IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2023

EDITORS
ROLF DACH
ELMAR BROCKMANN

ASTRONOMICAL INSTITUTE
UNIVERSITY OF BERN

International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

Astronomical Institute, University of Bern
Bern, Switzerland
Compiled in March 2024, by Rolf Dach and Elmar Brockmann (Eds.)

IGS INTERNATIONAL GNSS SERVICE

Technical Report 2023

IGS Central Bureau

https://www.igs.org

Editors: R. Dach, E. Brockmann
Astronomical Institute, University of Bern

Published in May 2024

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

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

IGS Technical Report 2023
ISSN: 2297-8526
ISBN: 978-3-03917-092-0 ; University of Bern, Bern Open Publishing.
DOI: 10.48350/191991

Cite as:
Dach, R., Bockmann, E. (eds.) (2024). *International GNSS Service Technical Report 2023 (IGS Annual Report)*. IGS Central Bureau and University of Bern; Bern Open Publishing DOI 10.48350/191991

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 2023* includes contributions from the IGS Governing Board, the Central Bureau, Analysis Centers, Data Centers, station and network operators, committees, pilot projects, and others highlighting status and important activities, changes and results that took place and were achieved during 2023.

This report is available in electronic version at
https://files.igs.org/pub/resource/technical_reports/2023_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.

Contents

Part I

Executive Reports

IGS Governing Board Annual Report 2023

Rolf Dach[1], Elisabetta d'Anastasio[2], Léo Martire[3], Allison B. Craddock[4]

[1] IGS Governing Board Chair
Astronomical Institute, University of Bern, Switzerland
[2] IGS Governing Board Vice Chair
Te Pū Ao, Lower Hutt, New Zealand
[3] IGS Central Bureau Deputy Director and
Governing Board Executive Secretary
NASA Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA
[4] International GNSS Service Central Bureau Director
NASA Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA

1 Introduction

In 2024, the International GNSS Service (IGS) will celebrate thirty years of operational service to science and society. The provision of free and openly available fundamental geodetic products (GNSS satellite orbits, clock corrections, contributions to the terrestrial reference frame, and Earth rotation parameters) has been at the core of IGS activities since its inception. Over the past three decades, IGS has extended its activities to a number of applications based on GNSS data, supporting weather monitoring, ionosphere characterization, or sea level change studies. All these activities have been performed on a voluntary basis by contributing agencies and institutions around the world. The quality of IGS products has continuously improved over time, and is nowadays a demonstration of the tremendous effort invested by the many people worldwide who provide the necessary work for the IGS. A guiding principle since the beginning of IGS was (and still is) the free access to high-precision GNSS data and products and an open exchange of experience and knowledge. The IGS is currently on the path towards a full multi-GNSS service with new multi-GNSS stations in the core network, extending the receiver antenna calibrations to new frequencies, and including all GNSS signals in the product generation. Several groups within the IGS community are currently working on developing a full multi-GNSS product combination for generating orbits and satellite clock products. This will be the last step of significant efforts towards a multi-GNSS service.

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. The GB continues to engage with our international user community and their partner organisations, 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.

After almost 5 years of virtual interaction and remote operations of IGS members as a response to the global pandemic, the IGS GB was able to meet again in person during 2023. And it is with great pleasure that IGS will finally be able to celebrate its 30 years of operations with an in person Symposium and Workshop that will take place in July 2024 in Switzerland.

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). During 2023, IGS counted over:

- 296+ AMs (representing 55 countries/regions),
- 150+ contributing organizations participating within the IGS, including:
  - 100+ agencies operating GNSS Network Tracking Stations,
  - 6 Global Data Centers,
  - 13 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 7 members (see Table 1 in Chapter “IGS Central Bureau”), holding all of the components of the IGS together by providing continuous management, technological support and coordination of the IGS Information System, website and outreach activities.

The IGS organisational structure map has been reviewed and will be released in the 2024 Technical Report. The IGS Terms of Reference have been thoroughly reworked and updated, and were released in 2023 (see next section).

2.2 2023 Revision of the IGS Terms of Reference

Over the past few years, the IGS Terms of Reference (ToR) underwent substantial revisions. Building on the 2019 version of the ToR, the 2023 Revision received unanimous approval from 14 voting GB Members, exceeding the required two-thirds majority for ToR changes.

Among other key changes, the 2023 ToR aligns IGS components to the IAG nomenclature, considering the function and lifecycle of each component. This resulted in an overhaul of IGS naming conventions, summarized in the table below. The 2023 ToR Revision provides detailed definitions for these components.

Previous nomenclature (2019 ToR)	Updated nomenclature (2023 ToR)
long-standing Working Groups	Committees
experimental Working Groups	Pilot Projects
Pilot Projects	Working Groups

IGS components that are providing or supporting operational products and services to IGS have been renamed from *Working Groups* to *Committees*. Those were the Antenna, Bias and Calibration, Clock, Ionosphere, Troposphere, Real-Time, Reference Frame, and RINEX *Working Groups* that are now transformed into *Committees*.
The IGS components that are experimenting or developing new IGS services or products have been renamed from Working Groups to Pilot Projects. Those are the GNSS Monitoring, PPP-AR, MGEX, and TIGA *Working Groups* that are now transitioned into *Pilot Projects*.
In 2023, only the Weather and Climate Research *Pilot Project* existed. This would have become a *Working Group* had it not become discontinued in 2023.
Alongside this nomenclature transition, all Committee and Pilot Project Chairs gained voting rights, underlining the GB’s desire for a shift in the governance structure.

Other noteworthy changes include the addition of a 2-year term limit for Appointed GB Members, and the doubling of the available Appointed Member positions from 3 to 6 in an effort to steer the GB to become more diverse and inclusive. The term limit for

the GB Vice-Chair was extended from 2 to 4 years, enhancing continuity in leadership. The revised ToR also explicitly states the IGS mission to provide standards for data provision and processing. Furthermore, the roles of the two "IAG Representative to the IGS" were renamed to "IAG President" and "GGOS President" for clarity and reflecting their organisational affiliations. Finally, the updated ToR clarifies that an individual may only hold up to 2 roles within the IGS and will possess only one voting right, ensuring transparency and accountability in the decision-making process.
Another focus has been to establish a clear lifecycle for all IGS Components, and encourage long standing components to enable sustainability and continuity of their activities through the establishment of a vice-chair position for each Committee.

The 2023 Revision of the IGS Terms of Reference encapsulates a meticulous commitment to elevate the Service, showcasing exhaustive efforts to refine and update its governance structure. This comprehensive overhaul ensures due recognition to the diverse contributions of all participants. Beyond restructuring, these changes strategically position the IGS for enhanced effectiveness and user-centric adaptability, fortifying the IGS's long-term sustainability and resilience in the ever-evolving GNSS landscape.

2.3 Current Status of the IGS Governing Board

We summarise in Table 1 the status of the Governing Board membership at the end of 2023. The GB is now led by Rolf Dach (AIUB, Switzerland), succeeding Felix Perosanz (CNES, France) since his election in July 2023. The position of GB Vice-Chair is now held by Elisabetta d'Anastasio (GNS Science Te Pū Ao, New Zealand), since her election in November 2023. Allison Craddock (NASA JPL, USA) continues her appointment as CB Director. Léo Martire (NASA JPL, USA) continues their appointment as CB Deputy Director, and took over the responsibility of GB Executive Secretary following Ashley Nilo's (NASA JPL, USA) transition out of the IGS.

Table 1: Members of the IGS Governing Board, as of December 2023.
Involvement is either of the following:
V if voting member, EC if member of the Executive Committee; observer otherwise.

Role	Name	Affiliation	Country	V	EC
Board Chair	*Rolf Dach*	Astronomical Institute, University of Bern	Switzerland	V	EC
Board Vice Chair	*Elisabetta D'Anastasio*	GNS Science Te Pū Ao	New Zealand	V	EC
CB Director	Allison Craddock	NASA Jet Propulsion Laboratory	USA	V	EC
CB Deputy Director	Léo Martire	NASA Jet Propulsion Laboratory	USA		EC
GB Executive Secretary	*Léo Martire*	NASA Jet Propulsion Laboratory	USA		EC
Network Coordinator	David Maggert	Earthscope Consortium	USA		
AC Coordinator	Thomas Herring	Massachusetts Institute of Technology (MIT)	USA	V	EC
AC Coordinator	Salim Masoumi	Geoscience Australia	Australia	*	
AC Representative	Sylvain Loyer	Collecte Localisation Satellites (CLS)	France	V	
AC Representative	Benjamin Männel	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences	Germany	V	
AC Representative	Paul Ries	NASA Jet Propulsion Laboratory	USA	V	
DC Coordinator	Patrick Michael	NASA Goddard Space Flight Center (GSFC)	USA	*	
DC Representative	Jianghui Geng	Wuhan University	China	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	Australia	V	EC
Network Representative	Wolfgang Söhne	Federal Agency for Cartography and Geodesy (BKG)	Germany	V	
Appointed Member	***Fernand Balé***	Bureau National d'Etudes Techniques et de Développement	Côte d'Ivoire	V	
Appointed Member	Werner Enderle	ESA/European Space Operations Centre (ESOC)	Germany	V	
Appointed Member	Satoshi Kogure	National Space Policy Secretariat (NSPS), Cabinet Office	Japan	V	
Appointed Member	José Antonio Tarrío Mosquera	University of Santiago de Chile (USACH)	Chile	V	
Appointed Member	**VACANT**			V	
Appointed Member	**VACANT**			V	

Changes since the last IGS Technical Report are coded: structural changes are in **bold**, new GB members are in ***bold italic***, GB members taking on a different or an additional role within the GB are in *italic*. The * denote changes in voting rights; see main text for explanations.

Table 1: Members of the IGS Governing Board, as of December 2023 (cont.)
Involvement is either of the following:
V if voting member, EC if member of the Executive Committee; observer otherwise.

Role	Name	Affiliation	Country	V	EC
Antenna Committee Chair	Arturo Villiger	Federal Office of Topography swisstopo	Switzerland	V	
Bias & Calibration Committee Chair	Stefan Schaer	Federal Office of Topography swisstopo	Switzerland	V	
Clock Products Committee Coordinator	Michael Coleman	Naval Research Laboratory (NRL)	USA	V	
Infrastructure Committee Coordinator	Markus Bradke	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences	Germany	V	EC
Ionosphere Committee Chair	Andrzej Krankowski	University of Warmia and Mazury in Olsztyn	Poland	V	
Real-Time Committee Chair	Axel Rülke	Federal Agency for Cartography and Geodesy (BKG)	Germany	V	
Reference Frame Committee Chair	Paul Rebischung	Institut National de l'Information Géographique et Forestière (IGN)	France	V	
RINEX-RTCM Committee Chair	Francesco Gini	ESA/European Space Operations Centre (ESOC)	Germany	V	
SVOD Committee Chair	**DISCONTINUED** (see GB Decision 64-02)			V	
Troposphere Committee Chair	Sharyl Byram	United States Naval Observatory	USA	V	
GNSS Monitoring Pilot Project Chair	Erik Schönemann	European Space Agency / European Space Operations Centre	Germany	V	
Multi-GNSS Pilot Project Chair	Oliver Montenbruck	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany	V	
PPP-AR Pilot Project Chair	Jianghui Geng	Wuhan University	China	V	
TIGA Pilot Project Chair	**DORMANT**			V	
Real-Time AC Coordinator	***Andrea Stürze***	Federal Agency for Cartography and Geodesy (BKG)	Germany	*	
IGS Representative to IERS	Elisabetta D'Anastasio	GNS Science Te Pū Ao	New Zealand	V	
IGS Representative to IERS	Rolf Dach	Astronomical Institute, University of Bern	Switzerland	V	
BIPM Representative to the IGS	Patrizia Tavella	Bureau International des Poids et Mesures (BIPM)	France		
FIG Representative to the IGS	Ryan Keenan	Positioning Insights	Australia		
GGOS President	***Laura Sánchez***	Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)	Germany	V	
IAG President	*Richard Gross*	NASA Jet Propulsion Laboratory	USA	V	
IERS Representative to the IGS	*Zuheir Altamimi*	Institut National de l'Information Géographique et Forestière (IGN)	France	V	

Changes since the last IGS Technical Report are coded: structural changes are in **bold**, new GB members are in ***bold italic***, GB members taking on a different or an additional role within the GB are in *italic*. The * denote changes in voting rights; see main text for explanations.

Zuheir Altamimi (IGN, France) stepped down from the voting role of IAG Representative to the IGS, and took with GB approval the voting role of IERS Representative to the IGS; his former role was renamed from “IAG Representative to the IGS” to “IAG President” for clarity. Richard Gross (NASA JPL, USA) stepped down from the voting role of IERS Representative to the IGS, and upon his election as IAG President took with GB approval the eponymous voting role in the GB. Basara Miyahara (GSI, Japan) stepped down from the voting role of IAG Representative to the IGS, and was succeeded with GB approval by past GB member Laura Sanchez (DGFI-TUM, Germany); the role in question was renamed from “IAG Representative” to the IGS” to “GGOS President” for clarity.

Importantly, numerous changes were introduced by the approval of the 2023 Revision of the IGS Terms of Reference (see Section 2.2). The changes pertaining to the GB structure and membership are as follows. The role of Data Centre Coordinator has lost its voting right by virtue of being absorbed under the Infrastructure Committee, whose Chair has voting rights. The role of Real-Time Analysis Centre Coordinator has lost its voting right by virtue of being absorbed under the Real-Time Committee, whose Chair has voting rights. The role of Analysis Centre Coordinator is currently jointly held by Geoscience Australia (Australia) and the Massachusetts Institute of Technology (MIT), but holds only one vote; for housekeeping purposes, we attribute it to MIT only, but note that the vote should reflect both institutions’ positions.

After reaching the end of their terms this year, some GB Members were subject to the renewal during the 2023 GB Elections. They were all renewed. Benjamin Männel (GFZ, Germany) was re-elected Analysis Centre Representative with 68% of all Associate Member votes against 32% for Rick Bennett (NOAA, USA). Ryan Ruddick was re-elected Network Representative with 89% of all votes against 11% for Venkat Ratnam (Centre for Atmospheric Sciences, India). Arturo Villiger (AIUB, Switzerland), Stefan Schaer (Swisstopo, Switzerland), Markus Bradke (GFZ, Germany), Andrzej Krankowski (University of Warmia and Mazury in Olsztyn, Poland), and Paul Rebischung (IGN, France) were all approved by their respective Committees’ members to run for another term, and were all approved unanimously for renewal by the GB. Ryan Ruddick (Geoscience Australia, Australia) continues as Co-Chair of the Infrastructure Committee. Samuel Branchu (IGN, France) becomes Co-Chair of the Reference Frames Committee. Zishen Li (Chinese Academy of Sciences, China) becomes Co-Chair of the Ionosphere Committee.

Some IGS Components were recently discontinued: SVOD (Satellite Vehicle Orbit Dynamics), TIGA (Tide Gauge), and CSWGG (Committee on Sustainable Working Group Governance), in July 2023, November 2023, and February 2024 respectively. The GB is particularly thankful to the service of their Chairs (respectively Tim Springer, Tilo Schöne, and Ryan Ruddick) and contributors. Should anyone be interested in taking over these Components, they are invited to come forward and contact the GB or CB.

2.4 Committee on Sustainable Working Group Governance

The third Goal of the IGS 2021+ Strategic Plan is to build a sustainable and resilient organisation. The Committee on Sustainable Working Group Governance (CSWGG) is progressing this goal through identifying ways in which the various IGS Components can be invigorated to ensure ongoing sustainability and be in a better place to support the IGS in successfully achieving its mission.

During 2023, the Committee on Sustainable Working Group Governance (CSWGG) engaged with the community to develop several recommendations that aim to improve the sustainability of the IGS. These recommendations have been summarised and delivered to the IGS GB, and were captured in an updated "Policy for the establishment and governance of IGS Committees, Working Groups and Pilot Projects". The CSWGG members, considering the community recommendations, contributed significantly to drafting the 2023 ToR and suggested a number of improvements, including the introduction of a lifecycle and the establishment of committee vice-chair positions.

In November 2023, the CSWGG recommended that the Governing Board embrace values of equity, diversity, and inclusion and endorse the formation of a Working Group to support the development of an EDI statement that will support the promotion of the IGS as a welcoming and inclusive organisation. This is detailed in the next Section.

