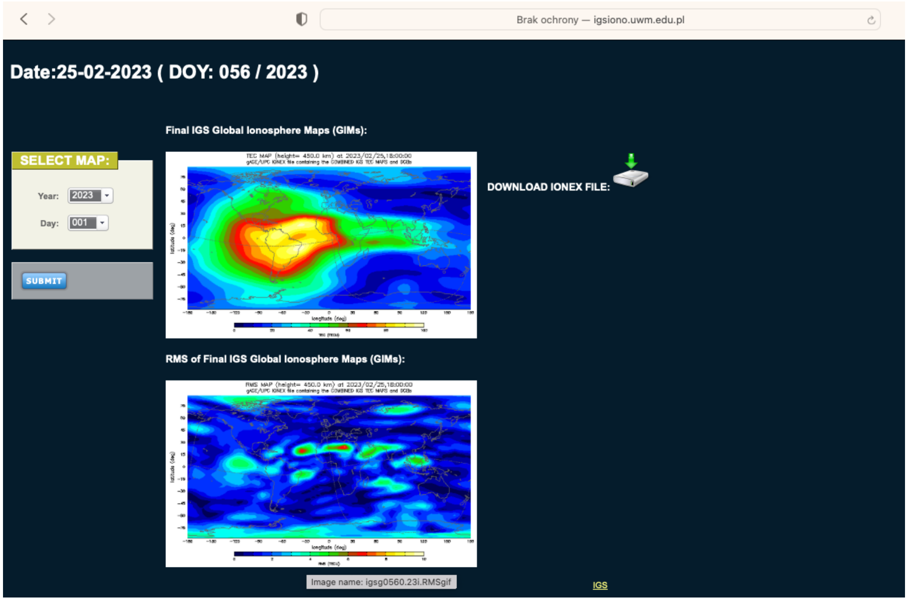

Figure 2: Final IGS Global Ionosphere Maps subpage

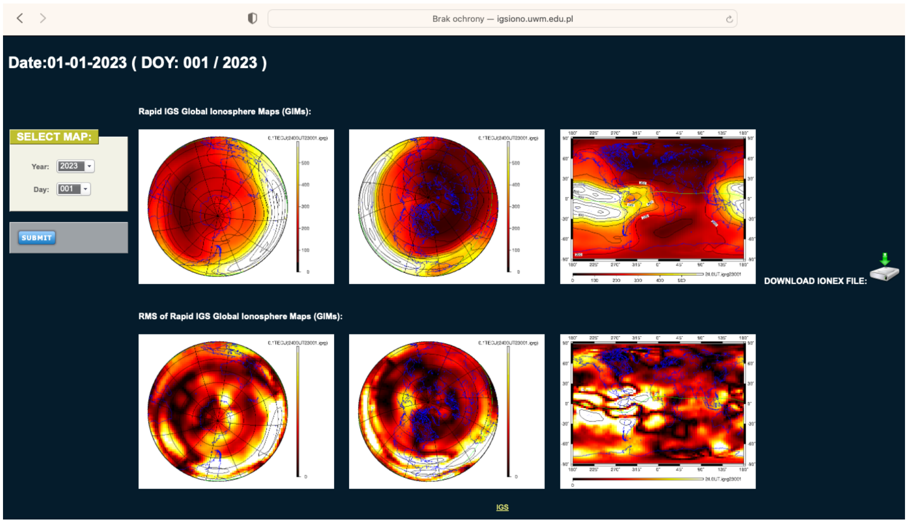

Figure 3: Rapid IGS Global Ionosphere Maps subpage

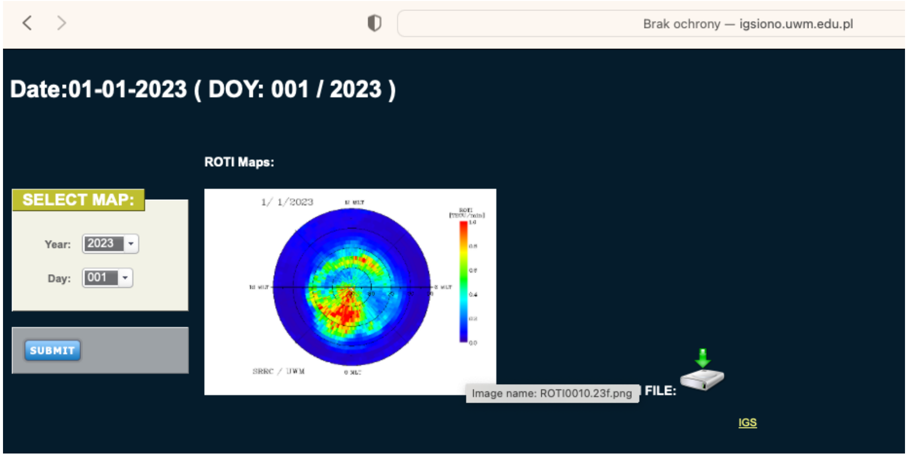

Figure 4: IGS ROTI maps subpage

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Multi-GNSS Working Group Technical Report 2022

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1 Introduction

The inclusion of *all* GNSS in *all* IGS products is the ultimate goal of the Multi-GNSS Pilot Project (MGEX) of the IGS Multi-GNSS Working Group (MGWG). Combined orbits and clocks are the key product of the IGS. In order to facilitate the development of a combined multi-GNSS orbit and clock product, the IGS combination task force was initiated in fall 2022. Although not directly affiliated with the MGWG, its members significantly contribute to this task force.

2 GNSS Evolution

The most recent Galileo satellites E223 and E224 launched in 2021 were finally declared healthy on 29 August 2022. Before that, E224 was used for tests of INAV message improvements (NAGU 2022027, 2022) reducing the overall time for a first position fix. The roll-out of this feature to all Galileo FOC satellites started in October 2022 and is expected to be completed in May 2023 (NAGU 2022037, 2022). The further deployment of the Galileo constellations was halted by the war between Russia and Ukraine making Soyuz launches from Kourou impossible. The next Galileo dual launch is planned for the end of 2023 with Ariane 6.

Table 1 lists the GNSS satellite launches of the year 2022. After a break of more than two years, launches of GLONASS spacecraft resumed: two GLONASS K1B satellites as well as the last GLONASS M+ satellite were launched.

Table 1: GNSS satellite launches in 2022.

Date	Satellite	Type
07-Jul-2022	GLONASS K1B	MEO
10-Oct-2022	GLONASS K1B	MEO
10-Nov-2022	GLONASS M+	MEO

The interface control document for the Galileo High Accuracy Service (HAS) was published in May 2022 (European Union, 2022c). First results of the HAS are given in Fernandez-Hernandez et al. (2022) and Hauschild et al. (2022). For the Galileo Open Service Navigation Message Authentication (OSNMA), the Signal-in-Space Interface Control Document (ICD, European Union, 2022a) as well as receiver guidelines (European Union, 2022b) were published. Septentrio PolaRx5 receivers widely used in the IGS network support this feature starting with firmware version 5.5.0 published in August 2022. Official initial services of OSNMA are planned for the first half of 2023 (de Smet, 2022).

In March 2022, the first QZSS satellite launched in 2010 was decommissioned. Its successor is the QZS-1R spacecraft launched in October 2021, declared operational in March 2022 and thus keeping the number of active QZSS satellites constant.

3 Network

As of January 2023, the IGS multi-GNSS tracking network comprises 394 stations, see Figs. 1 and 2. Compared to 2021, this is an increase of 24 stations. Nine stations of these stations are completely dormant and did not provide any observations in 2022.

4 Products

Table 2 lists the analysis centers (ACs) contributing orbit and clock products to the IGS Multi-GNSS Pilot Project. Like for the legacy IGS products, most ACs switched to the IGS20 reference frame and the igs20.atx antenna model on November 27, 2022 (GPS week 2238). Two ACs continue to provide their products in the IGS14 frame. Wuhan University switched the sampling of their SP3 files from 15 to 5 min together with their transition to IGS20 and igs20.atx. JAXA started the provision of daily ERP files in 2022 and submitted such files back to June 2017.

Multi-GNSS differential code bias (DCB) products are generated by CAS and GFZ (daily rapid products) as well as DLR (quarterly final product). Together with the switch to IGS20/igs20.atx, satellite antenna phase center offsets (PCOs) should be considered in the generation of DCB products. More details on this topic are given in Wang et al. (2022).

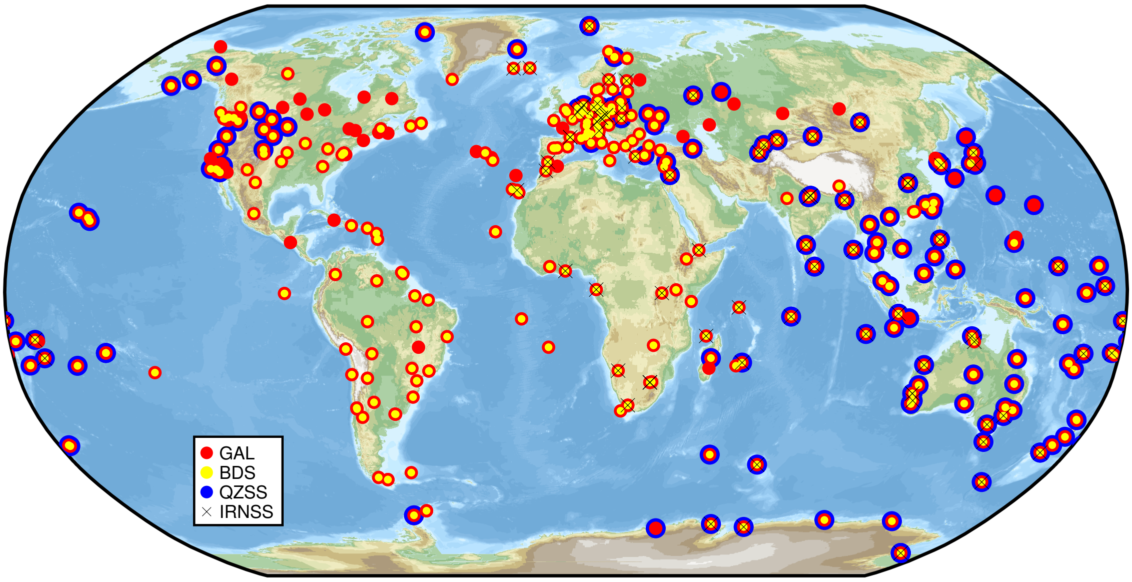

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2023.