2.5 Diversity, Equity, Inclusion, and Accessibility

Following one of the goals set for 2023 in the 2022 Technical Report (GB Chapter, Section 8, page 14), and in alignment with Goal 2 and 3 of the IGS Strategic Plan 2021+, the CSWGG proposed at the 65th Governing Board Meeting (Part A) the creation of a Working Group for the improvement of Diversity, Equity, Inclusion, and Accessibility (DEIA). The action was approved, resulting in the creation of the EDI Working Group whose end goals are to (a) write an official IGS EDI statement and (b) to develop a strategy to improve and monitor the IGS' involvement in equity, diversity, inclusion, and accessibility. The Working Group, co-chaired by Elisabetta d'Anastasio (GNS Science Te Pū Ao, New Zealand) and Léo Martire (NASA JPL, USA), started its activities in early 2024 with the creation of a charter and a timeline describing forthcoming efforts.

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 2023 GB meetings, see Table 2 in Chapter "IGS Central Bureau".

4 GB Accomplishments and Decisions in 2023

The past accomplishments and decisions can be found in the previous Technical Reports (https://igs.org/tech-report/). The accomplishments and decisions for 2023 are listed below:

- **GB 63 (May 2023)**

  No key decisions were made at this meeting.

- **GB 64 (July 2023)**

  Decision 64-01: Rolf Dach (AIUB, Switzerland) was unanimously approved as the new Governing Board Chair for the 2023-2027 period.

  Decision 64-02: The Satellite Vehicle Orbit Dynamics Working Group shall become a former Working Group ("Committee" under 2023 ToR nomenclature) effective immediately.

  Decision 64-03: Erik Schönemann (ESA ESOC, Germany) has been approved as the new GNSS Monitoring Working Group Chair ("Pilot Project" under 2023 ToR nomenclature).

  Decision 64-04: The RINEX 4.01 format has been approved.

  Decision 64-05: Andrea Stürze (BKG, Germany) has been approved as the new Real-Time Analysis Center Coordinator.

  Decision 64-06: The Policy for Geographical Description Standardizations and Usage Guidelines was approved, and the Infrastructure Committee shall move forward with the implementation plan.

  Decision 64-07: The IGS CORS Guidelines were approved.

  Decision 64-08: The current IGS Data Center approach shall be updated and guidelines for that matter shall be developed.

  Decision 64-09: The 2026 IGS Workshop location was decided - it shall occur in Santiago de Chile (Chile).

  Decision 64-10: José Antonio Tarrío Mosquera (USACH, Chile) shall join the Scientific Organising Committee for the 2024 IGS Workshop in Bern (Switzerland).

  Decision 64-11: The GB shall only meet in person up to once per year, preferably in the middle of the civil year; other meetings shall remain virtual only.

  Decision 64-12: The next GB meeting shall take place virtually in November.

  Decision 64-13: Associate Member meetings shall now take place only virtually.

- **GB 65a (November 2023)**

  Decision 65a-01: The 2023 Revision of the IGS Terms of Reference was approved.

  Decision 65a-02: The CB will host a ACC-Focused AM Meeting in early 2024, and ensure the inclusion of ACs and ACCs in future AM Meetings.

  Decision 65a-03: The TIGA Working Group ("Committee" under 2023 ToR nomenclature) is paused until further notice; the remaining duties of the TIGA Committee now fall under the Infrastructure Committee's duties.

Decision 65a-04: (a) Elisabetta D'Anastasio was elected GB Vice Chair. (b) Benjamin Männel was re-elected Analysis Centre Representative, Ryan Ruddick was re-elected Network Representative. (c) Satoshi Kogure was extraordinarily extended in his position as Appointed Member, Werner Enderle was extraordinarily extended in his position as Appointed Member, Fernand Balé was elected as Appointed Member. (d) Arturo Villiger, Stefan Schaer, Markus Bradke, Andrzej Krankowski, and Paul Rebischung were all approved by their respective Committees' members to run for another term, and were all approved unanimously for renewal by the GB. (e) Richard Gross, Laura Sánchez, and Zuheir Altamimi were all approved in their respective positions (IAG Representatives to the IGS as IAG President, GGOS Representatives to the IGS as GGOS President, and IERS Representative to the IGS).

Decision 65a-05: JGX was approved as a new Global Analysis Centre in the IGS.

Decision 65a-06: The latest revision of the IGMA ToR, with Schönemann's suggestions (see GB65a meeting minutes), is conditionally approved on the condition that the GNSS Monitoring Working Group ("Pilot Project" under 2023 ToR nomenclature) send out a Call for Participation in the near future to increase involvement as well as improving equity, diversity, inclusion, and accessibility in this Committee.

Decision 65a-07: An EDI Working Group is established, with the end goal being to (a) write an official statement and (b) improve the IGS' involvement in equity, diversity, inclusion, and accessibility.

Another item of note raised during the GB65a meeting is the official Geoscience Australia statement, conveying its willingness to maintain its ACC role at least until mid-2025; see the open letter from Anna Riddell (Geoscience Australia, Australia) to Rolf Dach (AIUB, Switzerland) dated 30 November 2023.

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 1) are maintained and operated globally by a broad 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 2023, 6 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 317 to 374 (+57), while the number of real-time-capable stations increased from 301 to 308 (+7). The CB wishes to gratefully acknowledge the efforts of the institutions in charge of the stations, both new and decommissioned.

Additionally, in 2023, there were 34 changes to the `rcvr_ant.tab`[1] file, 304 site log updates (≈25 per month), and 4 antenna changes (4 of them at IGS20 reference frame stations).

[1] https://files.igs.org/pub/station/general/rcvr_ant.tab, https://files.igs.org/pub/station/general/rcvr_ant.json

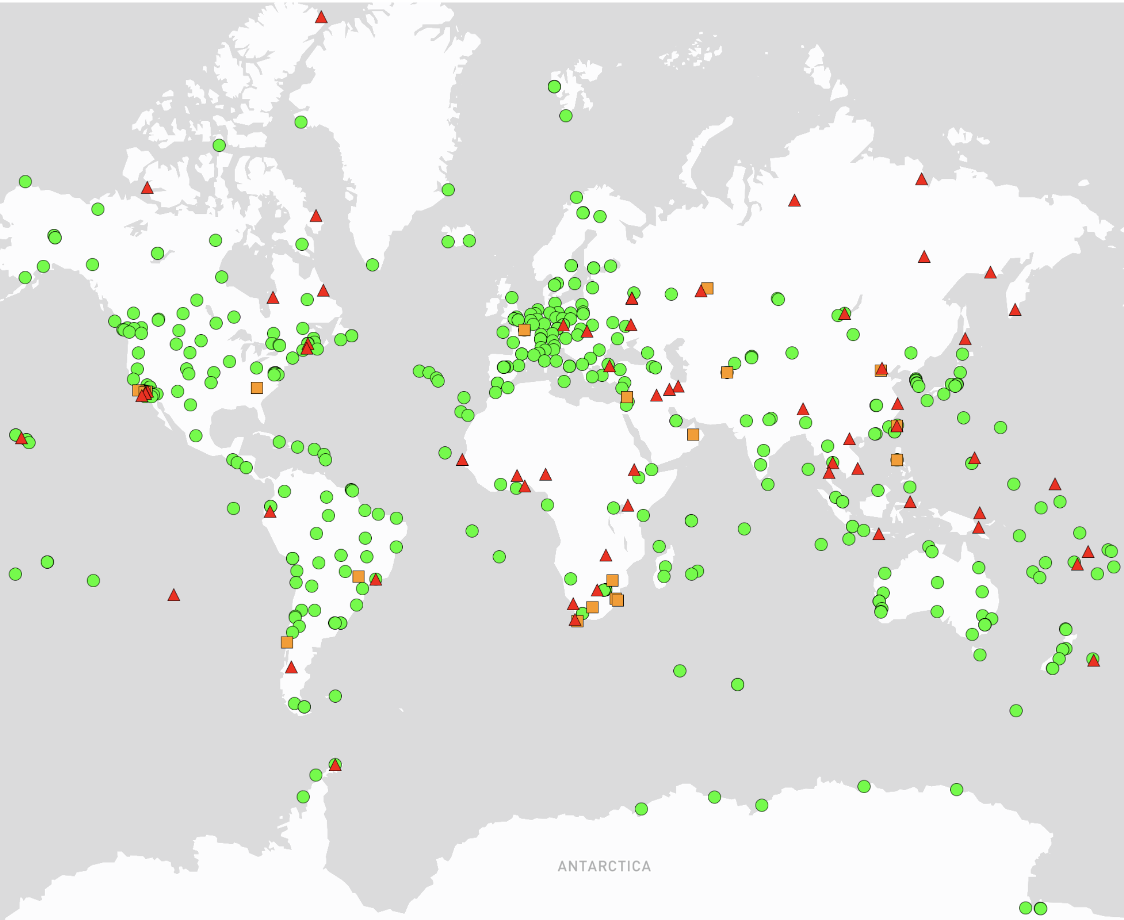


Figure 1: The IGS Network, as of the 27^{th} of December 2023. The map showcases 513 stations in total, including 374 tracking multiple GNSS constellations and 308 having real-time caster capabilities. The IGS collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations. The live version of this map is available at https://network.igs.org/.

5.2 Analysis Centre Coordination, Product Generation, and IGS Reference Frame Updates

The IGS Analysis Center Coordination (https://igs.org/acc) continued to be jointly led by Salim Masoumi (Geoscience Australia, Australia) and Tom Herring (Massachusetts Institute of Technology, USA). 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 2023. The IGS product generation continued to be carried out solely by personnel at Geoscience Australia. MIT provides scientific guidance and suggestions on p roducts. The IGS continues to maintain a very high level of product availability. For more details, see also Chapter "Analysis Center Coordinator".

In 2023, IGS welcomed a new Analysis Centre, JGX, jointly led by the Geospatial Information Authority of Japan (GSI) and the Japan Aerospace Exploration Agency (JAXA). Towards the end of 2023 and leading to early 2024, the IGS ACC started providing multi-GNSS ultra-rapid orbit combinations as demonstration products. These ultra-rapid orbits are combinations of GPS, Galileo, and GLONASS orbits provided by the IGS Analysis Centres, and are a step towards achieving a truly multi-GNSS IGS. The IGS ACC is contributing to the IGS multi-GNSS Task Force in forming the future of the multi-GNSS combined products.

The current term for the IGS ACC is going to end at the end of 2024. IGS has been working on a roadmap for the transition of the ACC to a new centre to occur in 2024/early 2025. The Transition map has a special focus on multi-GNSS where the goal is for the future ACC to obtain multi-GNSS capabilities.

More details on the ACC activities in 2023 and plans for 2024 can be found in Chapter "Analysis Center Coordinator".

The generation of the daily, weekly and long-term IGS terrestrial frame (SINEX) solutions continued to be carried out by IGN. Updates of the long-term IGS cumulative SINEX solution, which had been temporarily suspended after the switch to the IGS20/igs20.atx framework on November 27, 2022, resumed in April 2023, with a new version consistent with IGS20/igs20.atx and the repro3 standards, that contains long-term coordinates for nearly 1500 GNSS stations (see IGSMAIL #8331 and Chapter "Reference Frame Product Committee"). Besides, a new website (https://webigs-rf.ign.fr) dedicated to the IGS terrestrial frame products was open to the public in October 2023 (see IGSMAIL #8377 and Chapter "Reference Frame Product Committee" allows in particular:

- to visualize the station position time series obtained by combining the daily SINEX solutions provided by the IGS ACs,
- to visualize the models used to describe station trajectories in the IGS cumulative solution, and their residuals,

- to visualize statistics from the daily IGS SINEX combinations (i.e., "AC - IGS" station position, ERP, geocenter and scale residuals),
- to extract station coordinates from the IGS cumulative solution, as well as the latest IGS reference frames (IGS20, IGb14, IGS14).

5.3 Data Management

Thirteen Analysis Centers and twenty-one Associate Analysis Centers continue to utilise 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.

It is important to note here that the Multi-GNSS Transition Plan also has an impact on these activities. One of the first steps is the renaming of the formerly experimental differential code bias (DCB) files: in accord with the Guidelines for Long File Names in the IGS, the campaign/project identifier of those file names will be changed from "MGX" to "OPS" and the file extension will be changed from "BSX" to "BIA"; the change is scheduled to occur on the 23 January 2024, both onwards and retroactively back to the switch to IGS20 (see IGSMAIL #8399).

The amount of IGS tracking data and products hosted by each of the six global Data Centers on permanently accessible servers increased from 2 TB in 2017 to 62 TB (over 453 million files) at the end of 2023, 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 NASA's Goddard Space Flight Center:

- a total of 873 M files downloaded equating to 328 TB of GNSS data, and
- a total of 67 M files downloaded equating to 23 TB of GNSS products.

The average monthly download load in 2023 reaches

- 73 M GNSS data files equating to 27.6 TB downloaded from 19.3 K unique users per month, and
- 6 M GNSS product files equating to 2.2 TB downloaded from 7.9 K unique users per month.

The intense interest of users in IGS data and products is also reflected in the user activity recorded by the Data Center of Wuhan University (WHU), which has accumulated a total of 32.1 TB of GNSS data and products so far.

The average monthly download load in 2023 reaches a total of 43.2 M of GNSS data and product files (equating to 21.6 TB) downloaded by 1.2 K unique users per month (an increase of 6 TB since last year).

6 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.

IGS is an Associate Member of the **International Committee on GNSS (ICG)**, based under the aegis of the **United Nations Office for Outer Space Affairs (UN OOSA)**. Together with the International Federation of Surveyors (FIG), the 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"). Additionally, the ICG hosts the International GNSS Monitoring and Assessment (IGMA) Task Force (TF), in which the IGS' GNSS Monitoring Pilot Project holds a prime advisory role. Finally, the recently-created TF on "Applications of GNSS for Disaster Risk Reduction" (DRR TF) is led by IGS and co-chaired by China and Japan.

In 2023, CB Deputy Director Léo Martire (NASA JPL, USA) assumed the position of WG-D co-chair and DRR TF co-chair, and GNSS Monitoring Pilot Project Chair Erik Schönemann represented the IGS in the IGMA TF. At the 17th meeting of the ICG (ICG-17) in October 2023, the WG-D, the IGMA TF, and the DRR TF all reported significant progress. In particular, the IGS contributed to the update to the IGMA TF's Terms of Reference, and drafted an additional recommendation as part of the DRR TF[2]. The IGS also takes note of the Russian Federation's efforts in following the IGS CORS Guidelines for the installation of its new stations in 2023.

[2] ICG WG-D Recommendation #28 recommended the deployment of a multi-GNSS station in an area of sparse coverage for the demonstration of the usefulness of GNSS for natural hazards monitoring and early warning

7 Future Steps for 2024

The IGS continues to follow stakeholders' expectations for improved product timeliness, fidelity, and multi-GNSS compliance. A number of initiatives will be conducted in 2024. A transition to a new Analysis Center Coordinator will be a major focus area within IGS products and operational services. Analysis Centers will conduct an antenna calibration campaign, designed to include the remaining GNSS systems, namely BDS and QZSS, into the legacy product lines. This will be the final milestone of the multi-GNSS Pilot Project, after 12 years of activities of the IGS Multi-GNSS EXperiment (MGEX) Working Group. As these are achieved, reconsideration of the IGS mission and goals will eventually need to be undertaken to ensure the Service does not become tangential to the needs of our key players and users, the Associate Members. The GB, CB, and Associate Members continue their efforts towards enhancing advocacy for the IGS. Members of the IGS will continue giving presentations at a variety of forums within our discipline and outside of it, 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. Finally, the GB thanks all participants within the IGS for the efforts, with particular thanks going to the Component Chairs who ended their current terms this year. Without the contributions of all, the IGS could not have achieved the significant outcomes detailed in this report.

8 Publications and Official IGS Citation

Official publications pertaining to the IGS are:

- previous Technical Reports:
  - IGS 2020 Technical Report
  - IGS 2021 Technical Report
  - IGS 2022 Technical Report
- Terms of Reference:
  - IGS 2019 Terms of Reference
  - IGS 2023 Terms of Reference

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 2023

Allison B. Craddock[1], Léo Martire[2], David Maggert[3],
Robert Khachikyan[4], David Stowers[5], Ashley Nilo[6]

[1] International GNSS Service Central Bureau Director;
NASA Jet Propulsion Laboratory, California Institute of Technology
(Pasadena, California, USA)

[2] International GNSS Service Central Bureau Deputy Director
and Governing Board Executive Secretary;
NASA Jet Propulsion Laboratory, California Institute of Technology
(Pasadena, California, USA)

[3] International GNSS Service Central Bureau Network Coordinator;
EarthScope Consortium
(Washington, DC, USA)

[4] International GNSS Service Central Bureau CBIS Engineer;
Raytheon Technologies
(Pasadena, CA, USA)

[5] International GNSS Service Central Bureau CBIS Advisor;
NASA Jet Propulsion Laboratory, California Institute of Technology
(Pasadena, CA, USA)

[6] International GNSS Service Central Bureau Product Strategist;
NASA Jet Propulsion Laboratory, California Institute of Technology
(Pasadena, CA, USA)

1 Introduction

In order to sustain the multifaceted efforts of the IGS, the Central Bureau (CB) works to support and realise the IGS strategic goals: 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) and IGS Executive Committee (EC), which often tasks members of the CB with representing the outward face of IGS to a diverse global user community and the general public.

Table 1: IGS Central Bureau staff and responsibilities. NASA is the National Aeronautics and Space Administration. JPL is the Jet Propulsion Laboratory (Pasadena, USA). JPL is managed by the California Institute of Technology (Caltech) for NASA.

Name	Affiliation	Role
Allison Craddock	NASA JPL	Director
Léo Martire	NASA JPL	Deputy Director
David Maggert	EarthScope Consortium	Network Coordinator
David Stowers	NASA JPL	CBIS Advisor
Robert Khachikyan	Raytheon Technologies	CBIS Manager
Brian Kohan	Raytheon Technologies	CBIS Engineer
Ashley Nilo	NASA JPL	Product Strategist

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 Deputy Director Léo Martire (NASA JPL, USA). The CB also works as the command-and-control centre for tracking network operations, mostly overseen by the Network Coordinator, David Maggert (EarthScope Consortium, USA). Additionally, the CB manages the primary IGS Information System (CBIS), the principal information portal where the IGS web, data, and mail services are hosted; these tasks are led by Robert Khachikyan (Raytheon Technologies, USA). 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 2023. The CB has continued to pursue efficiency in holding IGS activities and leading administrative operations. 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 important considerations, the CB has also achieved the following items:

1. Supported the timely delivery of data and products.
2. Supported the Committee on Sustainable Working Group Governance (CSWGG).
3. Successfully organised three Governing Board Meetings, 6 Executive Committee meetings (see Table 2), the year-end Associate Member Meeting with 100+ participants (see `https://igs.org/am-meetings`), and two new stops for the Tour de l'IGS (see `https://igs.org/tour-de-ligs`).
4. Coordinated, supported, and participated in the Standing Elections Committee on

the 2023 GB elections.

5. Began the development of a new and improved IGS Network System; see Section 4.2 in this chapter.
6. Maintained the public IGS GitHub Repository, in particular with respect to issues submitted by users.
7. Supported the dissemination of IGS Products; namely including the release of the IGS Guidelines on Long Product Filenames, the RINEX 4.01 format, and the IGS CORS Guidelines.
8. Represented the IGS and its community interests at various stakeholder levels, including: the United Nations Office for Outer Space Affairs' International Committee on GNSS (ICG), the Subcommittee on Geodesy of the United Nations Committee of Experts on Global Geospatial Information Management (UN GGIM), the World Data System (WDS), the International Association of Geodesy (IAG) Inter-Commission Committee on Climate, and the IAG Global Geodetic Observing System (GGOS).
9. Released two new issues of "Constellations: the IGS Newsletter" and several other news items on `https://igs.org/news`.
10. Continued and enhanced the IGS' social media presence; see Section 5 in this chapter.
11. Coordinated highlights for Women's History Month and International Women's Day (`https://igs.org/news/whm23/`).

3 Coordination of Meetings in 2023

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 one Associate Member virtual meeting. In addition, the CB coordinated, supported, and participated in the Standing Elections Committee to organise the 2023 GB Elections. Allison Craddock (NASA JPL, USA) and Ashley Nilo (NASA JPL, USA) participated in the Committee on Sustainable Working Group Governance (CSWGG) meetings, chaired by IGS Network Representative Ryan Ruddick (Geoscience Australia, Australia). Finally, the CB also organised one virtual Stop for the Tour de l'IGS. A detailed list of these activities can be found in Table 2.

Table 2: 2023 meetings led and/or coordinated by the CB, and an overview of the general topics discussed during each one.

GB Meetings

13 April 2023 (GB63, virtual)
Discussion of the 2023 Review of the IGS Terms of Reference; discussion of the IGS Structure Map; discussion of GB member transitions; RTCM membership billing; updates on the CB-led Archiving Plan; and GB64 planning.

10 - 11 July 2023 (GB64, hybrid)
Approval of Rolf Dach as new GB Chair; updates and recommendations from the GGOS DOI Working Group; reorganisation and finalisation of the 2023 Revision of the IGS Terms of Reference; updates on the CB-led Archiving Plan; Working Group transitions and updates (TIGA, SVOD, GNSS Monitoring, RINEX, RTACC), including the approval of Erik Schönemann as new Chair of the GNSS Monitoring WG, the approval of the RINEX 4.01 format, and the approval of Andrea Stürze as the new Real-Time Analysis Centre Coordinator; update on JGX as the newest Global AC; SLM updates; IGS CORS Guidelines review and approval; global Data Centre survey; overview of the latest CB-led strategic communications; progress update on the implementation of the IGS Strategic Plan; 2024 IGS Workshop preparations; CB updates including review of actions in response to the 2022 CB Review, upcoming Tour de l'IGS Stops and other events, outreach calendar; and review of forthcoming IUGG sessions.

30 November 2023 (GB65a, virtual)
Approval of the 2023 Revision of the IGS Terms of Reference; GB 2023 elections; approval of JGX as the newest Global AC; ACC / Multi-GNSS Transition; updates on issues relevant to the Infrastructure Committee; presentation of ESA's GENESIS project; approval of the Terms of Reference for the ICG/IGS IGMA/GNSS Monitoring joint task force; updates on the CB-led Archiving Plan; establishment of an task force for diversity, equity, and inclusion; update to the PPP-AR and RINEX charters; decommissioning of the WCR Working Group; and updates on the IGS White Paper.

Table 2: 2023 meetings led and/or coordinated by the CB (cont.).

Executive Committee Meeting

13 Feb. 2023
GB transitions; GB63 planning; GB64 planning; discussion of the 2023 Review of the IGS Terms of Reference; AM elections; discussion of the IGS Structure Map; updates on the CB-led Archiving Plan; update on the ICG TF on DRR.

14 Mar. 2023
GB transitions; update on the ICG TF on DRR; AGU session planning; GB63 planning; GB64 planning; AM elections; MkDocs contributions to the CB-led Archiving Plan; updates on the CB-led Archiving Plan; discussion of the 2023 Review of the IGS Terms of Reference.

02 May 2023
GB64 planning; GB transitions; AM elections; discussion of a potential IGS-IVS collaboration; discussion of the 2023 Review of the IGS Terms of Reference.

28 Jun. 2023
Updates and recommendations from the GGOS DOI Working Group; GB transitions; SLM discussions; GB64 planning; AM elections.

14 Sep. 2023
Briefing from CDDIS on Pat Michael's time away from IGS; GB elections; AM elections; IAG's request to nominate an IGS Representative to GGOS; Multi-GNSS Transition, discussion of a potential policy for commercial companies using IGS data; drafting of a statement for equity, diversity, and inclusion.

25 Oct. 2023
End-of-year meetings planning, i.e., GB65a and 6th AM meetings; GB elections; Multi-GNSS Transition; drafting of a statement for equity, diversity, and inclusion; IAG's request to nominate an IGS Representative to GGOS; renewal of the IGS-WDS Memorandum of Understanding.

Table 2: 2023 meetings led and/or coordinated by the CB (cont.).

Associate Member Meeting

27 Nov. 2023 (6th meeting)
Updates on Committees and Working Groups.

Tour de l'IGS (https://igs.org/tour-de-ligs/)

1. **Topic:** "GNSS for Natural Hazards in the South Pacific".
   Date: 14 Feb. 2023 (5^{th} stop)
   Scientific Organizing Committee: IGS CB.
   Talks:
   - GNSS Tsunami Early Warning for the South Pacific (John LaBrecque), A nation-wide tsunami inundation and damage forecast system in Japan (Shunichi Koshimura);
   - GNSS Infrastructure and Technologies to Support Tsunami Early Warning System in Tonga (Viliami Folau);
   - Australian perspectives on the use of GNSS for Tsunami Warning (Simon McClusky);
   - Pacific Sea Level and Geodetic Stations for Natural Hazards (Andrick Lal);
   - GNSS for Natural Hazards in Aotearoa New Zealand (Elisabetta d'Anastasio).

2. **Topic:** "Galileo Constellation Spotlight".
   Date: 23 May 2023 (6^{th} stop)
   Scientific Organizing Committee: Navigation Support Office of ESA's European Space Operations Centre.
   Talks:
   - Galileo System (David Ibanez);
   - Galileo Services (Ignacio Fernandez, Juan Pablo Boyero);
   - Galileo Applications (Giovanni Lucchi);
   - Metadata (Francisco Gonzalez);
   - Galileo Geodetic Reference Frame (Erik Schönemann);
   - Galileo Precise Orbit and Clock Determination (Francesco Gini).

Note that the 6th Associate Member Meeting did not cover any updates from the Analysis Centres and/or the Analysis Centre Coordinator. Instead, a dedicated AM Meeting will take place in February 2024 for that specific purpose.

3.1 Standing Elections Committee and Governing Board Elections Coordination

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. Together with the SEC members, the CB contributes 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.

This year, the CB continued to lead administrative management of the GB elections, namely: posting the call for nominations and subsequent reminders when applicable, ensuring that the nomination and voting processes were transparent and successfully carried out (at the end-of-year GB meeting), and coordinating the communication the results of the appointments (after the end-of-year GB meeting).

In 2023, the SEC was chaired by Elisabetta d'Anastasio (GNS Science | Te Pū Ao, New Zealand) and composed of Léo Martire (NASA JPL, USA), Ryan Keenan (Positioning Insights, Australia), and Wolfgang Söhne (BKG, Germany). Importantly, since Elisabetta d'Anastasio was nominated to the position of GB Vice-Chair mid-elections, the SEC ensured that she would recuse from any discussions pertaining to the position of GB Vice-Chair from that point on.

3.2 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. While these events were organised in order to alleviate the impact of the COVID-19 pandemic, the GB and CB endorsed keeping it as a good practice. 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. 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.

In 2023, two Tour de l'IGS events took place (see Table 2), with the two highlighted topics working toward strategic objectives and goals set for 2023 in the 2022 Technical Report, spotlighting a GNSS provider and an underrepresented region (see Table 2).

3.3 Preparation of the 2024, 30th Anniversary IGS Workshop

The IGS started its operational service on the 1st of January 1994; the first IGS workshop was held at the premises of the University of Bern from the 25th to the 26th of March 1993, focusing on the Analysis Centres. The first decade of operational service was celebrated at an IGS workshop hosted again in Bern Switzerland by the University of Bern in March 2004. In 2024, the IGS will celebrate 30 years of operational service; once again, the University of Bern (together with the partners from the CODE consortium) invites the community to celebrate the third decade with an IGS workshop in Bern, Switzerland from the 1st to the 5th of July 2024. The 2024 Workshop will also take place in a two-part format, with 3.5 days of symposium-style presentations, keynotes, and poster sessions, and 1.5 days of in-depth working group sessions.

The Central Bureau has been working closely with members of the workshop's Local Organizing Committee and Scientific Organizing Committee to ensure the event – the first in-person workshop for the IGS community since the 2018 Workshop in Wuhan, China – is a success. The Central Bureau has supported developing the workshop website, as well as graphics and social media campaigns to inform the wider community of the event.

4 Central Bureau Information Systems (CBIS)

The CB continuously works toward maintaining and improving a number of critical public-facing web applications. The most important of them are the IGS Website, the Site Log Manager (SLM), the IGS Network Map, and the Associate Member (AM) Database. We describe in the following Sections the latest updates concerning these crucial systems.

4.1 IGS Website and Archives

The IGS Website, meticulously curated by the CBIS team, stands as the prominent public interface of Service, and must therefore embody a commitment to excellence. As of today, it prioritises user satisfaction, accessibility, and effectiveness; namely through an intuitive and secure navigation structure adhering to web accessibility standards. Regular content updates, covering news, events, and institutional changes, reflect a dedication to keeping our users informed. A cohesive brand identity and interactive features (including feedback mechanisms and multimedia content) ensure consistent user engagement and create a dynamic online environment with which they can interact.

Practically speaking, the IGS Website is 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 Associate Members Meetings (https://igs.org/am-meetings/). Furthermore, 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 in 2022. This effort consolidated all current information in a more visible and easily accessible part of the CBIS.

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 0.5 % from last year, going up from 117,880 to 118,434. There has also been a 6 % increase in the total number of sessions, from 254,698 to 269,963. Additional notable statistics include 567,270 page views, 3,214,707 file downloads, and a 55.2 % engagement rate (percentage of sessions longer than 10 seconds or having at least 2 pageviews).

In 2022, the IGS KnowledgeBase was retired to fully leverage the cpabilities of the new and improved IGS Website. After careful analysis, the CB made sure to have the most popular pages (based on visit statistics) either integrated directly on the IGS Website or archived on https://files.igs.org. The remaining IGS KnowledgeBase content (files with little to no traffic and/or with outdated information) has been backed up and archived internally for historical purposes and is available upon request to cb@igs.org.

4.2 Open-Source Site Log Manager and Network Map

Both the IGS Mission statement and IGS 2021+ Strategic Plan goals underline the importance of open access to data and products, which facilitates collaborations, standardisation, and inclusivity. Indeed, 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 data centres for sourcing GNSS data (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 Map 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. The primary goal of the new SLM and Network software is to maximise the reliability, accuracy, and searchability of site log metadata information. After gathering community feedback through a series of surveys and interviews, and a successful beta period in early 2023, the IGS SLM and Network Map 2.0 are now available at https://slm.igs.org and https://network.igs.org/, respectively. This fulfils one of the goals set for 2023 in the 2022 Technical Report.

Furthermore, 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.

4.3 Network Coordination

The CB Network Coordinator - with the help of the Infrastructure Committee - coordinates the monitoring of station logs and RINEX metadata, and evaluates all new IGS station proposals on a regular basis. Additionally, the CB Network Coordinator also collaborates with the Antenna Committee Chair and GNSS manufacturers to have their equipment added to the official IGS files (`rcvr_ant.tab` and `antenna.gra`). For the latest update on those fronts, see Section "Network Growth and Coordination" in Chapter "IGS Governing Board". Finally, the CB Network Coordinator also ensured timely responses to all email inquiries received from users about data, products, or general IGS information.

4.4 Associate Membership Database

Up until 2022, the IGS AM Database was a simple list of all IGS Associate Members. In order to better keep track of active AMs, the IGS CB developed a new AM Database and registration system, and deployed it in 2022. The new and legacy lists are available to explore at https://igs.org/am/.

The revised registration form gathers additional information from prospective members (to ensure they meet the minimum requirements for AM status) and comprehensively list all members through a database of individual profile pages (allowing CBIS to manage AMs more efficiently). Furthermore, a full secure login mechanism was implemented, namely providing members with the capability to manage and update their profiles on their own.

Throughout 2023, the CB has worked to transition all AMs from the legacy database to the new one - proceeding in batches so that all transfers may be double-checked by the IGS Governance. The transition process is still ongoing due to the large number of AMs, and is expected to complete in 2024.

5 Communication Efforts

The CB strives to comprehensively address the diverse applications of IGS, ensuring it fosters community engagement, disseminates IGS updates efficiently, and contributes adequately to global initiatives. This commitment is exemplified through the implementation and sustained management of a multifaceted communication strategy, encompassing academic interactions, community outreach, social media presence, newsletter circulation, and collaborations with influential entities.

The Tour de l'IGS makes up the academic side of IGS communications, allowing relevant interactions with / and outreach to the community; see Section 3.2.

Furthermore, the CB fosters diverse community engagements and collaborations through a strong presence on social media and the regular circulation of the IGS Newsletter. Numerous news pieces and social media posts covering IGS-related updates, activities, and other announcements were developed in collaboration with the Governing Board and relevant IGS Components. See LinkedIn, YouTube, X (formerly Twitter), and `https://igs.org/newsletter/`.

Finally, the CB keeps researching and developing many other opportunities for IGS engagement. For instance, 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. For more details, see Section "External Engagement" in Chapter "IGS Governing Board".

A final noteworthy contribution is that IGS CB Director Allison Craddock provided the English language voiceover for the GGOS outreach video on Terrestrial Reference Frames, playing a key part in effectively communicating technical information to the general public.