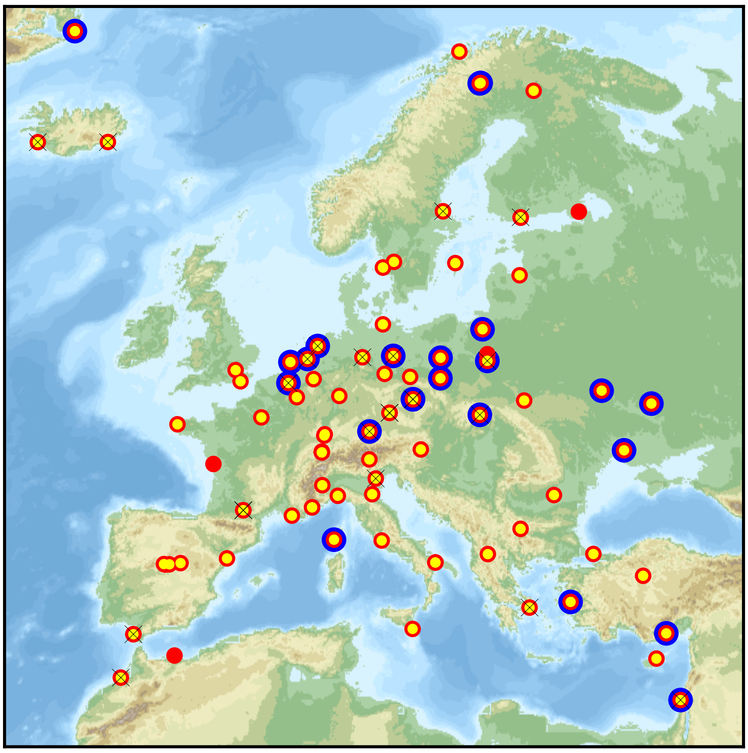

Figure 2: Distribution of European IGS multi-GNSS stations as of January 2023. See Fig. 1 for explanation of individual station labels.

Table 2: Analysis centers contributing to IGS MGEX as of December 2022.

Institution	Abbr.	GNSS	IGS20/igs20.atx
CNES/CLS	GRG0MGXFIN	GPS+GLO+GAL	27 Nov. 2022
CODE	COD0MGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS	27 Nov. 2022
GFZ	GFZ0MGXRAP	GPS+GLO+GAL+BDS2+BDS3+QZS	27 Nov. 2022
IAC	IAC0MGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS	–
JAXA	JAX0MGXRAP	GPS+GLO+QZS	27 Nov. 2022
SHAO	SHA0MGXRAP	GPS+GLO+GAL+BDS2+BDS3	–
Wuhan University	WUM0MGXFIN	GPS+GLO+GAL+BDS2+BDS3+QZS	11 Dec. 2022

CAS already started to provide a DCB and OSB product considering satellite antenna PCOs on 172/2022 labeled `CAS1MGXRAP`. This product is only available at the CAS ftp server `ftp.gipp.org.cn/product/dcb/mgex/`.

GFZ started the generation of a rapid DCB and OSB product labeled `GBM0MGXRAP` with day of year 321/2022 both considering PCO and PCV corrections (Deng, 2022). The quarterly DLR DCB files do not consider PCOs for the first three quarters of 2022. As the switch to the convention to apply PCOs occurred during the 4th quarter, separate DCB files are provided for days before and after November 27. QZSS C1C-C1L DCBs are included in the DLR product starting with the first quarter of 2022.

Since 1/2022, DLR provides a merged broadcast ephemerides product in RINEX 4.00 format (Montenbruck and Steigenberger, 2022). This product is labeled `BRD400DLR` and utilizes the new features of the RINEX 4.00 format (Romero, 2021) for modernized navigation messages like GPS CNAV, e.g., Earth rotation parameters (Steigenberger et al., 2022).

5 Satellite Metadata

The availability of satellite metadata like unique identifiers, satellite mass and transmit power is essential for the generation of high-precision GNSS products. The IGS satellite metadata file is maintained by the German Aerospace Center (DLR) and available at `https://files.igs.org/pub/station/general/igs_satellite_metadata.snx`. Whereas a description of the individual SINEX blocks including examples is available at the MGEX website at `https://igs.org/mgex/metadata/#metadata-sinex-format`, a formal description of the file format was lacking so far. A draft of the *IGS Satellite Metadata File Description* was discussed during the IGS Workshop 2022. The revised version of this document (Steigenberger and Montenbruck, 2022) was formally approved by the IGS Governing Board in December 2022.

Antenna phase and directivity patterns of the GPS III satellites were made available in October 2022 by the manufacturer Lockheed Martin (Fischer, 2022). They complement the GPS III antenna phase center offsets already published earlier.

6 Combination Task Force

In a call for participation issued in July 2022, the IGS has invited interested experts to form a new task force dedicated to the advancement of IGS product combination in a multi-GNSS context. While triggered by a recommendation of the IGS MGWG and currently chaired by the same person (O. Montenbruck), the new combination task force constitutes an independent entity, which aims to coordinate and advance existing efforts for product combination across the various IGS bodies (e.g., Mansur et al., 2022).

A total of 15 individuals from 7 institutions replied to the call and offered to participate in the new task force:

- DLR: Oliver Montenbruck, Peter Steigenberger
- GA: Salim Masoumi
- GFZ: Andreas Brack, Gustavo Mansur
- JAXA Kyohei Akiyama, Toshitaka Sasaki, Hiroshi Takiguchi
- SHAO: Bin Wang
- TUM: Bingbing Duan, Urs Hugentobler
- Université Paris-Cite: Paul Rebischung, Pierre Sakic
- Wuhan University: Guo Chen, Jianghui Geng

The members agreed on the following overall goals of the combination task force:

- Review and trade-off of existing concepts, algorithms, and tools for multi-constellation product combination within and outside the IGS
- Quality assessment and identification of harmonization needs for the various products to support combination (e.g. constellations, SP3 step size, availability of ERP, SINEX and attitude data, etc.)
- Definition and consolidation of requirements for a harmonized IGS product combination tool and process covering the needs of different IGS entities (Which types of products, which constellations, which satellites? Basic concepts and algorithms)
- Definition of a roadmap and responsibilities for generation of a consolidated combination tool chain; progressive build-up of a combined-product portfolio within the IGS

The work shall focus on the combination of orbit, clock/bias, and optionally frame-related products. In accord with the IGS strategic goal of “Multi-GNSS Excellence”, the combination shall aim to cover a reasonably wide range of different GNSSs. On the other hand, the combination of multi-GNSS troposphere and ionosphere products is beyond the scope of the task force and should be independently covered by the respective IGS working groups.

In a kick-off meeting in September 2022 it was agreed that the task force will initially focus on the orbit/clock/bias combination process in support of multi-GNSS PPP users. As a first step, the combination of orbit products without prior frame alignment will be addressed. For this purpose, a set of key requirements for a future IGS orbit combination software was compiled. Dedicated studies were conducted to address the step size and coverage of orbit products for input to the combination. Given large interpolation errors for the slightly eccentric orbits of two Galileo satellites and the increased interpolation errors near the begin and end of the daily data arcs, a 15-min step size was considered infeasible and all analysis centers will be requested to transition to 5-min orbit products. Likewise, it is desired to include the end-of-day midnight epoch into the individual orbit products to support proper interpolation of orbit data just prior to midnight (23:55 – 24:00) for the future clock combination. For the actual software implementation, Python has been selected as a programming language to make best use of prototype software already available at some of the participating institutions.

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
GA Geoscience Australia
GFZ Deutsches GeoForschungsZentrum
IAC Information and Analysis Center for Positioning, Navigation and Timing
JAXA Japan Aerospace Exploration Agency
SHAO Shanghai Observatory
TUM Technische Universität München
WU Wuhan University

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Precise Point Positioning with Ambiguity Resolution Working Group Technical Report 2022

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1 Introduction

The precise point positioning with ambiguity resolution (PPP-AR) working group (WG) has been established since 2018, dedicated to generating modernized clock/bias combined products to enable AR at the user end. The goal of PPP-AR WG contains two phases: assessing and improving the interoperability of clock/bias products from different analysis centers (ACs) in the first phase, and providing qualified IGS combined products in the second phase.

By the end of 2021, 7 ACs had been providing phase biases, with interoperability of part of them initially demonstrated (Banville et al., 2020)); the format of satellite attitude quaternions and the software to generate them had been decided (Loyer et al., 2021; Strasser et al., 2021), as well as the bias format description Bias SINEX v1.0 (Schaer, 2016); the task of clock combination in Repro3 had been taken as a chance to develop a modernized clock/bias combination software, preparing for the routine phase clock/bias combination in future.

In 2022, after the IGS workshop in June, Dr. Jianghui Geng took over the chair position of the PPP-AR WG. In the past year, the task of phase clock combination in Repro3 was completed, with a modernized software open-source to IGS; inconsistency from frequency-dependent PCO corrections in bias products was discussed among ACs, and finally, a new keyword was added in Bias-SINEX; decimal digits for attitude quaternions were investigated to cut down the file size; an efficient method to externally correct or remove the PCO effects from bias products was proposed with Geoscience Australia.

2 A new keyword for antenna phase centers in Bias-SINEX

After the virtual meeting of the IGS PPP-AR WG held on 16th September 2021, ACs of the IGS have agreed that the frequency-specific antenna phase centers result in inconsistencies among the geometry-free (GF) biases such as differential code biases (DCBs) and wide-lane (aka Melbourne-Wübbena) biases. The old convention did not cover this issue and needed an update. Between the IGS Workshop and the switch to ITRF 2020, contributors of WG had a series of discussions to have a new convention. Finally, all ACs were required to apply the antenna phase center offset corrections (APC) to geometry-free combination observables, and a new keyword "APC_MODEL" for antenna phase center corrections was added in the Bias-SINEX format description.

The APC model has been considered in the generation of both code and phase bias products. The BDS-2 group delay variations were discussed but no agreement has been reached, despite that some ACs have already corrected it into code biases. A new keyword "APC_MODEL" was added to the section "BIAS/DESCRIPTION" in the format of "APC_MODEL igs20_WWWW.atx", once APCs were considered for GF biases. The new keyword brought two advantages to our current work. On one hand, it is a reminder for users to apply the same PCO corrections in their processing; on the other hand, the keyword could make product combination easier since diversities of ACs still exist in the convention and the antenna file.

After the switch to ITRF 2020, 4 ACs provide daily phase bias products (Table 1). Daily bias products including COD, GFZ, GRG, and WHU have followed the new convention.

Table 1: Daily bias products and contributors

Center for Orbit Determination (COD)		
Product Line	Key Word	Start Date
Final	APC_MODEL IGS20	2022-331
MGEX	APC_MODEL IGS20	2022-331
German Research Center for Geosciences (GFZ)		
Product Line	Key Word	Start Date
MGEX	APC_MODEL IGS20_WWWW	2022-331
Centre National d'Études Spatiales/Collecte Localisation Satellites (GRG)		
Product Line	Key Word	Start Date
FINAL	APC_MODEL IGS20_WWWW.ATX	2022-331
Wuhan University (WHU)		
Product Line	Key Word	Start Date
MGEX	APC_MODEL IGS20_WWWW.ATX	2022-331

3 Phase clock/bias combination in Repro3

The phase clock/bias combination work in Repro3 has been well completed (IGSMAIL #8248) and the combined products from 1995 to 2020 were uploaded to `https://cddis.nasa.gov/archive/gnss/products/repro3/`. 9 ACs' repro3 clocks were involved in combination work, four of which provided phase biases, including CODE, EMR/NGS, GRG, and TUG. For products of earlier years, from 1995 to DOY 123 of 2000, only legacy clocks were combined since no phase biases were provided except TUG. For products from DOY 124 of 2000 to 2020, both clock and phase biases were taken into consideration in the combination.

The RMSE of difference between combined clock products and those from each ACs demonstrates the consistency of the combined clocks. GPS, GLONASS, and Galileo consistency are shown in Figure 1, Figure 2, and Figure 3 , respectively. Figure 1 and Figure 3 show a significant improvement over time in terms of product consistency for GPS and Galileo. According to Figure 2, the consistency of GLONASS legacy clocks is improving in general but the RMSE is always larger than GPS and Galileo.

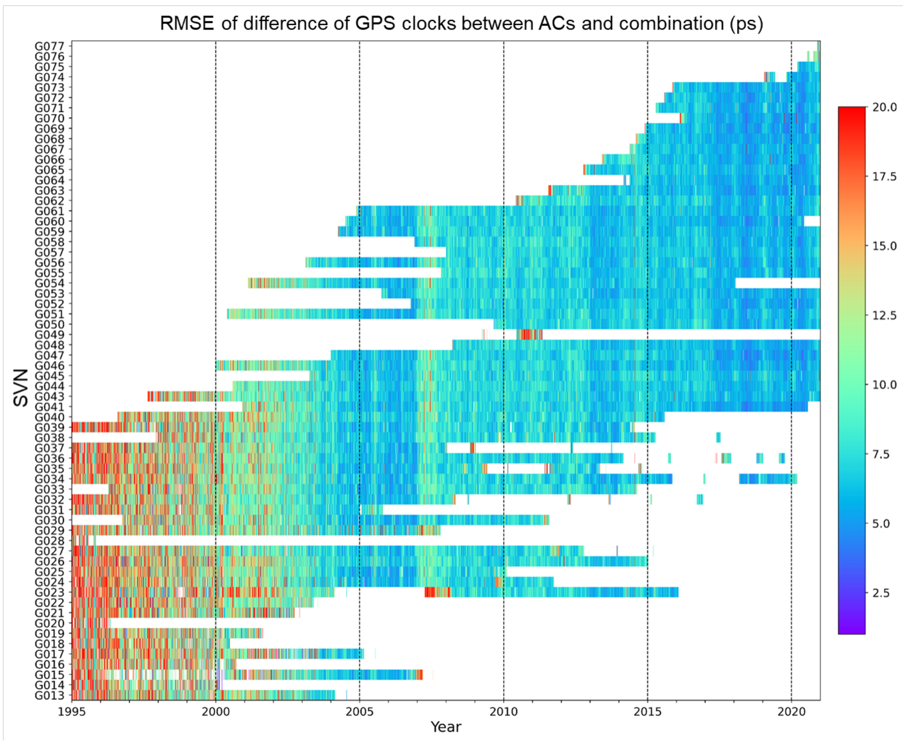

Figure 1: Consistency (ps) of GPS clocks between ACs and combination from 1995 to 2020 .

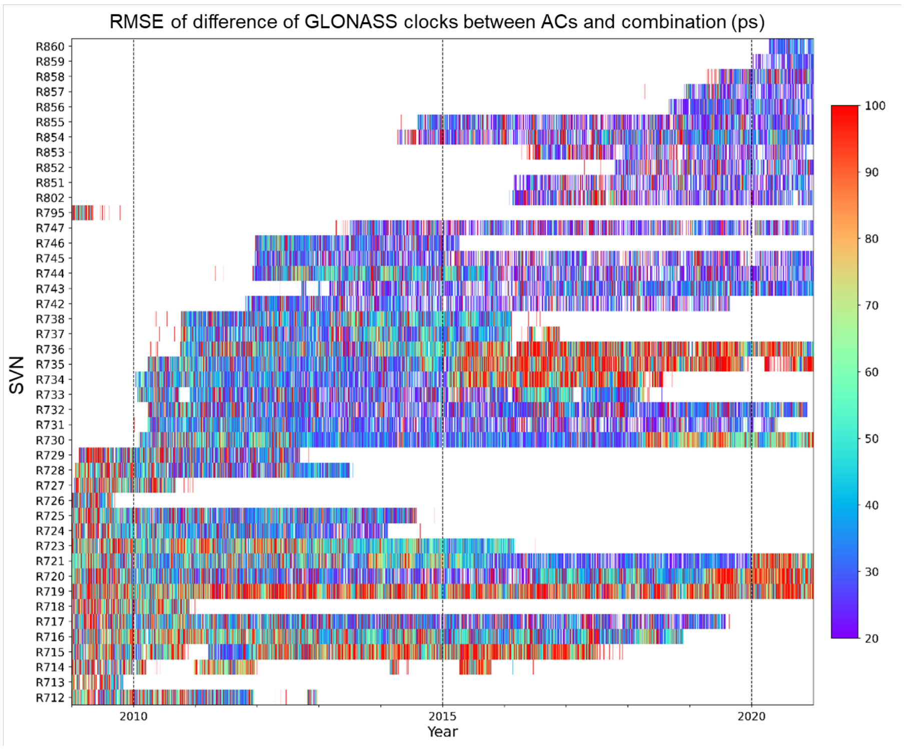

Figure 2: Consistency (ps) of GLONASS clocks between ACs and combination from 2009 to 2020 .

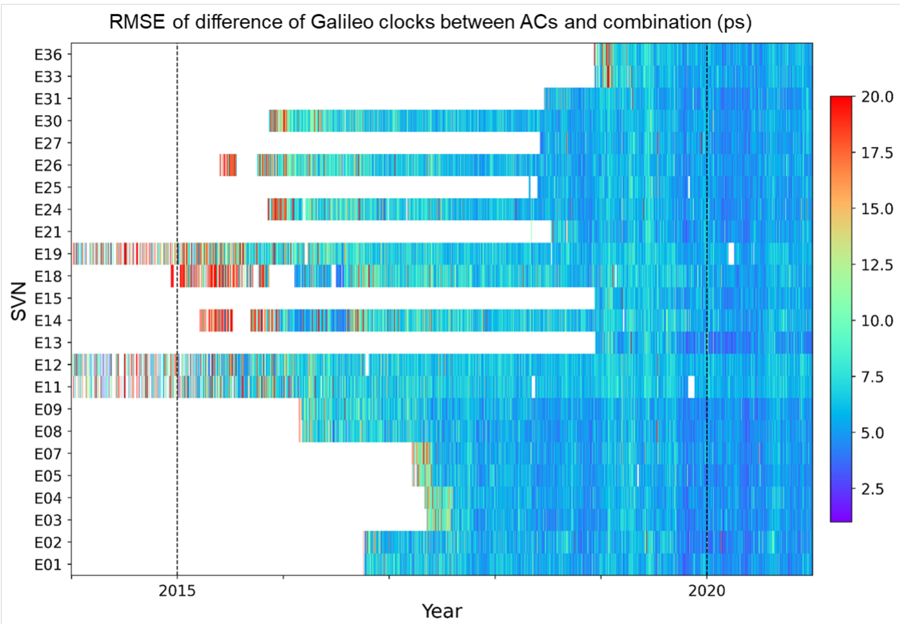

Figure 3: Consistency (ps) of Galileo clocks between ACs and combination from 2014 to 2020 .