The 2021-launched IGS "Constellations" quarterly newsletter showcases IGS and other relevant news and articles to our community members (`https://igs.org/newsletter/`). In 2023, two issues were edited:

- The April 2023 (seventh) issue's first article presented an update on the latest innovations on the use of GNSS and geodesy for disaster risk reduction, discussing collaborations with international organisations, the 5th Tour de l'IGS Stop, and challenges faced by Pacific islands. It also related opinions of subject matter experts, stressing the importance of real-time data and modelling, and described some ongoing initiatives such as the UN OOSA TCG DRR TF mailing list and the LaBrecque's GTEWS efforts. The second article highlighted how SIRGAS, the Geodetic Reference System for the Americas, actively operates almost 500 GNSS geodetic stations, making it the largest regional network in the world; it emphasised the vital collaboration between SIRGAS and IGS, with SIRGAS providing infrastructure and IGS contributing crucial data, aiming to bring geodesy closer to people with at least one IGS station in each country.

- The October 2023 (eighth) issue and last issue of the year's first article emphasised the Infrastructure Committee's new guidelines for Continuously Operating Reference Stations (CORS), and the revised process for proposing new IGS stations. The second article reported on the successful Technical Seminar on Reference Frames at the FIG Working Week 2023, discussing themes such as geodetic reference frames, IGS & OGC collaboration, and case studies from various regions. The third article presented the brand-new RINEX 4.01 format (noting namely accommodations for modernised GNSS navigation messages and compatibility notes with respect to previous versions), and encouraged station operators to switch to RINEX 4.0x for future-proofing GNSS observations.

For social media in particular, the CB implemented a consistent cross-linking within the IGS website and across various social media platforms in order to enhance the clarity and utility of community resources. Beyond promoting IGS news and events, the CB actively engaged with followers by participating in trends associated with international holidays relevant to geodesy and diversity in science. In terms of pure statistics, the IGS Social Media accounts grew as follows (as of 29 January 2024):

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

- 2084 followers (up from 2075 followers at the end of 2023)

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

- 432 subscribers (+83 since 2022, +7/month)
- 18239 views (+4046 since 2022, +337/month)

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

- 2504 followers (+504 since 2022, +42/month)

6 Future Steps for 2024

Most of the goals set in the 2022 Technical Report were fulfilled in 2023. The new SLM and Network Map were deployed alongside the open-source code for the SLM (see Section 4.2), the Tour de l'IGS spotlighted a GNSS provider and an underrepresented region (see Table 2), the CB heightened its advocacy efforts even more by highlighting and incubating further the novel approach of using GNSS for disaster risk reduction (see Section "External Engagement" in Chapter "IGS Governing Board"), and the consistent improvement in coverage enabled by the constant addition and/or improvement of stations in the IGS Network. Importantly, the GB and CB started focusing their efforts on the multi-GNSS transition of the IGS, and involving the relevant Components in this next step forward.

In 2024, the IGS CB will focus on achieving substantial milestones in various critical areas. One key objective is to make significant strides in both the Multi-GNSS and ACC Transitions, ensuring a sustainable and truly multi-GNSS IGS. Another crucial endeavour involves finalising the preparation and successful execution of the 2024 IGS Workshop, fostering collaboration and knowledge exchange within the GNSS community. Simultaneously, efforts will be directed towards the completion of the AM Database Transition, eventually streamlining the management of the member database. Moreover, the IGS CB will enhance outreach and engagement activities in Africa, with one particular goal being the improvement of the GNSS infrastructure in this region through capacity development initiatives. Finally, the CB will continue to fulfil all of its regular administrative tasks and duties, including event coordination, governance support, network coordination, and communications.

7 Acknowledgements

The Central Bureau gratefully acknowledges the contributions of our colleagues at the Astronomical Institute at the University of Bern, who edit, assemble, and publish the IGS Annual Technical Report as a service to the Central Bureau and IGS community. The Central Bureau also wishes to thank all Governing Board members who actively participated in committees, review panels, and other efforts that have contributed to the improvement and sustainability of this organisation and its administration.

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2023

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

[1] Geoscience Australia, Canberra, ACT, Australia
E-mail: acc@igs.org, Salim.Masoumi@ga.gov.au

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

1 Introduction

The IGS Analysis Center Coordinator (ACC) is responsible for monitoring the quality of products submitted by individual analysis centers, and combining them to produce the official IGS products. The IGS ACC also has the overall responsibility for coordinating the changes, developments and improvements within the contributing analysis centers to produce the IGS products using the latest models and standards. The IGS products continue to perform at a consistent level, and in general the solutions submitted by the analysis centers maintain a consistent level of 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.

In 2023, IGS welcomed a new Analysis Center, JGX, jointly led by the Geospatial Information Authority of Japan (GSI) and the Japan Aerospace Exploration Agency (JAXA). This was following a number of extensive assessment campaigns for the JGX products both by the IGS Reference Frame Coordinator and the IGS Analysis Center Coordinator. The JGX products were then included in the IGS combinations without weight (for comparison) for a period of about six months between July-December 2023 for formal evaluations, before being approved by the IGS governing board as a new official Analysis Center that can have their products weighted in the IGS combinations. As a result, the JGX products have been contributing to the IGS combined products starting from 19 November 2023.

Towards the end of 2023 and leading to 2024, the IGS ACC started providing multi-GNSS ultra-rapid orbit combinations as demonstration products. These ultra-rapid orbits are combinations of GPS, Galileo and GLONASS orbits provided by the IGS Analysis Centers, and are another step towards achieving a truly multi-GNSS IGS after the successful inclusion of multi-GNSS combinations in the Repro3 campaign. IGS ACC is contributing

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
Geospatial Information Authority of Japan (GSI) and the Japan Aerospace Exploration Agency (JAXA)	JGX
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 ultra-rapid experimental GLONASS	IGV
IGS real-time	IGC
IGS rapid	IGR
IGS final	IGS

to the IGS multi-GNSS Task Force in forming the future of the multi-GNSS combined products.

In January 2024, the combinations of the orbits and clocks of the Repro3 products for the extended period of 2021-2022 were completed and made publicly available. As a result, the full set of reprocessed products, for the whole period from 1994 until the time of the switch to the IGS20/igs20.atx frame, is now available.

2 Introduction of JGX as a new IGS global Analysis Center

In 2023, IGS welcomed JGX as the most recent IGS global Analysis Center. JGX is led jointly by the Geospatial Information Authority of Japan (GSI) and the Japan Aerospace Exploration Agency (JAXA). Prior to the introduction of JGX as an Analysis Center, an extensive series of testing campaigns were carried out by both the IGS Reference Frame Coordinator and the IGS Analysis Center Coordinator where the JGX products were put into comparison against the IGS combined products.

After a number of successful testing campaigns and the presentation of the results by the

JGX to the IGS governing board, the governing board accepted the JGX as a new Analysis Center candidate [IGSMAIL-8350]. Following this decision and starting from July 2023 (GPS week 2269), JGX started submitting rapid and final products to the global data centers on a routine basis. These products included station position (SINEX) solutions, as well as satellite orbits, satellite and station clocks and earth rotation parameters (ERP). The JGX products were initially included in the IGS combinations without weight and for comparison purposes only. After almost six months of their products being routinely assessed against the combined products, the results were reported to the IGS governing board in December 2023, and the governing board officially accepted JGX as the newest IGS global Analysis Center. Following the decision and based on the assessment results, the JGX products started to be included with weight in the IGS combinations in November 2023, starting from the products of GPS week 2291 for the rapid products and GPS week 2289 for the final combinations. The JGX rapid orbits and clocks, as well as the JGX final terrestrial frame and orbits are currently weighted in the IGS combinations. Further details of the JGX product inclusions and their precision compared with the combined products can be found in Section 3.

3 Product Quality and Reliability

In 2023, the delivery of the ultra-rapid, rapid and final products were well within the expected latencies for most of the year. The number of delayed cases for the IGS operational products improved significantly compared to the previous year, with only one instance of delayed rapid products over the whole year and only two cases of delayed ultra-rapid products. Of these failures, one was due to a problem in the orbit solution of one of the Analysis Centers which the combination software failed to remove as an outlier, one was due to an issue in depositing the combined products to global data centers, and one due to a storage disk issue in the operational server. There was also an instance of resubmission of the combined rapid clocks due to an issue in the alignment of the clocks to the IGS Timescale (IGST).

3.1 Ultra-rapid

The ultra-rapid is one of the most widely utilized IGS products, often used for real-time and near-real-time applications. In 2023, IGS received submissions from eight 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).

The combined IGS ultra-rapid orbit can be split into two components, a fitted portion based on observations, and a predicted component reliant upon forward modelling of the satellite dynamics. The fitted portion of the ultra-rapid orbits continues to agree to the rapid orbits with a median value of 6 mm (see Figure 1) and has been consistently at this

Table 2: ACs contributing to the IGS ultra-rapid products; *W* signifies a weighted contribution, *C* is comparison only. The SIO and WHU ERP solutions are by default weighted, with the exception of the length of day estimate which are excluded from the combination for these two ACs.

Analysis center	Orbit	ERP	Clock
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 (LoD C)	C

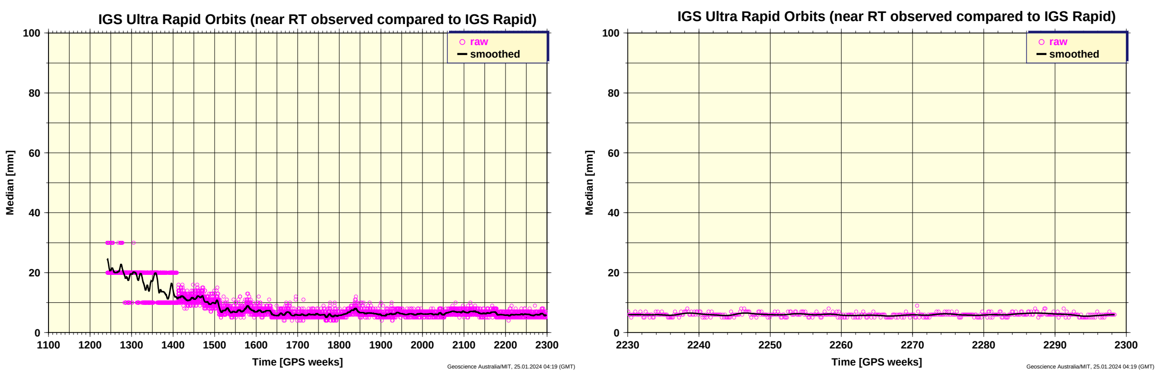


Figure 1: The median difference of the fitted component of the IGS ultra-rapid (IGU) combined orbits with respect to the IGS rapid (IGR) orbits. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right.

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 26 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.

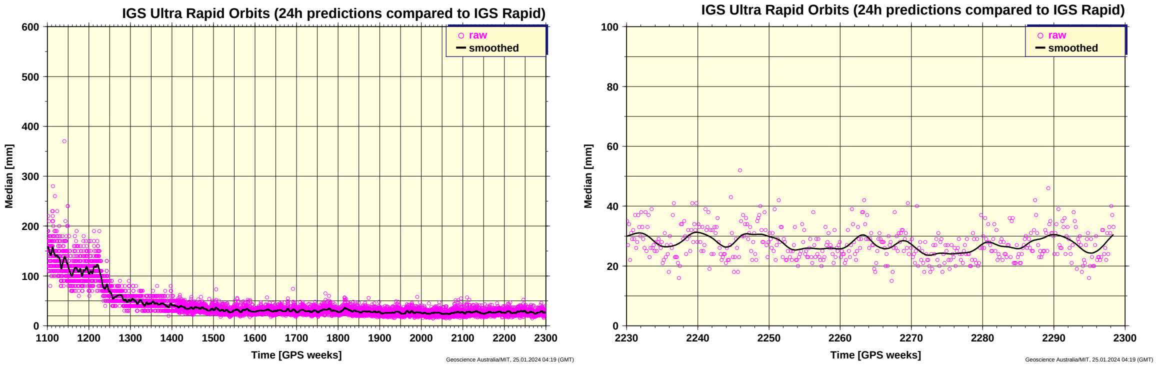


Figure 2: Median of IGU combined predicted orbits compared to IGR. The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. Note the change in scale of the Y axis.

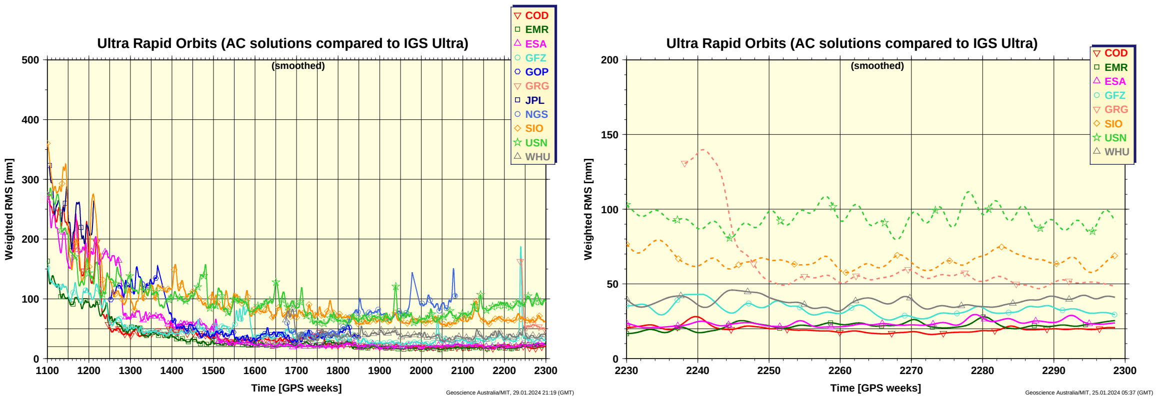


Figure 3: Weighted RMS of AC Ultra-rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. The dashed lines on the figure on the right are the solutions that are unweighted as of January 2024, while the solid lines are the weighted solutions. Note the change in scale of the Y axis.

3.2 Rapid

In total, eleven individual analysis centers contributed to the IGS rapid products in 2023 (see Table 3). The GRG rapid orbits, clocks and ERPs, which were not weighted in the combinations at the start of the year, started to be included with weight from May 2023 (GPS week 2261) following a series of tests that showed their rapid products were consistent with the other ACs and the combined products. JGX rapid orbits, clocks and ERPs started to be included in the combinations with weight from December 2023 (GPS week 2291), while they were included as unweighted (only for comparison) before that.

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. The GRG rapid orbits, clocks and ERPs were included with weight starting from May 2023 (GPS week 2261). JGX orbits, clocks and ERPs were included with weight in the IGS Rapid combinations starting from December 2023 (GPS week 2291).

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
JGX*	W	W	W
JPL	W	W	W
NGS	W	W	C
SIO	C	C	-
USN	C	C (LoD W)	C
WHU	W	W	W

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 at or 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). The clock RMS values of the weighted centers were also consistently below 150 ps at all times, with most ACs hovering around or below 100 ps.

3.3 Final

In total, there are ten individual ACs contributing to the IGS final products (see Table 4). Immediately following the switch of the IGS products to the IGS20 reference frame in GPS week 2238, most of the analysis centers switched to submitting their final products in the IGS20 reference frame, except for JPL and EMR that decided to carry out internal evaluations of their products in IGS20 before releasing them.

JPL is still submitting their final products in the IGb14 frame; therefore, JPL final products are still not weighted in the IGS combinations. The higher RMS of the JPL orbits and clocks from GPS week 2238 is clearly observed in Figures 6 and 7.

EMR, after a pause in their final product submissions, restarted submitting their final products in the IGS20 frame since December 2023 (GPS week 2290). After a few weeks of assessing their products, the EMR station position solutions, ERP and orbit solutions

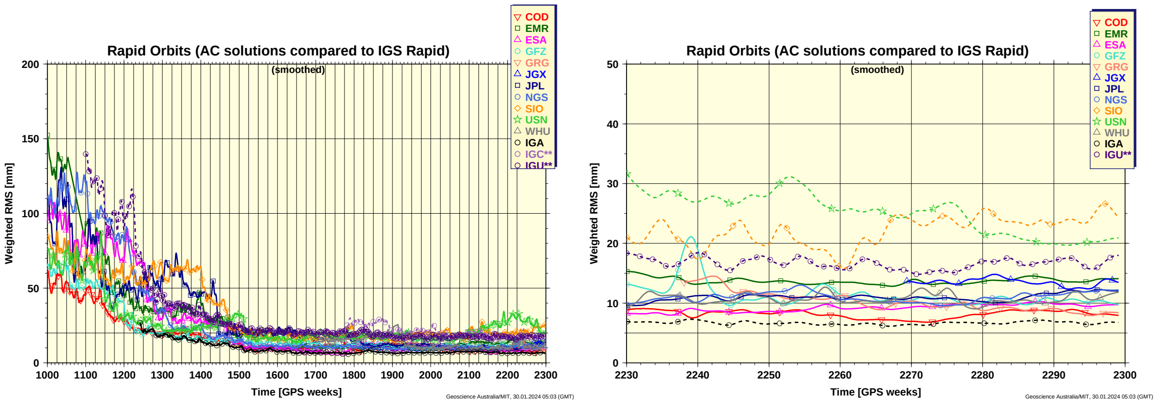


Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time stream. IGU** consists of four separate comparisons to IGR done each day over the first 6 hours of each IGS Ultra-rapid product. The dashed lines on the figure on the right are the solutions that are unweighted as of January 2024, while the solid lines are the weighted solutions. Note the change in scale of the Y axis.