4 Decimal digits for attitude quaternions

The satellite attitude demonstrates the orientation of GNSS satellites in space. The inconsistent attitude model adopted between the server and user side could harm the PPP-AR solutions. Therefore, IGS was committed to promoting satellite attitude quaternion products based on the ORBEX format (Loyer et al., 2021). Up to the end of 2022, four ACs including COD, GFZ, GRG, and WUM have provided attitude products. However, the ORBEX specification specifies 16 decimal places for quaternions, such that the file size of a 30 s-rate attitude product could be more than 30MB, which is a burden for storage and transmission. Meanwhile, the decimal digits of ESA's SWARM satellite attitude product are generally 6 to 7 (Olsen et al., 2013). If GNSS adopts the same decimal digits, the file size could be cut down significantly.

In PPP-AR processing, attitude quaternions are used to correct PCO offsets and phase wind-up effects, thus a proper reduction of decimal digit is ought to keep PCO and phase wind-up corrections degrading at a tolerant level. Experiments showed that the difference of PCO corrections between a decimal place of 16 and 5 is around 0.05mm and a decimal digit reduction to 6 or 7 has an even smaller, negligible effect on the PCO corrections, as listed in Table 2.

Figure 4 shows the PCO correction degradation for each satellite in the maximum direction from 16 decimal digits to 6 . Due to the large PCO offsets of the BDS and GLONASS satellites, the PCO difference calculated with different decimal digits is certainly more significant than that of GPS and Galileo satellites. However, the result shows that the PCO difference is mostly below 0.005 mm, and the average value of the PCO difference for all satellites is around 0.0025 mm. That is to say, 6 decimal digits may be proper considering the accuracy of PCO corrections.

As for the phase wind-up effects, Figure 5 shows the maximum value of phase wind-up difference calculated with 6 and 16 decimal places. The maximum value of the phase wind-up difference for each system is almost equal, with an average value of 0.000000262 cycle, which is negligible in GNSS date processing.

Table 2: The maximum difference for all satellites between PCO calculated with different decimal quaternions and PCO calculated with 16 decimal quaternions.

Decimal digits	ΔX (mm)	ΔY (mm)	ΔZ (mm)
3	5.044	4.909	4.792
5	0.050	0.051	0.052
6	0.00745	0.00511	0.00480
7	0.000501	0.000501	0.000504

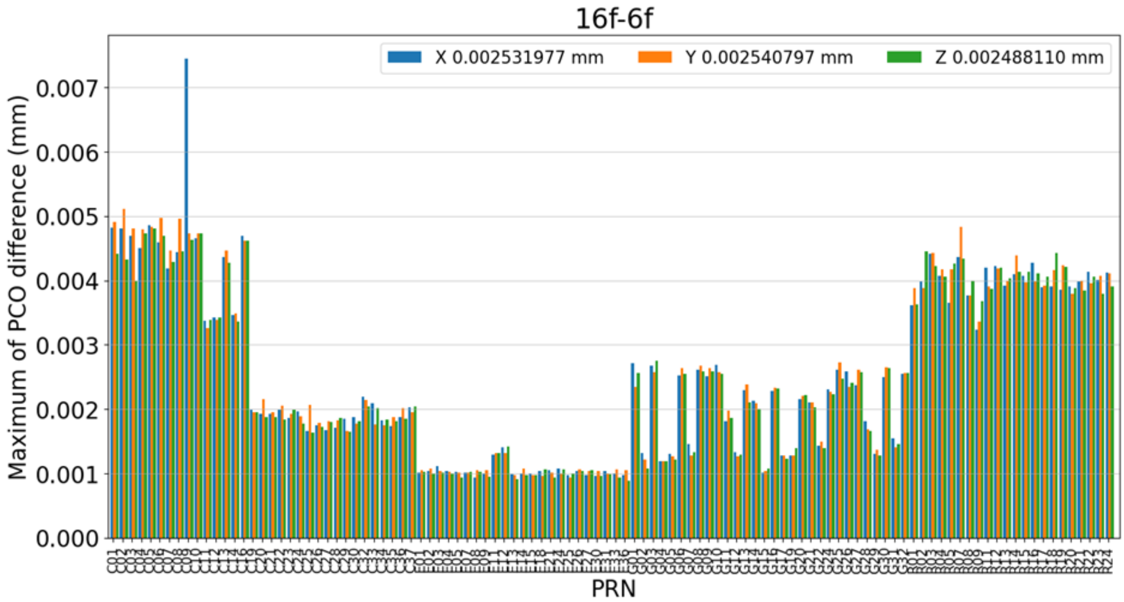

Figure 4: The maximum difference (mm) for each satellite between PCO corrections calculated with 6 decimal quaternions and those calculated with 16 decimal quaternions.

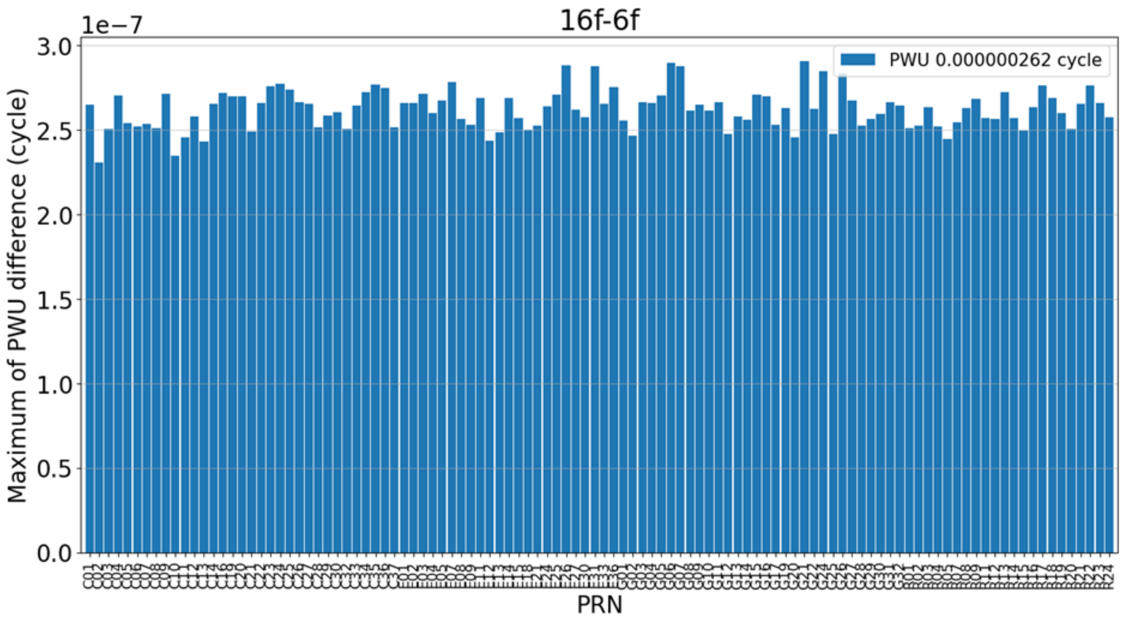

Figure 5: The maximum difference (cycle) for each satellite between phase wind-up effects calculated with 6 decimal quaternions and those calculated with 16 decimal quaternions.

By reducing the number of decimal digits from 16 to 6 on that day, the file size of the attitude product is reduced from 31 Mb to 21 Mb. Therefore, a decimal digit of 6 is recommended to provide attitude products.

5 Outreach

The PPP-AR working group and Geoscience Australia have recently collaborated on an article titled "Correcting Antenna Phase Center Effects to Reconcile the Code/Phase Bias Products from the Third IGS Reprocessing Campaign", published on the GPS Solution. The article referred to the issue of PCO, which has been recognized as "APC_MODEL" keyword later, and proposed an efficient PCO correcting method.

The inconsistency among the code/phase bias products from different ACs was caused by their different approaches to handle satellite antenna phase center (APC) effects. To address this issue, this article proved that z-PCO corrections could be additionally applied to bias products to improve the interoperability of bias products, and this simplification harms almost nothing for AR performance.

With this approach, the combined clock/bias products significantly reduce the inconsistency with all ACs' satellite clock/bias products, as demonstrated in Figure 6, Figure 7, and Figure 8, where the average combination residuals of DCB and wide-lane phase biases are within 0.1 ns and 0.03 cycles, respectively. The correction method proposed in the article has been adopted in the generation of IGS repro3 clock/bias combination products.

6 Future work

Over the upcoming year, the main focus of the PPP-AR WG will be the routine combination of daily clock/bias products, as well as their assessment in the form of clock consistency and PPP-AR performance. The assessment results will be presented on the IGS website.

Moreover, QZSS phase biases and multi-frequency phase biases should studied. BDS-3 AR performance is still inferior to GPS and Galileo. How to improve BDS-3 bias products will be one of the next topics in the generation of bias products.

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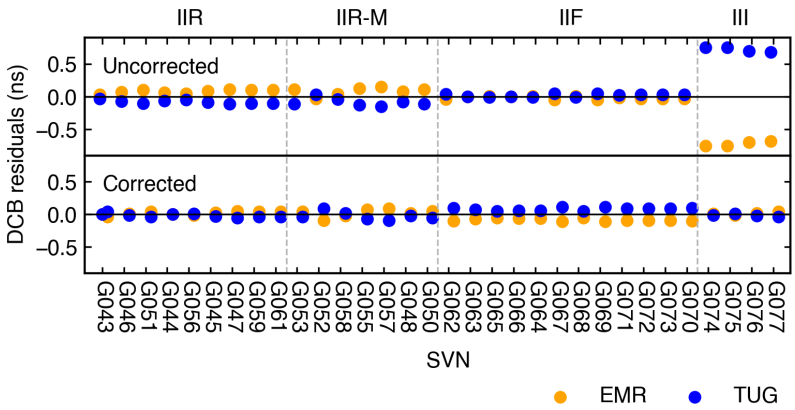

Figure 6: Mean residuals (ns) from the DCB combination in 2020 for each GPS .

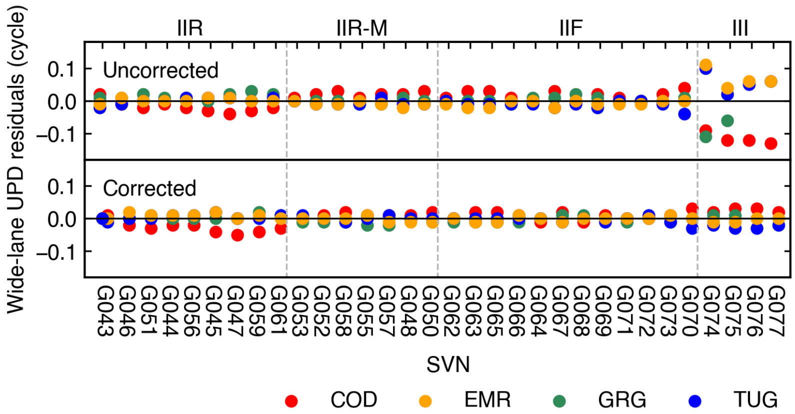

Figure 7: Mean residuals (cycle) from the wide-lane UPD combination in 2020 for each GPS satellite.

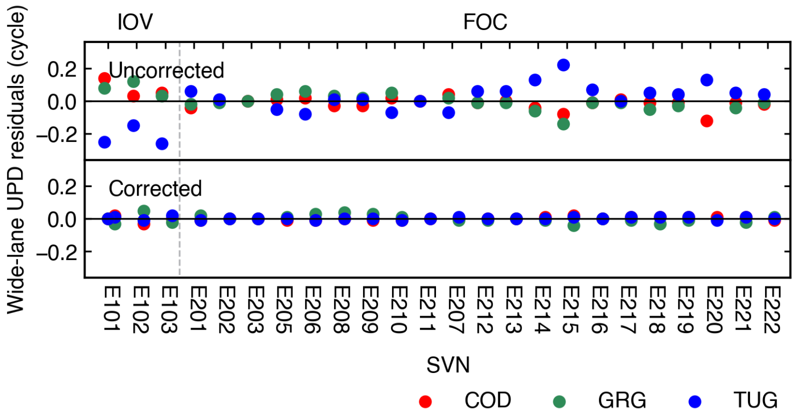

Figure 8: Mean residuals (cycle) from the wide-lane UPD combination in 2020 for each Galileo satellite.

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IGS Real-Time Working Group Technical Report 2022

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1 Introduction

The IGS Real-Time working group held telephone conferences in 2022 in March and November as well as a full session during the virtual IGS workshop in June. A comprehensive summary of these telephone conferences and the workshop session is provided in this technical report.

2 Successor for RT-WG Chair

After four years of service, André Hauschild has stepped down from the position of real-time working group chair in December 2022. The working group chair will in the future be assisted by a vice-chair, which is a newly created position for this and other working groups of the IGS. An online vote has been conducted among the members of the real-time working group for the positions of chair and vice-chair. A total of 52 valid votes have been submitted for two candidates. Based on the results, the IGS Central Bureau has approved Axel Rülke (BKG) as the new RT-WG chair and Ningbo Wang (CAS) as the new RT-WG vice-chair effective January 2023.

3 BeiDou B2b-PPP Correction Service

A data stream generated from the BeiDou-3 PPP correction service on the B2b frequency is hosted on the CAS caster. Conversion to IGS-SSR and potential relaying to IGS casters is discussed. Interested users can get access to raw correction streams on CAS caster.

4 Security of real-time casters

For a number of regional and global casters it was possible to stream data to them without authentication. The caster operators have been contacted and the issue has been fixed in the meantime. The next step is to think about the overall streaming architecture. More secure protocols are needed to transport information offline or real-time.

5 IGS Workshop

The real-time session at the IGS workshop started with an overview of the completed tasks and achievements since the last workshop. Then, the following four presentations on scientific use cases for real-time products have been given:

- **Qi Liu** (UPC)
  "The cooperative IGS RT-GIMs: a global and accurate estimation of the ionospheric electron content distribution in real-time"
- **Tomasz Hadas** (UPWR)
  "Overview of real-time GNSS meteorology: ZTD accuracy, horizontal gradients, low-cost receivers"
- **Xinyuan Jiang** (GFZ)
  "Real-Time GNSS processing for geohazard early warning: implementation in the EWRICA project"
- **Attila Komjathy** (JPL)
  "Ionospheric Detection of the 2022 Tonga Event Using Real-Time GDGPS Observations"

The remainder of the session was a collection of ideas for the development of a future roadmap of the working group and compile workshop recommendations. The results of this brainstorming and the recommendations are summarized in the next section.

6 Roadmap Development based on IGS Workshop

The following roadmap items have already been recommended to the IGS governing board after the workshop:

- Extend IGS-SSR format with new messages for attitude and SRP(APC)/CoM offset
- Define an agreed format and broadcast the RMS map associated to the RT-VTEC product

The following items are potential roadmap candidates, which need further discussion:

- Extend IGS-SSR format with new messages for PCV/GDV
- Define an agreed format and broadcast a satellite-dependent slant TEC (potential indicators about Slant TEC or Vertical TEC, global VTEC or regional VTEC with sector identifier or spatial range and interval, might be considered)
- Multi-layer RT-VTEC
- Phase biases for PPP-AR

The following ideas have emerged from a brainstorming during the workshop and serve as an idea pool for future activities:

- Real-time solar Xray GNSS signal reduction monitoring
- GNSS signal interference monitoring
- Messages for troposphere corrections/estimations
- Real-Time GNSS-based Integrated Water Vapour (IWV)
- Integrity messages
- For earthquake applications: standard format for station movements
- Real-time Crustal Deformation Monitoring
- Real-time time/clock synchronization

Reference Frame Working Group Technical Report 2022

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After the latest version of the International Terrestrial Reference Frame, ITRF2020 (Altamimi et al., 2022), was released in April, the rest of year 2022 was mainly dedicated to the preparation and organization of its implementation within the IGS. The IGS realization of ITRF2020, called IGS20 and described in Section 2, was designed jointly with a new set of ground and satellite antenna phase center corrections, igs20.atx. The radial antenna phase center offsets (z-PCOs) of the GPS, GLONASS and Galileo satellites were in particular re-evaluated based on the ITRF2020 scale, as described in Section 3. IGS20 and igs20.atx were published on July 26, 2022 (IGSMAIL #8238). The upcoming switch of the IGS operational products to the new IGS20/igs20.atx framework, as well as to the repro3 analysis standards and to long product file names, was announced at the same time for the beginning of October, following a two-month trial period. It was later decided to extend this trial period (IGSMAIL #8256), and the switch to IGS20/igs20.atx eventually happened with the products of GPS week 2238 (November 27, 2022).

Before the rest of this report goes into more details about IGS20 and the satellite z-PCO values in igs20.atx, Section 1 provides a brief overview of the operational IGS SINEX combination results in 2022.

1 Operational SINEX combinations

Figure 1 shows the WRMS of the Analysis Center (AC) station position residuals from the daily IGS SINEX combinations of year 2022, 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, until the switch to IGS20/igs20.atx indicated by the black vertical lines in Figure 1. Afterwards, it can be observed that:

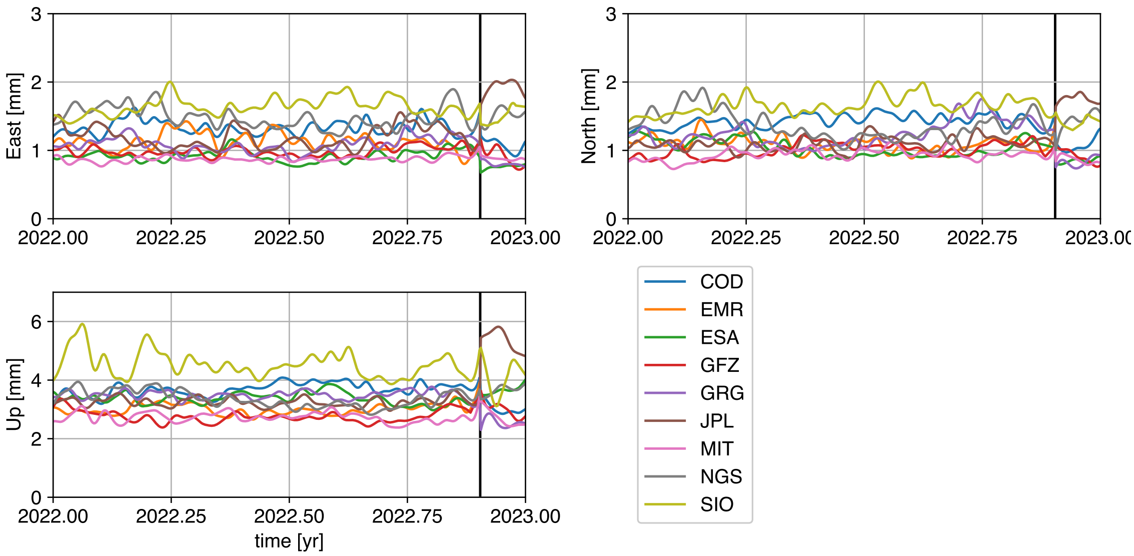

Figure 1: WRMS of AC station position residuals from the 2022 daily IGS SINEX combinations. The black vertical lines indicate the date of the switch to IGS20/igs20.atx. All WRMS time series were low-pass filtered with a 20 cpy cutoff frequency, separately before and after the switch.