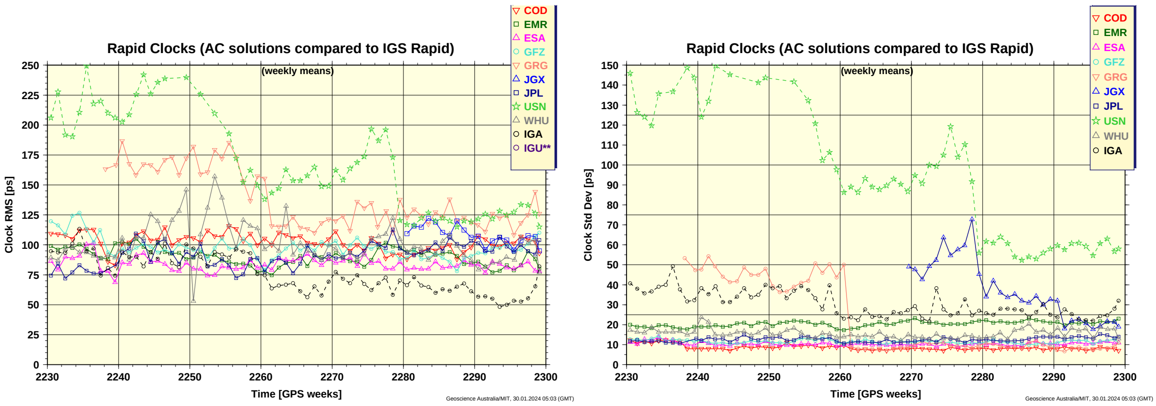


Figure 5: Weighted RMS (left) and standard deviation (right) of ACs Rapid clock submissions (smoothed). IGC** are 24-hour products each containing four 6-hour segments from each update interval of the IGS real-time stream. IGU** consists of four separate comparisons to IGR done each day over the first 6 hours of each IGS Ultra-rapid product. The dashed lines on the figure on the right are the solutions that are unweighted as of January 2024, while the solid lines are the weighted solutions. Note the change in scale of the Y axis.

started to be weighted in the IGS combinations from GPS week 2294. The EMR clock solutions remain unweighted at this point as some inconsistencies were observed in their final clock solutions.

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. EMR clocks were missing for most of 2023 but were re-started since GPS week 2290. JGX orbits started to be weighted since GPS week 2289. SIO orbits were unweighted since GPS week 2257 due to large Y rotations with respect to the other AC orbits; however, they have started to be included with weight in the combinations since GPS week 2297 as the issue has been resolved.

Analysis center	Orbit	ERP	Clock
COD	W	W	W
EMR*	W	W	C
ESA	W	W	W
GFZ	W	W	W
GRG	W	W	W
JGX*	W	W	C
JPL*	C	C	C
MIT	W	W	C
NGS	W	W	C
SIO*	W	C	-

As described in Section 2, JGX final orbits started to be included with weight in the IGS combinations from GPS week 2289. The JGX clocks were initially included but then unweighted after a few weeks, as inconsistencies were observed in some days between the final clocks of the JGX and those of the other ACs. The JGX clocks will be monitored and may be weighted in future if their level of consistency with the other ACs becomes stable.

An issue was identified in the SIO final orbits where they suffered from large Y rotations with respect to the other AC orbits (and the combined orbits). This had a negative impact on the alignment of the combined orbits to IGS20/igs20.atx. As a result, SIO orbits were unweighted in the combinations starting from GPS week 2257. However, this problem with the SIO final orbits has been resolved now and the SIO orbits have started to be included with weight in the IGS final combinations from GPS week 2297.

Most of the AC final orbit solutions that are weighted in the IGS combinations are comparable at around the 10 mm RMS level (see Figure 6). The final clock solutions from the weighted ACs are all below 150 ps level of RMS compared to the combined final clocks, and the standard deviations of the final clock solutions for the weighted centers are below 20 ps level for most of the weighted centers (Figure 7).

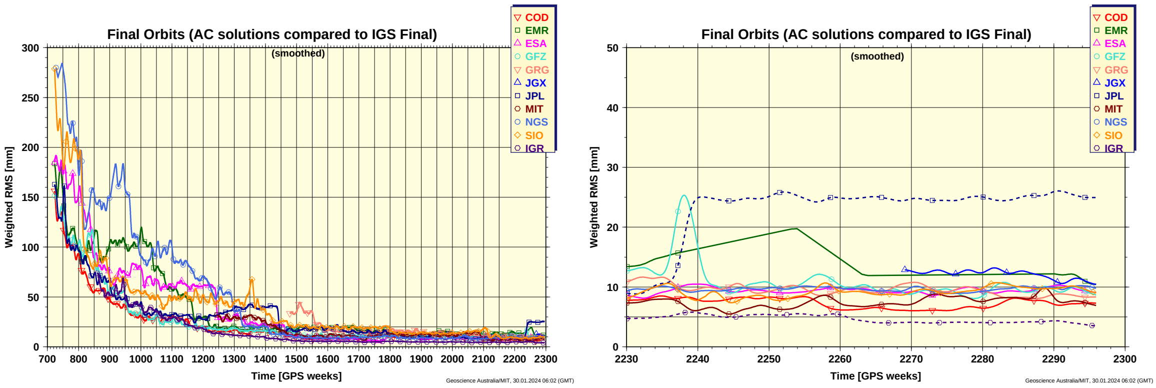


Figure 6: Weighted RMS of IGS Final orbits (smoothed). The historical time series of comparison results is shown on the left, and recent comparison results are shown on the right. The dashed lines on the figure on the right are the solutions that are unweighted as of January 2024, while the solid lines are the weighted solutions. Note the change in scale of the Y axis.

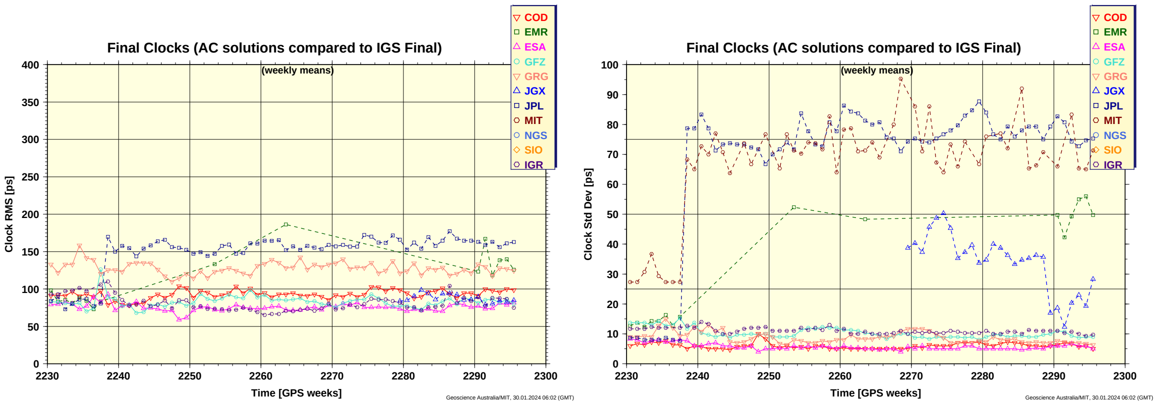


Figure 7: Weighted RMS (left) and standard deviation (right) of IGS Final clocks (smoothed). The dashed lines on the figure on the right are the solutions that are unweighted as of January 2024, while the solid lines are the weighted solutions. Note the change in scale of the Y axis.

4 Extension of the combined products for the third IGS reprocessing campaign to 2021-2022

In 2023, the Repro3 orbit and clock combinations were carried out for the remaining period from the end of 2020 until the time of the switch to the IGS20/igs20.atx frame and Repro3 standards (GPS week 2237; November 6, 2022). The set of extended Repro3 combined orbit and clock products were published in the global data centers in January 2024 ([IGSMAIL-8421]). Therefore, the full set of historic Repro3 orbit and clock prod-

Table 5: ACs contributing to the IGS demonstration multi-GNSS ultra-rapid orbits; W signifies a weighted contribution, C is comparison only.

Analysis center	GPS	GLONASS	Galileo
COD	W	W	W
EMR	W	W	-
ESA	W	W	-
GFZ	W	W	W
GRG	C	-	W
WHU	W	W	C
SIO	C	-	-
USN	C	-	-

ucts (as well as the combined bias products for most of the period) until the switch to IGS20/igs20.atx is now available in the global data centers.

The extended Repro3 combined products generally follow the same combination methodology as those for the period 1994-2020. The only exception is that, since only two Analysis Centers provided phase biases for this extended period, a robust combination of phase biases and integer clock combinations was not possible. Therefore, the combined clocks for this extended period consist of multi-GNSS legacy clocks with no combined bias products. Similar to the full Repro3 period, the orbit combinations were performed by the IGS Analysis Center Coordinator at Geoscience Australia, and the clock combinations were performed at Wuhan University led by the IGS PPP-AR Working Group. The reference attitudes for the solutions were computed in Geoscience Australia using the GROOPS software developed by Graz University of Technology (Mayer-Guerr et al. , 2021).

A detailed description of the Repro3 orbit combination strategy, as well as analysis of the IGS Repro3 orbits together with validations with Satellite Laser Ranging (SLR) observations were published in Zajdel et al. (2023).

5 Multi-GNSS ultra-rapid demonstration combined orbits

In 2023, the IGS ACC conducted tests to combine Repro3-like multi-GNSS (GPS, Galileo and GLONASS) ultra-rapid orbits on an operational basis. Starting from GPS week 2294 (December 24, 2023), these experimental products were made available in the global data centers as demonstration products on a regular basis (see [IGSMAIL-8413] for details and locations of the available products). These multi-GNSS ultra-rapid products are currently made available four times a day approximately 20 minutes after the legacy GPS-only (and experimental GLONASS) ultra-rapid orbits are published. The demonstration multi-GNSS orbit combinations use the same software developed and used for the Repro3 campaign, and follow the same methodology used for the IGS Repro3 campaign and described by Zajdel et al. (2023).

While still in the early phase, it is worthwhile to demonstrate some early results from these experimental combinations. Table 5 lists the Analysis Centers currently contributing to the multi-GNSS ultra-rapid orbit combinations. The consistencies of the individual AC orbits with the combined multi-GNSS orbits are displayed in Figure 8. Note that there were two gaps in the multi-GNSS combinations, around October and early December, as the combinations were internally being tested in Geoscience Australia. The combinations started to be publicly released starting from the products of late December. Figure 9 shows the RMS of the AC ultra-rapid orbit solutions per GNSS satellite.

From Figures 8 and 9, the RMS levels of the different AC solutions for GPS orbits are very similar to those observed for the legacy GPS-only solutions (Figure 3) at below 50 mm for the weighted AC orbits. The comparison with the IGS ultra-rapid GPS-only legacy combinations (Figure 8, dashed black lines) also shows that the multi-GNSS combinations are generally very close to the GPS-only combinations for the GPS constellation, with the RMS level between the two at a median of about 6 mm. This RMS level is higher than that observed for the Repro3 orbits (Villiger and Dach (2022); Figure 8) between the multi-GNSS and legacy GPS-only combinations (1.4 mm). This larger difference can be likely attributed to the generally lower accuracy of the orbit modelling for the ultra-rapid orbits compared to the reprocessed orbits, particularly for the predicted half of the orbits.

The consistency of the AC orbits for the GLONASS satellites is in the range 50-80 mm for different ACs (Figure 8). The multi-GNSS combined orbits are consistent with the experimental legacy GLONASS-only combinations at about 14 mm level. Similar to what was observed for the Repro3 campaign, the disparities between the different AC orbit solutions are the largest for the older Block M satellites, in particular R719, R720, R721 and R730, while they have improved for the more recent satellites, e.g. R802 from the Block K1B or more recent launches in Block M such as R851 (see Figure 9).

There are currently four ACs that provide Galileo ultra-rapid orbits, of which three (COD, GFZ and GRG) are currently weighted in the combinations. The weighted AC contributions for Galileo are consistent with each other at the level of about 50-75 mm. COD and GFZ have been generally the most consistent in their ultra-rapid Galileo orbits. More recently, GRG orbits have increased deviation from the COD and GFZ solutions, while WHU (which is currently unweighted) has improved RMS relative to those two ACs. The IGS ACC will keep monitoring the AC solutions and will work with the ACs to ensure the consistencies are maintained in the combination. More AC contributions to the Galileo operational solutions is encouraged.

5

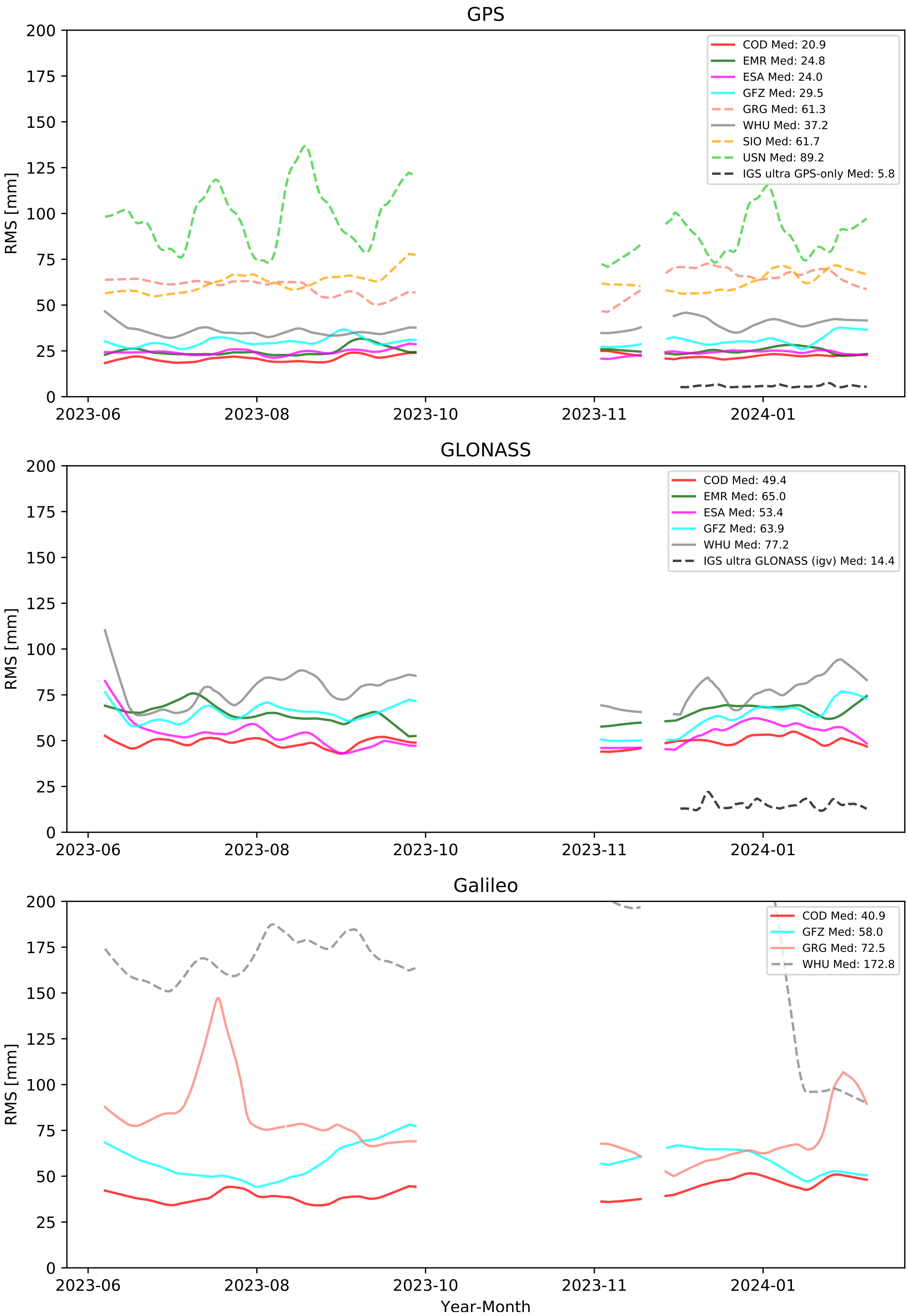


Figure 8: RMS of analysis center orbit solutions (smoothed) compared to the IGS combined orbits for the IGS multi-GNSS ultra-rapid demonstration products for GPS (top), GLONASS (middle) and GALILEO (bottom). The dashed lines are the AC solutions that are not weighted in the combinations, while the solid lines are the weighted ACs.