- EMR (NRCan) has not provided SINEX solutions since the switch. They are currently finalizing the transition to IGS20/igs20.atx and a new product line.
- The WRMS of JPL's residuals have notably increased, because JPL has not transitioned to IGS20/igs20.atx yet. Their solutions have been included for comparison only in the IGS SINEX combinations since the switch.
- The WRMS of COD's and GRG's residuals, as well as ESA's East and North residuals, seem to reach lower levels than before the switch. More time will however be needed to precisely assess the impact of the switch on the level of consistency between AC SINEX solutions.

2 The IGS20 reference frame(2)

The IGS20 reference frame was derived from ITRF2020 in a similar way as its predecessors (IGS08, IGS14) were derived from previous ITRF releases (see, e.g., Rebischung et al., 2012). It is essentially a subset of selected stable IGS station coordinates from ITRF2020. To make this selection among all IGS stations in ITRF2020, candidate reference frame stations were first identified based on the following criteria:

- ITRF2020 time series longer than 5 years and including at least 1000 (daily) data points;

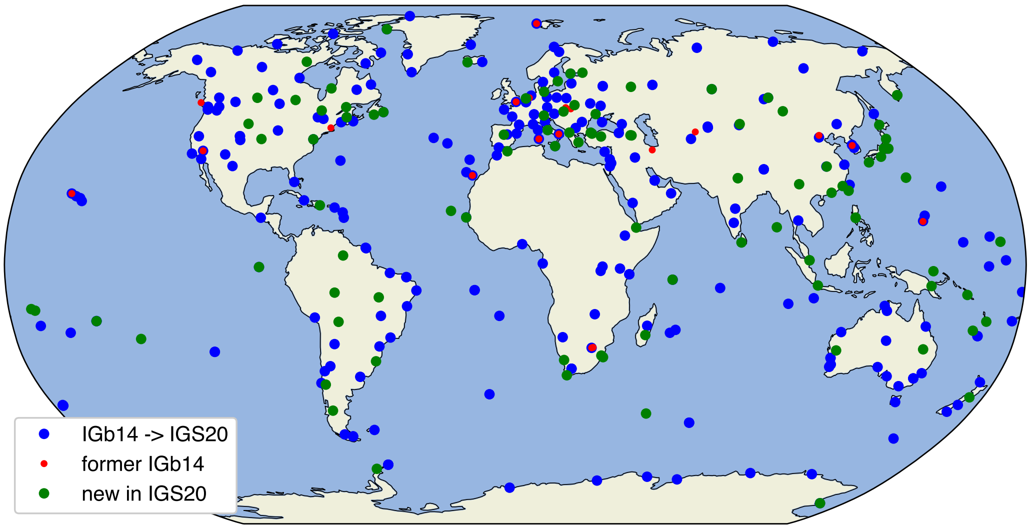

Figure 2: Distribution of IGS20 reference frame stations. In blue: IGb14 stations which were reinstated in IGS20 . In red: IGb14 stations which were discarded in IGS20. In green: new IGS20 stations.

- WRMS of ITRF2020 residual time series (including seasonal signals) < 2 mm in horizontal / < 7 mm in vertical;
- maximum formal error of ITRF2020 coordinates propagated over expected IGS20 lifetime < 1 mm in horizontal / < 3 mm in vertical.

The stations in the previous IGS reference frame, IGb14 (IGSMAIL #7921), were then reviewed, based on the criteria above and a visual inspection of their repro3 position time series. Three IGb14 stations (HOLB, TASH, WES2) were found to have quite unstable time series, due to either numerous offsets, non-linearities or both, and were therefore discarded in IGS20. A number of redundant couples of stations were also identified in IGb14, among each of which only the most suitable station was kept in IGS20. In total, 25 IGb14 stations were thus discarded in IGS20.

The non-IGb14 candidate stations were then also reviewed based on the criteria above and a visual inspection of their repro3 position time series. 98 new stations were thus selected for inclusion in IGS20, mostly in areas previously sparsely covered by IGb14 stations (southeastern Europe, Asia-Pacific, northern South America). In particular, several Japanese stations that had not been selected in IGS14 due to uncertain post-seismic deformation models at the time of ITRF2014 were reinstated as reference frame stations in IGS20. Note that to allow the selection of IGS20 stations in some especially sparse areas, some of the criteria listed above had to be relaxed. Figure 2 illustrates the distribution of the selected IGS20 reference frame stations.

At the same time as the IGS operational products switched to the IGS20 reference frame, an updated set of ground antenna calibrations, compiled in igs20.atx, was also adopted (see details in Section 2 in Chapter "Antenna Working Group"). While ITRF2020 station coordinates are consistent with the set of ground antenna calibrations used in repro3 (igsR3.atx), the IGS20 station coordinates had to be made consistent, when needed, with the updated igs20.atx antenna calibrations. For that purpose, the impacts of the antenna calibration updates on the positions of the affected IGS20 stations were assessed by four IGS Analysis Centers (ACs) by means of differential PPP analyses. Weighted averages of the AC position offset estimates were then applied to the ITRF2020 coordinates of the affected IGS20 stations. The AC position offset estimates and their weighted averages can be found in ITRF2020_to_IGS20.txt. Note that although some station coordinates differ between ITRF2020 and IGS20 due to the ground antenna calibration updates from igsR3.atx to igs20.atx, both frames share the same underlying origin, scale and orientation. The transformation parameters between ITRF2020 and IGS20 are thus zero.

IGS20 station coordinates are generally represented by piecewise linear functions, i.e., several position+velocity sets valid over successive time intervals. Each set is denoted by a solution number (soln) whose validity period is given in soln_IGS20.snx. This discontinuity list is based on the ITRF2020 discontinuity list but also includes recent discontinuities and will be regularly updated as new position offsets occur at IGS20 stations. Because IGS20 does not include coordinates for solns starting after December 31, 2020 (end of ITRF2020 input data), stations affected by such recent discontinuities cannot be used as reference frame stations anymore.

Like in ITRF2020, the reference coordinates of some IGS20 stations include post-seismic deformation models in the form of exponential and/or logarithmic functions. These models are given in psd_IGS20.snx. Details on their application can be found in ITRF2020-PSD-model-eqs-IGN.pdf. The IGS20 positions+velocities of the affected stations cannot be used without the post-seismic deformation models.

On the other hand, while coefficients of annual and semi-annual station displacements were provided with ITRF2020, it was agreed among IGS ACs not to implement these seasonal terms for the time being. IGS20 is thus provided without seasonal terms. Users wishing to experiment with the ITRF2020 seasonal terms may nevertheless add them to the IGS20 piecewise linear coordinates+post-seismic deformation models. IGS ACs are in particular encouraged to investigate the potential benefits of using the ITRF2020 seasonal terms for the alignment of their products to the reference frame.

Finally, for the purpose of aligning global GNSS solutions to IGS20, a well-distributed sub-network of IGS20 stations, called IGS20 core network, was designed. It is composed of 55 clusters of stations (i.e., 55 primary stations, each with possible substitutes) selected to ensure a homogeneous global distribution and the best possible temporal stability of the core network. It is based upon the IGb14 core network, to which only minor adjustments were brought, and is illustrated in Figure 3 . The list of IGS20 core stations is given in

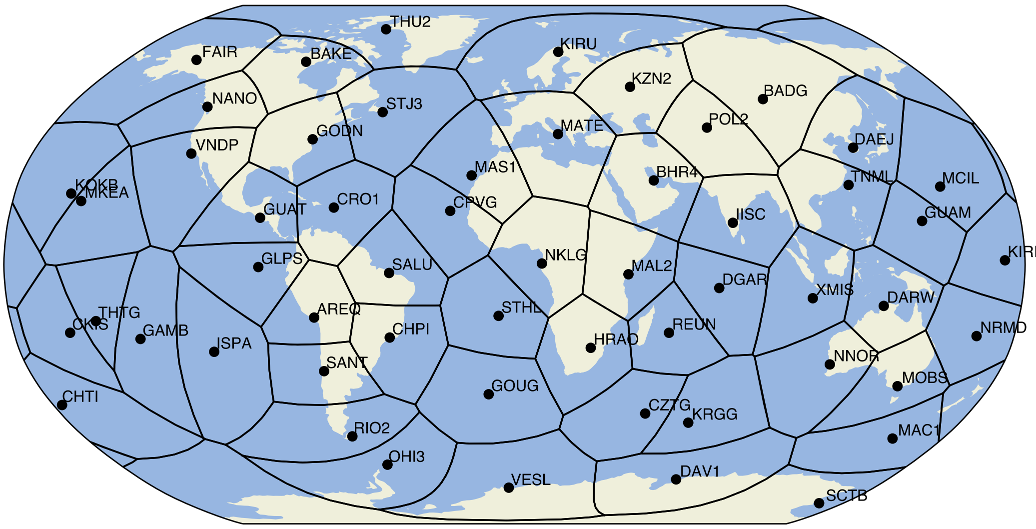

Figure 3: Primary stations of the IGS20 core network and their Voronoï diagram.

IGS20_core.txt.

3 Satellite z-PCO updates in igs20.atx

The IGS repro3 campaign made use of the pre-flight antenna calibrations of the Galileo satellites published by the European GNSS Service Centre. Those were included in the igsR3.atx file together with revised values for the GPS and GLONASS satellite z-PCOs based on the same Galileo satellite antenna calibrations (Rebischung, 2020). As a result, the IGS contribution to ITRF2020 provided for the first time an ITRF-independent, Galileo-based estimate of the terrestrial scale, which could potentially have contributed to the definition of the ITRF2020 scale. The ITRF2020 analysis however evidenced a significant bias (+4.3 mm at epoch 2015.0) as well as a small but clear drift (+0.11 mm/yr) between the scale of the IGS repro3 solutions and the average of the SLR and VLBI inputs to ITRF2020 (Altamimi et al., 2022), whose origins remain to be elucidated. The scale of ITRF2020 was thus defined, like for previous ITRF realizations, from an average of selected SLR and VLBI solutions. So that the IGS operational products would keep giving access to the ITRF scale after the switch to IGS20/igs20.atx, it was therefore necessary to update the satellite z-PCO values in igs20.atx. For that purpose, corrections to the GPS, GLONASS and Galileo satellite z-PCO values in igsR3.atx were derived from the daily repro3 SINEX solutions of nine ACs. In a first step, each daily AC SINEX solution was unconstrained, then re-inverted after having fixed the satellite x- and y-PCOs as well as the UT1-UTC offset to their a priori values and applied no-net-rotation, translation nor scale constraints with respect to ITRF2020, while letting satellite z-PCOs be freely estimated. The obtained time series of daily satellite z-PCO estimates were then visually inspected for offsets. None were found, except a series of offsets for two GLONASS satellites (R730 and R737) which were already accounted for in igsR3.atx, as well as apparent offsets for several Galileo satellites in March 2017 . Since they have different amplitudes across ACs and coincide with the activation of four new Galileo satellites, the latter are thought to be artificial rather than to reflect real changes of the Galileo satellite z-PCOs, hence were ignored in the following steps.

The SLR/VLBI-based ITRF2020 scale rate does not match the "intrinsic" GNSS scale rate implied by assuming GNSS satellite z-PCOs constant with time, as in the IGS ANTEX files. This manifests, for instance, by the +0.11 mm/yr scale drift between the IGS repro3 solutions and ITRF2020, but also by the presence of mean trends in the time series of satellite z-PCO estimates obtained from the first step described above and based on the ITRF2020 scale (rate). Those trends, if left uncorrected, would have averaged differently over each satellite lifetime and eventually led to average z-PCO estimates inconsistent across satellites. To re-estimate (constant) satellite z-PCOs based on the ITRF2020 scale, it was therefore necessary to first correct these trends, which was actually achieved by aligning ITRF2020 to the intrinsic GNSS scale rate.

For that purpose, the daily AC repro3 SINEX solutions were re-inverted like described above, but with no-net-scale constraints applied with respect to several variants of ITRF2020, with its scale rate modified by different amounts. Time series of daily satellite z-PCO estimates were thus obtained for each AC, satellite and tested scale rate. A linear trend was fitted to each of these time series (accounting for offsets in case of the GLONASS satellites R730 and R737). For each tested scale rate, weighted averages and WRMS of the satellite z-PCO trends were computed, separately for each AC as well as across all ACs. They are shown in Figure 4 as a function the scale rate with respect to ITRF2020. The scale rates for which the weighted averages of satellite z-PCO trends are zero (indicated by the vertical dashed lines in the upper plot) indicate which scale rate correction to ITRF2020 is most consistent with the assumption of constant satellite z-PCOs. Their values are quite consistent across ACs, ranging from +0.063 mm/yr for TUG to +0.137 mm/yr for COD and ULR. The weighted average of satellite z-PCO trends across all satellites and ACs is zero for a scale rate value of +0.112 mm/yr, which matches the scale drift of +0.11 mm/yr observed between the IGS combined repro3 solutions and ITRF2020.

In the next steps toward deriving the igs20.atx satellite z-PCO values, ITRF2020 corrected for a +0.112 mm/yr scale rate was thus used. This implies that the igs20.atx satellite z-PCO values are not consistent, nor do they give access to the ITRF2020 scale strictly speaking. They do give access to the ITRF2020 scale at its reference epoch 2015.0, but the scale they imply actually departs from the ITRF2020 scale at a rate of about +0.11 mm/yr . This is a similar situation as with the igs14.atx satellite z-PCO values, which implied a scale consistent with the ITRF2014 scale at epoch 2010.0, but departing from the ITRF2014 scale at a rate of about +0.17 mm/yr . Note by the way that the

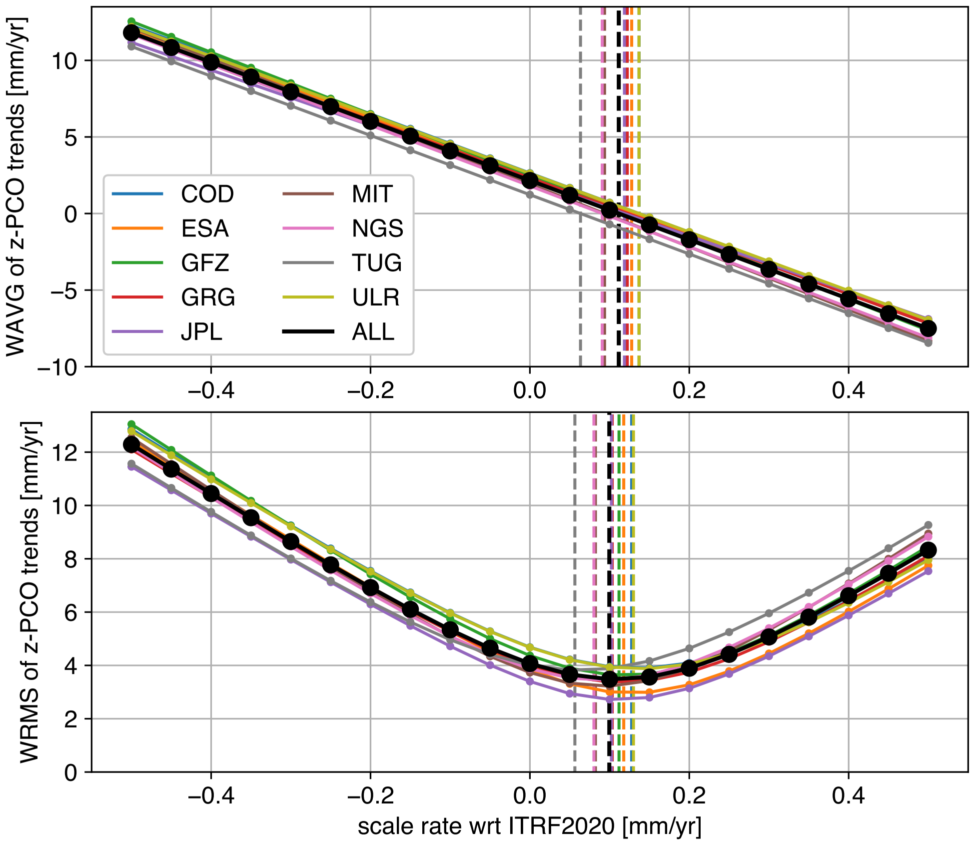

Figure 4: Weighted averages and WRMS of satellite z-PCO trends obtained for different scale rate corrections to ITRF2020.

ITRF2020 scale rate is a slightly better agreement (0.11 mm/yr) with the intrinsic GNSS scale rate than the ITRF2014 scale rate was (0.17 mm/yr).

In the next step, the daily AC repro3 SINEX solutions were inverted once more, with no-net-scale constraints applied with respect to ITRF2020 corrected for a +0.112 mm/yr scale rate. Time series of z-PCO estimates (or rather of increments to the igsR3.atx z-PCO values) were extracted from the obtained solutions for each AC and satellite, then weighted averaged. Figures showing the obtained weighted averaged increments to the igsR3.atx z-PCO values are not included here due to space limitations but can be found in Rebischung (2022).

For the GPS satellites, the average z-PCO estimates from the different ACs are very consistent with each other, except for TUG, whose z-PCO estimates are systematically larger by about 5 cm. The average increments to the igsR3.atx z-PCO values of the different satellites are scattered around a mean value of +10 cm, which corresponds, according to Zhu et al. (2003)'s rule of thumb, to a +5 mm terrestrial scale offset. This is close to the

+4.3 mm scale offset observed at epoch 2015.0 between the IGS combined repro3 solutions and ITRF2020. For the GPS Block III satellites (G074 – G078), it is also interesting to compare the new estimated values with the calibrated z-PCOs released by Lockheed Martin. The estimated increments to the calibrated values (weighted averages across all ACs) are +97.9, +77.5, +131.3, +100.8 and +67.1 mm for satellites G074, G075, G076, G077 and G078 respectively. They are rather consistent across the different Block III satellites (within about ±3 cm of their mean). It was therefore decided to estimate in a last step, and apply in igs20.atx, a single increment to all calibrated GPS Block III satellite z-PCOs.

For GLONASS, the consistency between z-PCO estimates from the different ACs is again reasonable, although the estimates from COD, ESA and especially TUG tend to be systematically larger than those from GFZ and GRG by a few cm. Like for GPS, the average increments to the igsR3.atx z-PCO values of the different GLONASS satellites are scattered around +10 cm, except, as could be expected, for some of the most recent satellites (R805, R858, R859, R860).

For the Galileo satellites, clear systematic differences can be observed between the z-PCO estimates from the different ACs. Those from TUG are systematically larger than the AC average by about 5 cm; those from MIT systematically smaller by about 10 cm. Smaller systematic differences can also be observed between COD and ESA on one hand, GFZ and GRG on the other. The reasons for these systematic differences are still under investigation. For the purpose of deriving the igs20.atx Galileo z-PCO values, it was decided to exclude MIT and TUG and rely only on COD, ESA, GFZ and GRG.