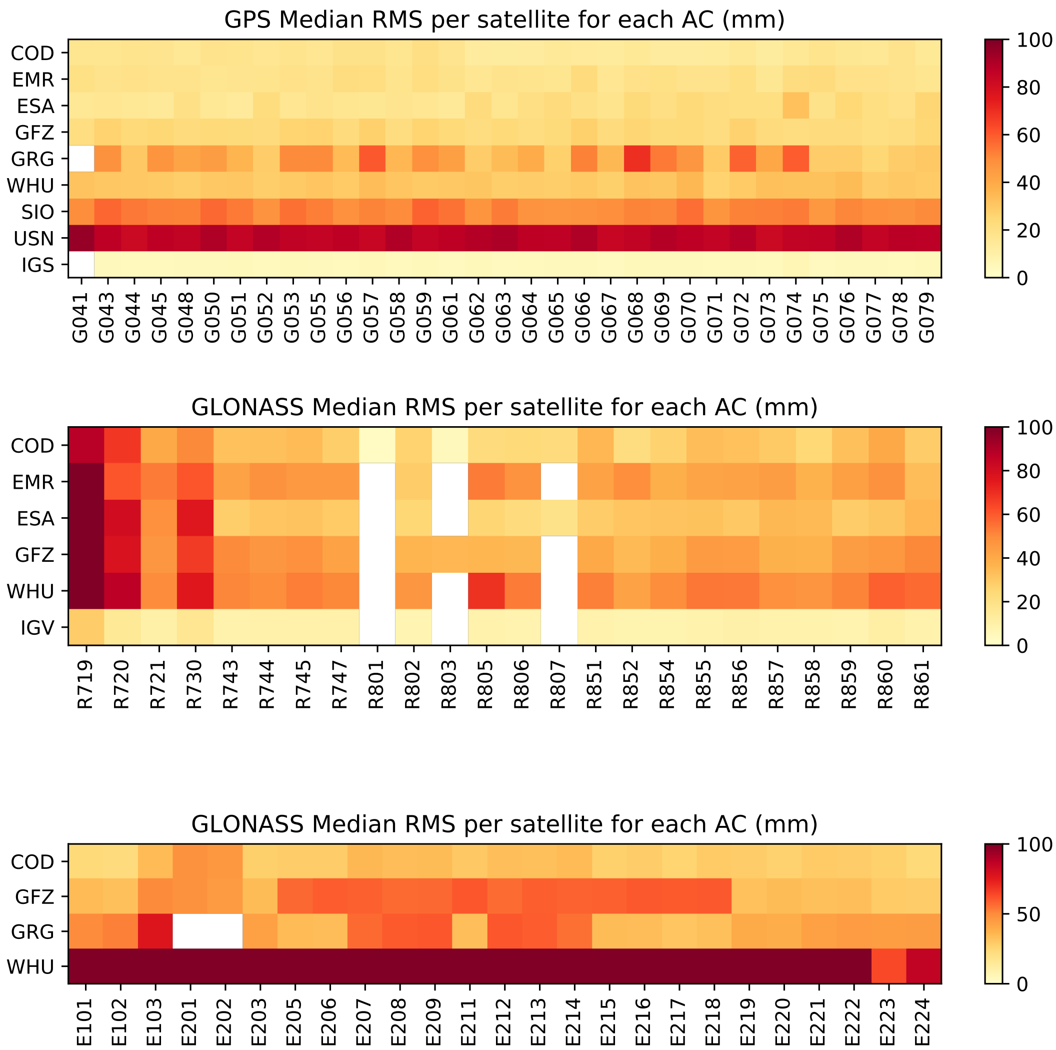


Figure 9: Median RMS of the individual satellites compared to the combined orbits for the multi-GNSS ultra-rapid solutions for GPS (top), GLONASS (middle), and Galileo (bottom). IGS is the IGS ultra-rapid legacy GPS-only combined orbits, and IGV is the current experimental ultra-rapid GLONASS-only combined orbits.

6 Future Work

The current term for the IGS ACC will conclude at the end of 2024. This marks the end of two terms (8 years) that Geoscience Australia and MIT have jointly served in this role, consistently providing a set of IGS combined products, in particular ultra-rapid, rapid, final and reprocessing orbits, clocks and ERPs. In 2024, a major focus of the IGS ACC will be on the transition of the role to the next institute who will undertake the task. A transition roadmap was drafted by the IGS, which will be followed as a guide to complete the transition process. This includes a call for participation for new ACC candidates in February 2024 with a focus on multi-GNSS capability of the new ACC. The current ACC will continue to provide legacy combinations beyond its current term and until a new multi-GNSS ACC is established.

As part of the transition to multi-GNSS, we intend to open-source the multi-GNSS orbit combination software developed in Geoscience Australia. This initiative aims to make the software accessible to the IGS community while also fostering future enhancements to the combinations. The IGS ACC continues to participate in the IGS multi-GNSS task force in developing a new fully multi-GNSS combination software by consolidating the efforts made by different IGS-affiliated organisations.

The ITRF2020 is being planned to be updated on a yearly basis with the first update to be released late 2024. The adoption of the ITRF2020 updates will be mainly carried out by the IGS Reference Frame Coordinator, but the IGS ACC will support the Reference Frame Coordinator in incorporating the updates where relevant.

In 2024, there will be a campaign on the assessment of including BeiDou and QZSS constellations in the IGS operational processing. The campaign is mainly led by the IGS Reference Frame Coordinator and the Antenna Committee Chair for the estimation of satellite antenna PCV and PCO values, and involves the participation of a number of interested Analysis Centers in the estimation. The IGS ACC will support this campaign, and will eventually evaluate the impact of the inclusion of BeiDou and QZSS satellites in the IGS operational products.

References

Mayer-Guerr, Torsten and Behzadpour, Saniya and Eicker, Annette and Ellmer, Matthias and Koch, Beate and Krauss, Sandro and Pock, Christian and Rieser, Daniel and Strasser, Sebastian and Suesser-Rechberger, Barbara and Zehentner, Norbert and Kvas, Andreas GROOPS: A software toolkit for gravity field recovery and GNSS processing. In *Computers & Geosciences*, page 104864, 2021. ISSN 0098-3004. doi: https://doi.org/10.1016/j.cageo.2021.104864 https://www.sciencedirect.com/science/article/pii/S009830042100159X

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.

Zajdel, Radosław and Masoumi, Salim and Sośnica, Krzysztof and Gałdyn, Filip and Strugarek, Dariusz and Bury, Grzegorz Combination and SLR validation of IGS Repro3 orbits for ITRF2020 In *Journal of Geodesy*, 97(10):87, 2023.

Center for Orbit Determination in Europe (CODE) Analysis Center Technical Report 2023

R. Dach[1], S. Schaer[2], D. Arnold[1], E. Brockmann[1], M. Kalarus[1]
U. Meyer[1], L. Prange[1], P. Stebler[1], A. Jäggi[1],

A. Villiger[2], D. Ineichen[2], S. Lutz[2], D. Willi[2],

D. Thaller[3], L. Klemm[3], A. Rülke[3], W. Söhne[3], J. Bouman[3],

U. Hugentobler[4], B. Duan[4]

[1] Astronomical Institute, University of Bern, Bern, Switzerland
E–mail: code@aiub.unibe.ch
[2] Federal Office of Topography swisstopo, Wabern, Switzerland
[3] Federal Agency of Cartography and Geodesy,
Frankfurt a. M., Germany
[4] Institute for Astronomical and Physical Geodesy,
Technical University of Munich, Germany

1 The CODE consortium

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

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

Tables 5 and 6 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.Z)
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 product
COD0OPSULT.ION (old: COD.ION_U)
Last update of CODE rapid ionosphere product (1 day) complemented with ionosphere predictions (2 days), Bernese format
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_05D.SP3 (old: COD.EPH_5D)
CODE 5-day GNSS orbit predictions
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, SINEX format

`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, bias SINEX format v1.00
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.gz` (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/COD0OPSFIN_yyyyddd0000_01D_01D_GIM.RNX.gz` (also still available: `yyyy/CGIMddd0.yyN.Z`)
Improved Klobuchar-style ionosphere coefficients, navigation RINEX format

`yyyy/COD0OPSFIN_yyyyddd0000_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_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)

`yyyy/COD0OPSFIN_yyyyddd0000_07D_01D_SUM.SUM.gz` (old: `yyyy/CODwwww7.SUM.Z`)
CODE weekly summary file (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.Z`	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.Z`	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.

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

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

Files generated from three–day long–arc solutions:

COD0OPSFIN_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

COD0OPSFIN_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

COD0OPSFIN_yyyyddd0000_01D_01D_SOL.SNX.gz (old: codwwwwd.snx.Z)
GNSS daily coordinates/ERP/GCC from the long–arc solution in SINEX format

COD0OPSFIN_yyyyddd0000_01D_30S_CLK.CLK.gz (old: codwwwwd_v3.clk.Z)
COD0OPSFIN_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)

COD0OPSFIN_yyyyddd0000_01D_05S_CLK.CLK.gz (old: codwwwwd_v3.clk_05s.Z)
COD0OPSFIN_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)

COD0OPSFIN_yyyyddd0000_01D_01D_OSB.BIA.gz (old: codwwwwd.bia.Z)
CODE daily code and phase bias solution corresponding to the above mentioned clock products

COD0OPSFIN_yyyyddd0000_01D_30S_ATT.OBX.gz (old: codwwwwd.obx.Z)
Satellite attitude information in ORBEX format

COD0OPSFIN_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

COD0OPSFIN_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

COD0OPSFIN_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.

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

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

Files generated from three–day long–arc MGEX solutions:
`CODOMGXFIN_yyyyddd0000_01D_05M_ORB.SP3.gz` CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format
`CODOMGXFIN_yyyyddd0000_01D_12H_ERP.ERP.gz` CODE MGEX final ERPs belonging to the MGEX final orbits
`CODOMGXFIN_yyyyddd0000_01D_30S_CLK.CLK.gz` CODE MGEX final clock product consistent to the MGEX final orbits, clock RINEX 3.04 format, with a sampling of 30 sec for the GNSS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`CODOMGXFIN_yyyyddd0000_01D_01D_OSB.BIA.gz` GNSS code and phase (GPS and Galileo only) biases related to the MGEX final clock correction product, Bias SINEX format v1.00
`CODOMGXFIN_yyyyddd0000_01D_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; Brockmann, Elmar; Kalarus, Maciej Sebastian; Prange, Lars; Stebler, Pascal; Jäggi, Adrian (2023). *CODE final product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: https://www.aiub.unibe.ch/download/CODE; DOI: 10.48350/185744.
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Brockmann, Elmar; Kalarus, Maciej Sebastian; Prange, Lars; Stebler, Pascal; Jäggi, Adrian (2023). *CODE rapid product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: `https://www.aiub.unibe.ch/download/CODE`; DOI: 10.48350/185740.
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Brockmann, Elmar; Kalarus, Maciej Sebastian; Prange, Lars; Stebler, Pascal; Jäggi, Adrian (2023). *CODE ultra-rapid product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: `https://www.aiub.unibe.ch/download/CODE`; DOI: 10.48350/185741.
- Prange, Lars; Arnold, Daniel; Dach, Rolf; Brockmann, Elmar; Kalarus, Maciej Sebastian; Schaer, Stefan; Stebler, Pascal; Jäggi, Adrian (2023.). *CODE product series for the IGS MGEX project*. Published by Astronomical Institute, University of Bern. URL: `https://www.aiub.unibe.ch/download/CODE_MGEX`; DOI: 10.48350/185742.

3 Statistics on the CODE solution

3.1 Selected general statistics

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 118 satellites of five satellite systems.

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

3.2 Ambiguity resolution rate

It is interesting to inspect the percentage of resolved ambiguities displayed in Figure 3. During the year 2023 it is for the fist time, where more ambiguities for Galileo than for GPS are resolved. This holds for the CODE rapid and MGEX series. In the CODE final

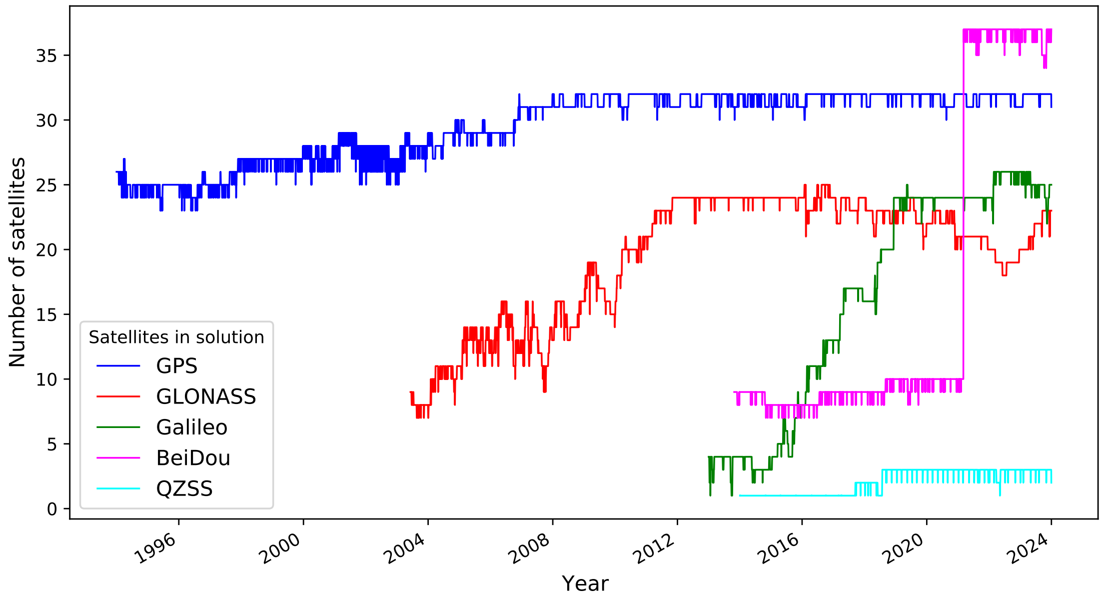


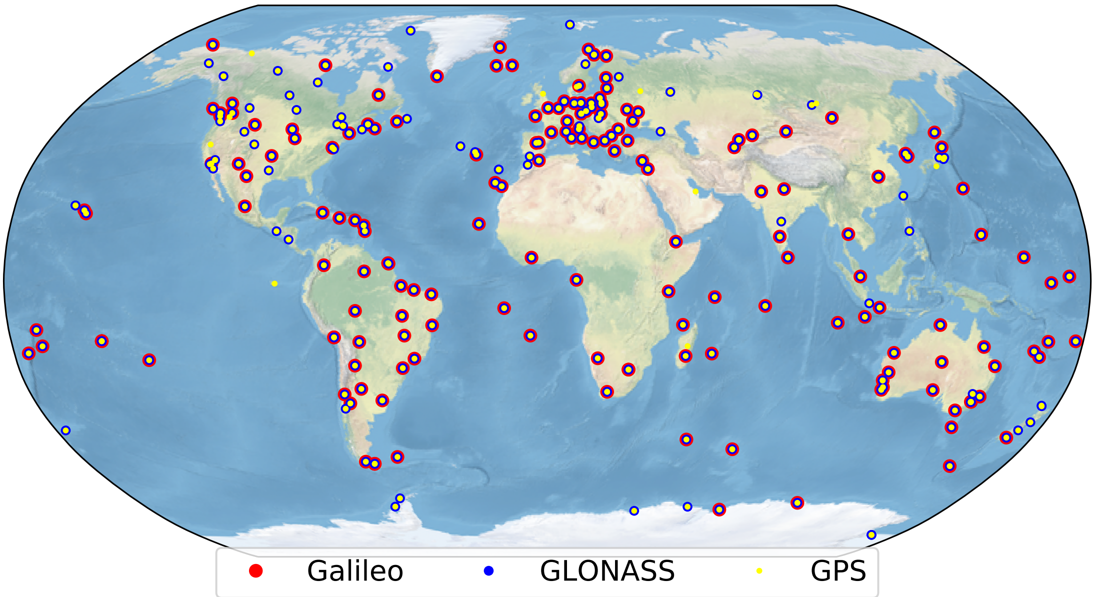
Figure 1: Development of the number of satellites in the CODE orbit products.

series both numbers are still in the same range with a small advantage for GPS (as in Figure 3 for the first part of year 2022). We assume that with a denser network of Galileo tracking stations (and calibrated receiver antennas) the picture for Galileo will change as well in future.

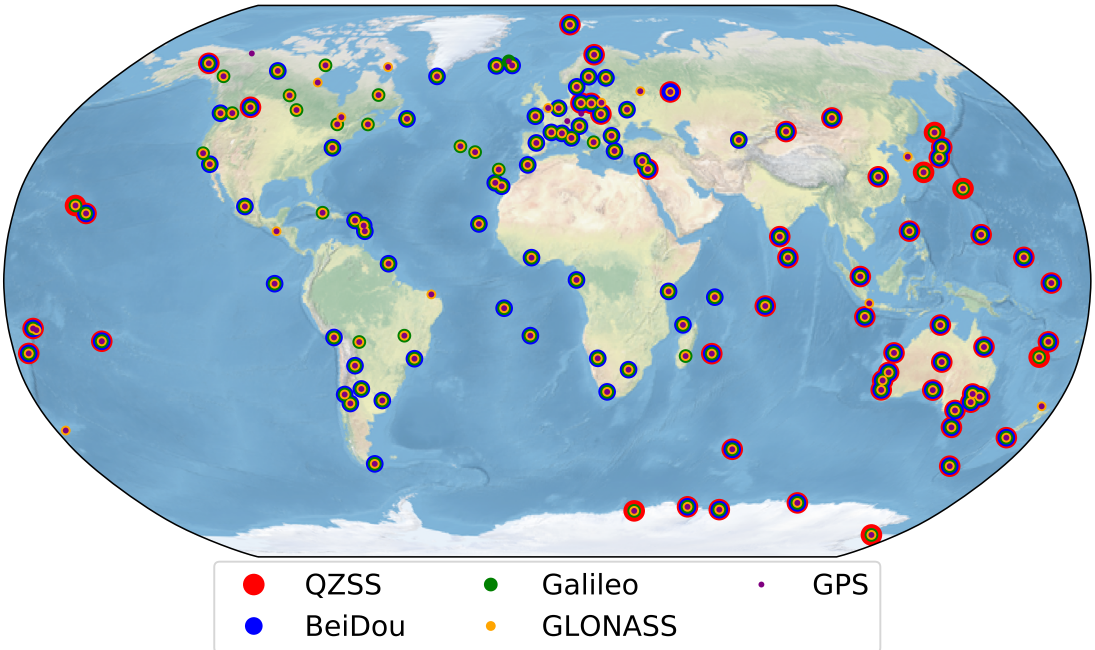
3.3 Performance of the satellite clock solution

An overview on the performance of the clock products (final series with a sampling of 30 seconds) is provided in Figure 4 . The RMS of a linear fit of all estimated clock corrections of a day is shown. The plots show the different performance of the satellites for the GPS and Galileo constellations. The great performance of most of the Galileo satellite clocks is nicely visible by the dark blue color. At the same time, a few Galileo satellite show a degraded clock performance (in particular E11, E19, and E12).

Whereas the Galileo satellites are ordered according to the orbital planes (number 99 was used for the two satellites in the elliptic plane) the GPS satellites are ordered according to the SVN ID, meaning regarding their age. Disregarding the two satellites SVN G072 (PRN G08) and G073 (PRN G10) there is an improvement in the performance for the newer satellite types with respect to the older ones. Satellites from the Block IIF type range between SVN G062 to G073. The latest type Block IIIA starts the numbering with SVN G077. In particular for the satellites of the various Block II-types a dependency of the clock performance in the CODE solution from the elevation of the Sun above the orbital plane is visible.



(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 2023.

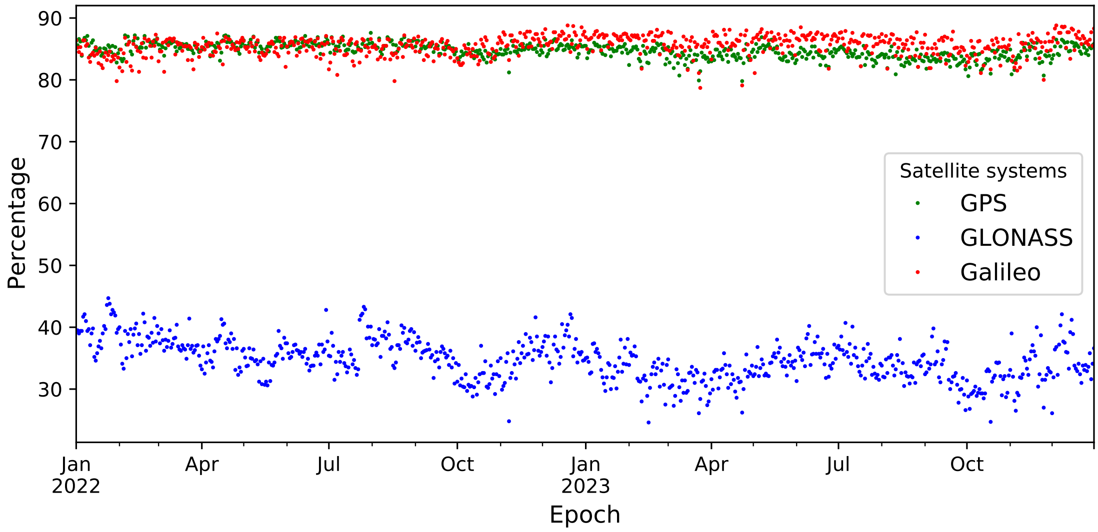
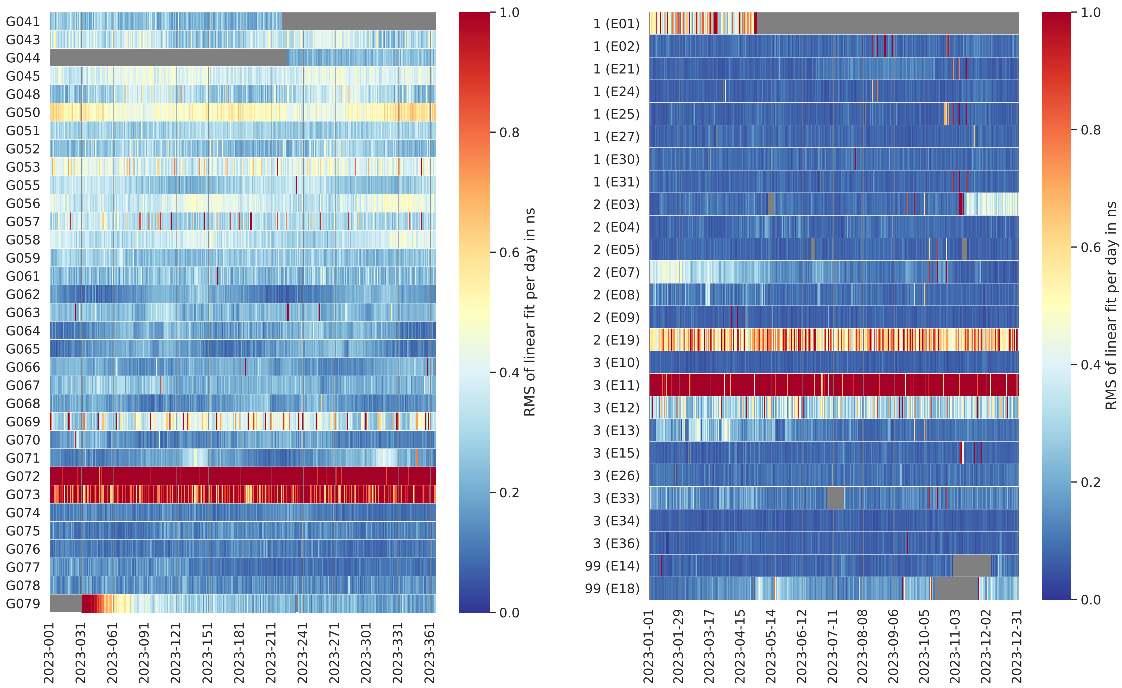


Figure 3: Percentage of resolved ambiguities in the CODE rapid product series.



GPS constellation
plotted with respect to the SVN

Galileo constellation
plotted by PRN sorted by the orbital planes

Figure 4: Performance of the GPS and Galileo satellite clock corrections as provided in the CODE final solution (30-second sampling).

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 changes of the previous year 2022 were published in the last technical report in Dach et al. (2023).

In Section 4.1 we give an overview of important development steps in the year 2023. The change of the gravity field in the CODE operational processing for the IGS is described in Section 4.2 .

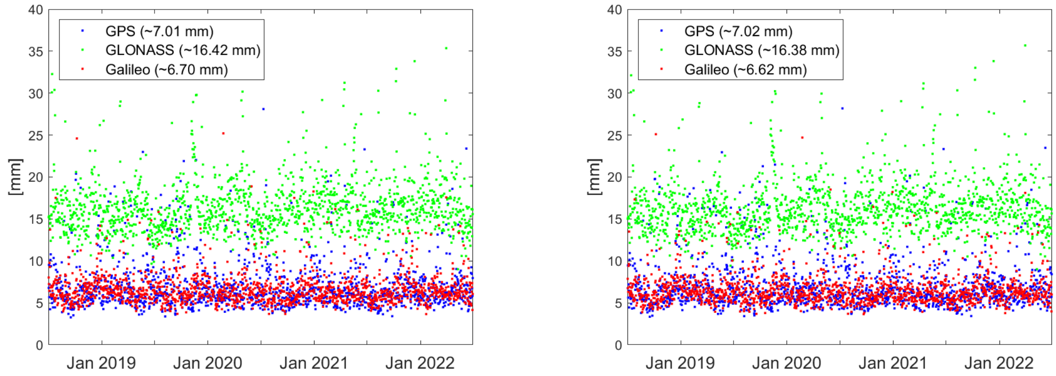
4.1 Overview of changes in the processing scheme in 2023

Table 7 gives an overview of the major changes implemented during the year 2023. 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 7 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.

Table 7: Selected events and modifications of the CODE processing during 2023.

Date	DoY/Year	Description
18-Jan-2023	015/2023	Ignore observations from systems where no system-specific receiver antenna corrections are available. For the CODE final processing line (**about 30% of the Galileo-tracking stations get lost**))
01-Mar-2023	056/2023	Use estimated ionosphere model from the CODE rapid solution chain for ambiguity resolution and higher order ionosphere corrections in the CODE MGEX solution.
11-Apr-2023	099/2023	GLONASS R25/R807 included in all CODE analysis lines.
09-May-2023	127/2023	Replace the static gravity field model (EGM2008) by a time variable Fitted Signal Model as provided by the COST-G service (COSTG_FSM_2212, where 2212 indicates that the coefficients have been fitted with data up to December 2022)
09-Aug-2023	221/2023	Consideration of RINEX4 observation data enabled
20-Sep-2023	260/2023	Updated time variable gravity field model from COSTG_FSM_2212 to COSTG_FSM_2303.
04-Oct-2023	277/2023	Fix a bug in the ambiguity resolution scheme, mainly affecting short baselines
14-Nov-2023	308/2023	R26 switch from R801-R803 (GLONASS-K2) Reprocessing of the interval for GPS weeks from 2253 to 2287 with the corrected satellite type for R26; resubmitted the related results



Using EGM2008 gravity model

Using COSTG_FSM model

Figure 5: Orbit overlaps (RMS of the 3-dimensional vector) using different gravity fields.

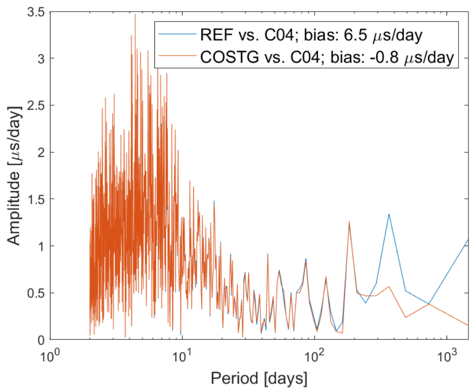


Figure 6: Amplitude spectrum of the Length of Day component estimated from GNSS based on different gravity fields (REF: EGM2008 and COSTG_FSM) with respect to the C04(20) values.

4.2 Changing the gravity field

To aid operational precise satellite orbit determination the Combination Service for Time-variabel Gravity fields (COST-G) of the International Association of Geodesy (IAG) provides a Fitted Signal Model (FSM), which allows to reliably predict temporal gravity variations over time-spans of several months Peter et al. (2022). The FSM is adjusted to the monthly GRACE-FO gravity field combinations (Meyer et al., 2024), which are generated with a latency of about 3 months, and is updated quarterly.

The impact of the temporal gravity variations on the orbits of the high-flying GNSS satellites is only marginal in general. Consequently the orbit misclosures at midnight do not change due to the exchange of the used gravity field (EGM2008 and COSTG_FSM in Figure 5). On the other hand, the variations in the Earth's flattening, represented by the C_{20} coefficient, strongly correlate with the Length Of Day estimates determined in the frame of the GNSS-POD. When comparing the obtained Length of Day values to the C04(20) series in Figure 6, a non-negligible positive impact on LOD has been observed.

Since GPS week 2261 (May 2023) the CODE analysis center is using the the COST-G FSM gravity model for its operational GNSS POD (see 7). Meanwhile, the first update in September 2023 has been carried out without any degradation of the (multi-day) solution. There was even an alarming system implemented before such a time variable gravity field expires.

5 Development of a combined Earth Orientation Parameters product at BKG

The Earth Orientation Parameters (EOP) describe the rotation between the Terrestrial Reference Frame (TRF) and the Celestial Reference Frame (CRF) and represent an essential component of the Global Geodetic Reference Frame (GGRF).

The publicly available EOP time series provided by the IERS, e.g. Bulletin A or C04, result from the combination of EOP derived from individual space geodetic solutions, i.e. a combination at parameter level. This approach represents the least rigorous combination method, as each parameter type is combined independently and correlations between the different parameters are not taken into account.

One of the current activities of the Federal Agency for Cartography and Geodesy (BKG) focuses on the development of a more rigorous combination strategy at the level of normal equations (NEQs). The main objective is to improve the consistency between space geodetic techniques through common parameters, in particular Earth Rotation Parameters (ERPs). The developed ERP product is characterized by a continuous, daily and regular temporal resolution and a short latency. This is particularly important for the highly variable parameter dUT1.

The processing is based on datum-free NEQs. The NEQs of seven consecutive days are combined into one NEQ system before the datum constraints are applied and the parameters, in particular ERPs and station coordinates, are estimated. The combination procedure is repeated on a daily basis. This gives a time series with daily resolution for the ERPs. Each daily ERP solution is represented by a continuous 7-day polygon with piece-wise linear offsets estimated every 24 hours.

Different combination approaches were investigated using VLBI and GNSS data provided via SINEX (Solution INdependent EXchange) files from the BKG IVS Analysis Center and the CODE IGS Analysis Center.

Overall, a significant improvement in accuracy was achieved compared to the individual

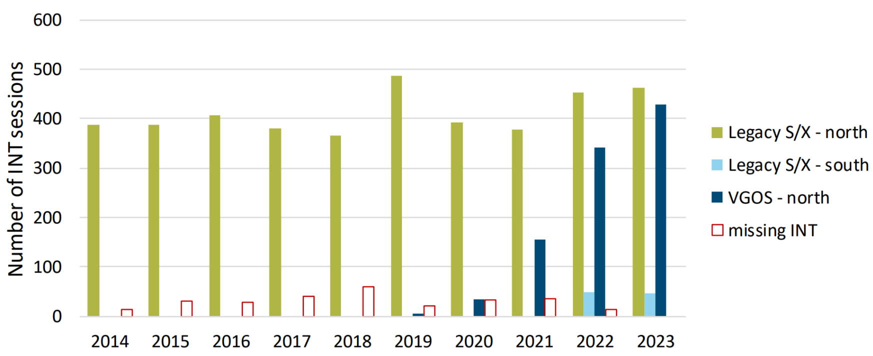


Figure 7: Number of different types of Intensives sessions per year: the legacy S/X sessions with networks in the Northern (green) and Southern (light blue) Hemispheres, and the new VGOS sessions. Additionally, the number of days with missing Intensives SINEX file in the IVS data center is shown in red.

technique-specific solutions, especially for the highly variable component dUT1. A detailed description of the different combination methods, including the chosen parameterization, the parameter a priori values, the datum conditions, as well as a detailed discussion of the resulting ERP series can be found in Lengert et al. (2021, 2022) and Klemm et al. (2024a,c).