Except for satellite E102, whose calibrated z-PCO value had previously been identified as inconsistent with those of the other Galileo satellites, the Galileo z-PCOs in igsR3.atx are those from their pre-flight calibrations. The estimated increments to the igsR3.atx values can therefore be interpreted as increments to the calibrated Galileo satellite z-PCOs. E102 still excepted, and E104 also excepted because of a uniquely large but poorly determined increment, the estimated increments to the calibrated z-PCOs of the different Galileo satellites average to +15.6 cm. They mostly lie within ±3 cm of that average value. It was therefore decided to estimate in a last step, and apply in igs20.atx, a single increment to all calibrated Galileo z-PCOs except for E102.

In the last step of the derivation of the igs20.atx satellite z-PCO values, the daily unconstrained AC repro3 SINEX solutions were first reparameterized: the satellite-specific z-PCO parameters of all GPS Block III satellites were stacked into a single increment to their calibrated z-PCOs, and the same operation was performed for all Galileo satellites with the exception of E102. The reparameterized solutions were then inverted, with no-net-scale constraints applied with respect to ITRF2020 corrected for a +0.112 mm/yr scale rate. Time series of daily estimated increments to all GPS Block III calibrated z-PCOs, to all Galileo calibrated z-PCOs, and to the igsR3.atx z-PCOs of each other individual satellite were finally extracted from the inverted solutions, and weighted averaged over time and ACs. The satellite z-PCO values in igs20.atx are based on these weighted averaged increments. It is worth emphasizing that, even if igs20.atx does not include the original calibrated z-PCOs of the Galileo satellites, these values were only modified by a single common offset, so that the relative information between the calibrated z-PCOs of the individal Galileo satellites is preserved. The same holds for the GPS Block III satellites.

Since the switch to IGS20 and the adoption of the igs20.atx satellite z-PCO values, the scale factors estimated between the IGS daily combined SINEX solutions and the IGS20 reference frame have been scattered around a mean value of 0.9 mm. This matches the value expected from the drift between the intrinsic GNSS scale rate and ITRF2020 (+0.11 mm/yr) over 8 years (from 2015.0 to ≈ 2023.0).

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RINEX Working Group Technical Report 2022

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1 Introduction

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

2 Membership

Current membership has been adjusted during 2022 due to a few additions and retirements, and is current and correct on the IGS website; https://www.igs.org/wg/rinex/#members .

3 Summary of Activities in 2022

Over 2022 the most important development has been the implementation and adoption by the IGS of the RINEX 4.00 format definition standard published back in 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 files have been generated by the IGS both for Navigation and Observations for a set of stations and made available to all users at the IGS Data Center CDDIS for testing and experimentation over a six-month period. During this time the RINEX WG has received many questions and clarifications, some of which will be included in the next format document version.

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 2023 Activities

A new RINEX WG Chair will be selected during 2023 as the current chairperson will retire from this position in December 2022. The current WG chairperson will remain a WG member and can assist the transition to the new Chair.

During 2023 RINEX version 4.01 will be created incorporating all the clarifications, small updates, etc, as suggested during the 2022 RINEX 4.00 testing campaign.

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 2022

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M. Gravelle, M. Guichard, D. Hansen, T. Herring, A. Hunegnaw,
M. Jia, M. King, S. Masoumi, M. Merrifield, G. Mitchum,
E. Prouteau, L. Sánchez, A. Santamaría-Gómez, N. Teferle,
D. Thaller, S. Williams, G. Wöppelmann

1 Introduction

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

The main aims of the TIGA Working Group are:

1. Maintain a global virtual continuous GNSSTide 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 2022

- (Virtual) IGS Workshop (Boulder) with 49 participants and 4 presentations:

  G. Mitchum: A brief history of the GLOSS, TIGA partnership;

  G. Wöppelmann: Estimates of vertical land motion at tide gauges from multiple solutions (IGS-repro3 and others);

  B. Männel: Results of the GFZ's TIGA repro3 contribution;

  E. Prouteau: Status of the TIGA Network and status of SONEL.

  For details see https://igs.org/event/igs-workshop-2022

- TIGA-AC's contributed to the IGS-repro3 campaign with dedicated TIGA and GNSSTideGauge solutions. ULR processed a network of 468 GNSSTideGauge stations and GFZ a network of 254 GNSSTideGauge.

- 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 2022 in total 233 (2021: 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 1253 (2021: 1229) (TIGA: 122 stations, with 19 decommissioned) stations (607 stations active, 199 stations decommissioned). Still there are 181 stations where the GNSS data is not (yet) available for scientific research.

3 Related important Outreach activities and (selected) TIGA-related publications in 2022

- IGS Meeting Boulder (TIGA Session, online 28.06.2022)
- Participation IGS Governing Board Meetings, March. May, June 2022
- IGS Associate Member Meeting, 11. December 2022 (pre-recorded)
- Männel, B., T. Schöne, M. Bradke, and H. Schuh (2022). Vertical land motion at tide gauges observed by GNSS: a new GFZ-TIGA solution. In International Association of Geodesy Symposia. Berlin, Heidelberg: Springer. doi:10.1007/1345_2022_150
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- Zhou, D., Y. Liu, Y. Feng, H. Zhang, Y. Fu, Y. Liu, and Q. Tang (2022): Absolute sea level changes along the coast of China from tide gauges, GNSS, and satellite altimetry. Journal of Geophysical Research: Oceans, 127, e2022JC018994. doi:10.1029/2022JC018994

4 TIGA Working Group Members in 2022

Working group members are listed in Table 1.

Table 1: TIGA Working Group Members in 2022

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
Salim Masoumi	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 2022

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1 Introduction

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

Dr. Sharyl Byram has chaired the working group since December 2015 and also oversees production of the IGS FTEs. IGS FTEs are produced within the USNO Earth Orientation Department GPS Analysis Division, which also hosts the USNO IGS Analysis Center.

2 IGS Final Troposphere Product Generation/Usage 2022

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 (Böhm 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. The ITRF2020 frame was implemented in November of 2022 starting with estimates for GPSweek 2238. Further processing details can be obtained from Byram and Hackman (2012).

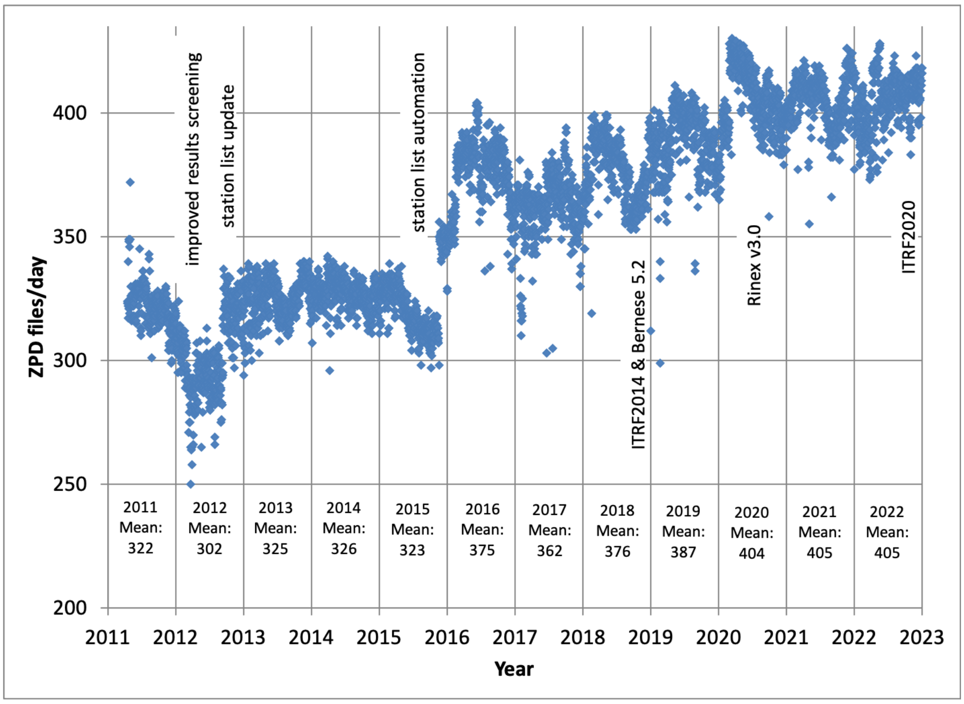

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011–2022.

Figure 1 shows the number of receivers for which USNO computed IGS FTEs 2011-2022. The average number of quality-checked station result files submitted per day in 2022 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 21.7 million in 2022.

3 IGS Troposphere Working Group Activities 2022

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 and coordinate activities using the IGS TWG email list.

In 2022, a TWG meeting was held virtually during the 2022 IGS Workshop. Communications on news and activities were distributed via the TWG mailing list.

Recommendations from the 2022 TWG Meeting:

1. **Test newer troposphere models in final troposphere estimates**
   GMF is currently being used in the IGS Final Troposphere estimates. The recommendation of the working group is to test the VMF model. However, there is concern about the 6 hour release discontinuities with the VMF model. Analysis of the effect of these discontinuities will be conducted. Other models will also be investigated as well.

2. **Repro3 reprocessing**
   The working group recommends that the Repro3 combination products suitability for troposphere reprocessing is investigated. If determined to be a suitable time series for PPP reprocessing, the working group recommends creating a reprocessed troposphere estimate time series consistent with the Repro3 combination products. It was determined that the Repro2 combination products were not suitable for long time span PPP processing.

3. **Multi-GNSS investigation**
   The final recommendation from the working group meeting was to begin testing production and analysis quality of a multi-GNSS final troposphere product including other fully operational constellations. The quality analysis of these multi-GNSS estimates should be of combined observations as well as evaluating individual constellation inclusion into the estimates.

A review of the Troposphere Working Group Charter began in 2022 as well.

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: https://twg.igs.org
- subscribe to the IGS Troposphere Working Group email list: https://lists.igs.org/mailman/listinfo/igs-twg

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