Daily and rapid availability of input data is essential to achieve the above characteristics of the ERP product. In particular, the daily VLBI INT sessions play an important role for accurate and rapid dUT1 estimation. However, there are gaps in the series of daily SINEX files of the legacy VLBI INT campaigns in the past. Most of the gaps are caused by missing observations due to technical outages of an antenna or problems in the correlation process. For example, in 2018 there are no SINEX files available for a total of 60 days (see Figure 7).

Data gaps in the INT series are problematic for the continuity and reliability of the combined ERP. With the development of the VLBI Global Observing System (VGOS), the next generation of VLBI, numerous new VLBI INT sessions have been added to the VLBI observing schedule since 2020, and the missing data situation has improved significantly in recent years. The integration of VGOS data in the combination process leads to a constant slight decrease in the WRMS of the dUT1 residuals compared to external ERP series. For example, for the most recent day of the combination (i.e., the seventh day of the 7-day polygon), the WRMS of the dUT1 estimates with respect to the IERS Bulletin A series decreases by 0.5 µs from $16.7\,\mu s$ to $16.2\,\mu s$ when comparing a solution based on all INT sessions to a solution based on legacy INT sessions only. The increasing number of available INT sessions with independent networks, up to four per day, also increases the continuity and reliability of the combined ERP solution. More detailed information can be found in Klemm et al. (2024a).

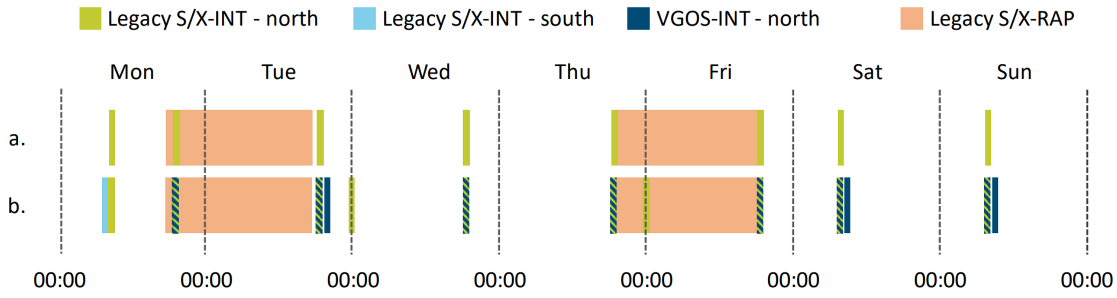


Figure 8: Weekly session distribution of the different VLBI sessions in 2014 (a.) and 2022 (b.): legacy S/X INT of the Northern (green) and Southern (light blue) Hemispheres, Rapid (R1/4) (light orange), and the new VGOS INT (dark blue).

References

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

Dach, R., S. Schaer, S. Lutz, D. Arnold, H. Bock, E. Orliac, L. Prange, A. Villiger, L. Mervart, A. Jäggi, G. Beutler, E. Brockmann, D. Ineichen, A. Wiget, D. Thaller, H. Habrich, W. Söhne, J. Ihde, P. Steigenberger, and U. Hugentobler. CODE Analysis center: IGS Technical Report 2014. In Y. Jean and R. Dach, editors, *International GNSS Service: Technical Report 2014*, pages 21–34. IGS Central Bureau, May 2015. doi: 10.7892/boris.80306.

Dach, R., S. Schaer, D. Arnold, M. Kalarus, L. Prange, P. Stebler, A. Villiger, A. Jäggi, E. Brockmann, D. Ineichen, S. Lutz, D. Willi, M. Nicodet, D. Thaller, L. Klemm, A. Rüilke, W. Söhne, J. Bouman, and U. Hugentobler. CODE Analysis center: IGS Technical Report 2022. In A. Villiger and R. Dach, editors, *International GNSS Service: Technical Report 2022*, pages 45–64. IGS Central Bureau, May 2023. doi: 110.48350/179297.

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

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

Klemm L., D. Thaller, C. Flohrer, A. Walenta, D. Ullrich, H. Hellmers. Intra-Technique Combination of VLBI Intensives and Rapid Data to Improve the Temporal Regularity and Continuity of the UT1-UTC Series. To appear in: Proceedings of the IAG International Symposia. Springer, Berlin, Heidelberg, 2024a. https://doi.org/10.1007/1345_2023_235

Klemm L., D. Thaller, C. Flohrer, A. Walenta, D. Ullrich, H. Hellmers. Consistently Combined Earth Orientation Parameters at BKG – Extended by new VLBI Intensives Data. To appear in: Proceedings of the 28th General Assembly of the International Union of Geodesy and Geophysics (IUGG2023) in Berlin, Germany, 2024b.

Klemm L., D. Thaller, C. Flohrer, H. Hellmers, A. Kehm, M. Bloßfeld, R. Dach. Single- and Multi-day Combination of VLBI and GNSS Data for Consistent Estimation of Low-Latency Earth Rotation Parameters. *Journal of Geodesy*, to be summitted, 2024c.

Meyer, U. M. Lasser, C. Dahle, C. Förste, S. Behzadpour, I. Koch, and A. Jäggi. Combined monthly GRACE-FO gravity fields for a Global Gravity-based Groundwater Product. *Geophysical Journal International*, 236(1):456–469, 2024.

Peter, H., U. Meyer, M. Lasser, and A. Jäggi. COST-G gravity field models for precise orbit determination of Low Earth Orbiting Satellites. *Advances in Space Research*, 69 (12):4155–4168, 2022.

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

ESA/ESOC IGS Analysis Centre Technical Report 2023

E. Schönemann[1], F. Gini[1], W. Enderle[1],
F. Dilßner[2], V. Mayer[3], M. van Kints[4], I. Romero[5], T. Springer[2], B. Traiser[3],
the ESA/ESOC IGS team

[1] European Space Operations Centre, Darmstadt, Germany
[2] PosiTim, Seeheim-Jugenheim, Germany
[3] LSE Space GmbH, Darmstadt, Germany
[4] VisionSpace Technologies, Darmstadt, Germany
[5] Canary Space Consulting, Bristol, UK

1 Introduction

The IGS Analysis Centre of the European Space Agency (ESA) is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The ESA/ESOC Analysis Centre has been involved in the IGS since its inception in 1992. In this report we give a summary of the IGS related activities at ESOC in 2023.

2 ESA IGS Contributions

2.1 Routine Products

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

- Final GNSS products
  - Constellations included: GPS, Galileo, GLONASS
    - Soon (in 2024) to also include: BeiDou, QZSS
  - Provided weekly, normally on Friday after the end of the observation week

  - Based on 24hour solutions using 150 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of the GNSS measurements, using a total of around 80 GNSS satellites
  - Consisting of Orbits, Clocks (30s), daily SINEX with station coordinates and EOPs, and Global Ionosphere Maps
- Rapid GNSS products
  - Constellations included: GPS, GLONASS
  - Provided daily for the previous day
  - Available within 3 hours after the end of the observation day
  - Based on 24hour solutions using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of the GNSS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, EOPs, and 1- and 2-hourly Global Ionosphere Maps
- Ultra-Rapid GNSS products
  - Constellations included: GPS, GLONASS
  - Provided 4 times per day covering a 48 hour interval; 24 hours of estimated plus 24 hours of predicted products
  - Available within 3 hours after the end of the observation interval ending at 0, 6, 12, and 18 hours UTC
  - Based on 24 hours of observations using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of the measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, and EOPs
- Global Ionsphere Maps
  - Constellations included: GPS, GLONASS, Galileo, BeiDou, QZSS (finals only)
  - Provided as final and rapid products
  - Final products are 2 hourly maps available 4 days after the end of the observation day
  - Rapid products are 1 and 2 hourly maps available 10 hours after the end of the observation day

- Real-Time GNSS services
  - Generation of two independent real-time solution streams
  - Analysis Centre Coordination
  - Generation and dissemination of the IGS Real Time Combined product stream
  - Discontinued in first quater 2024
- GNSS Sensor Stations
  - A set of 11 globally distributed GNSS sensor stations, which are a part of ESOC's global GNSS Sensor Station network, called EGON
  - Station data available in real-time with 1 second data sampling

A general overview of all the different ESA GNSS products may be found at:
http://navigation-office.esa.int/GNSS_based_products.html

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

2.2 Multi-GNSS Products

In 2017 ESOC has started to routinely publish its experimental multi-GNSS products on a best effort basis using the normal IGS products and naming convention. Meanwhile, the products have matured to a standalone product in the ESOC portfolio. Starting 2024, the multi-GNSS products are generated by ESOC's new CHAMP system and published as ESA0MGNFIN. The key difference between the ESOC IGC AC solution and this solution is the station selection. The daily processing includes a network of 200 stations and over 120 satellites: Galileo, GPS, GLONASS, BDS-3 and QZSS. The homogenous time series starts in 2017 and is continuously advanced. The products we provide on our web-site are:

- Daily SP3 orbits (5 min sampling to accommodate for eccentric orbits).
- Daily ERP file in normal IGS format
- Daily Clock-RINEX files with 30 second sampling of the clocks
- Daily SINEX file
- Daily summary file
- Troposphere SINEX

The ESA/ESOC multi-GNSS products (ESA0MGNFIN) are publicly available from our web-site under:
http://navigation-office.esa.int/products/gnss-products/

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

2.3 Product Changes

As we did not report to the IGS since 2019 there were many changes since our last report. Below a brief summary of the main processing changes:

- Several updates of the NAPEOS software from 4.4 to version 4.9
- In 2024 we will switch to our new software, called "EPNS"
  - ESA Precise Navigation System
- Contineous improvements in and tuning of our GNSS box-wing and attitude models
  - Our understanding of the Galileo satellites keeps improving
  - BeiDou satellites seem to have significant differences between the two manufacturers but also significant differences from launch to launch
  - GPS Block IIIA completely new models for radiation pressure and attitude, (Dilßner, 2024)
  - Initial models for NavIC
- Switch to the ITRF2020
- Switched to using our own ANTEX for the satellites as we continue to use the Galileo calibrations

2.4 Reprocessing Activities

ESA/ESOC has participated in all the IGS reprocessing efforts (repro1, repro2, and repro3) for the IGS contribution to the realisation of the International Terrestrial Reference Frame 2008, 2014 and 2020 (ITRF2008, ITRF2014 and ITRF2020). In fact reprocessing has almost become a routine activity at ESA as this is necessary to make sure that the results from the different satellites in all the different GNSS are aligned with each other. Of particular importance here are:

- The radiation pressure modelling of the satellites
- The attitude modelling of the satellites
- The phase center offset and variations of the satellites

And it should be noted that even between satellites of the same type and generation significant differences may exist as many GNSS satellites carry undisclosed payloads that may have a significant effect on the radiation pressure and the center of mass of the satellite.

2.5 Product Highlights

The ESA/ESOC Analysis Centre products are among the best and most complete products available from the individual IGS analysis centres. We provide a consistent set of GNSS orbit *and* clock products that can be used for mulit-GNSS precise point positioning. In particular for this purpose, the sampling rate of our final clock products is 30 seconds. A special feature of the ESA products is that they are based on completely independent 24 hour solutions. Although this does not necessarily lead to the best products, as in the real world the orbits and EOPs are continuous, it does provide a very interesting set of products for scientific investigations as there is no aliasing and no smoothing between subsequent solutions. Another unique feature is that our rapid products are one of the most timely available products. Normally our rapid GNSS products are available within 2 hours after the end of the observation day whereas the official GPS-only IGS products become available only 17 hours after the end of the observation day, a very significant difference. Another important feature of the ESA products is that we use a box-wing model for the GNSS satellites to a priori model the Solar- and Earth Albedo and IR radiation pressure. The GNSS block type specific models are regularely tested and improved where needed. In particular new satellites have to be reviewed carefully as many GNSS satellites carry unspecified "extras" which in many occasions significantly affect the radiation pressure on the satellite.

2.6 IGMA Activities

ESA/ESOC contributes to the IGS IGMA Pilot Project by chairing the project since 2019. Currently ESA/ESOC is setting up an internal monitoring system for all GNSS constellations and coordinating the IGS Monitoring Analysis Centers (MACs). Dedicated processing systems are being implemented at ESA/ESOC and at the other IGS MACs to convert the navigation messages of all GNSS constellations compare them to precise products and document how well each GNSS is performing with respect to its own ICD.

2.7 Other ESA IGS Contributions

- Dr Werner Enderle is a voting member of the IGS Governing Board since 2015
- Dr Francesco Gini is the Chairman of the RINEX committee, which he took over from Dr Ignacio (Nacho) Romero, to ensure format standardization to meet the needs of the IGS and of the the GNSS industry.

- Dr Erik Schönemann is the Chairman of IGMA pilot project which he took over from Dr Tim Springer.
- Dr Loukis Agrotis was the Real-Time Analysis Centre Coordinator and a voting member of the IGS GB but retired in 2023.
- Dr Florian Dilßner is involved in the committee for the estimation and validation of the GNSS PCO and PCVs. Also contributes significantly to the estimation and validation of the GNSS attitude modes, in particular during the eclipse phases.

3 GNSS Sensor Station Network Upgrade

ESA/ESOC continues to provide worldwide data for all GNSS constellations to the IGS via 10 of its 11 public stations, and to expand its total station network EGON (ESA's GNSS Observation Network), currently operating 25 stations, Figure 1. This expansion is accomplished by focusing on the establishment of collaborations with third parties to install new stations at geographically varied locations around the world such as in South Africa, Mexico, Argentina, Brazil, Malaysia, Kyrgyzstan, New Zealand, etc. The two most recent additions to the network are in Raufarhöfn, Iceland (2020) and Cartago, Costa Rica. No data is publicly available for the time being for any of the newly installed stations.

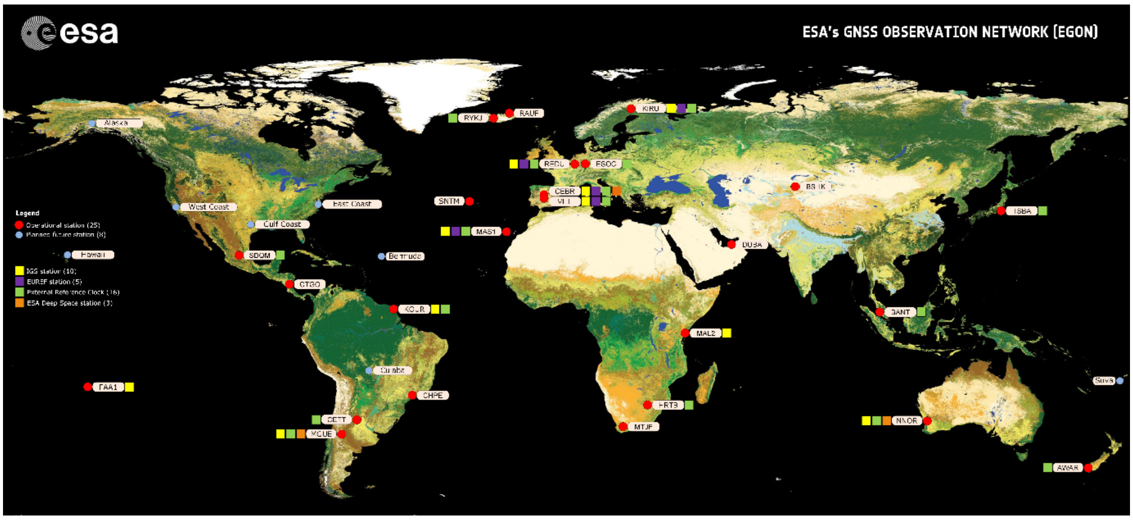


Figure 1: ESA/ESOC GNSS Station Network

Since 2023, the ESA GNSS network operates exclusively Septentrio PolarRx5(TR) receivers, and Septentrio PolaNt Choke Ring B3E6 antennas, with the exception of MGUE, MAL2, MAS1 and FAA1 where Leica AR25.R4 antennas are installed. The Septentrio PolaRx5 receivers were chosen as the next step in the station evolution as they can track the new signals at B3/E6 from QZSS, BeiDou and Galileo plus all the GNSS legacy signals.

The ESOC GNSS Reference Station network operates Septentrio PolaRx5TR timing receivers at all 3 ESA Deep Space sites and 4 other ESA tracking locations which together make up the core ESA network. In addition, a PolaRx5TR timing receiver is operated at ESA/ESOC, for which data is now also publicly available.

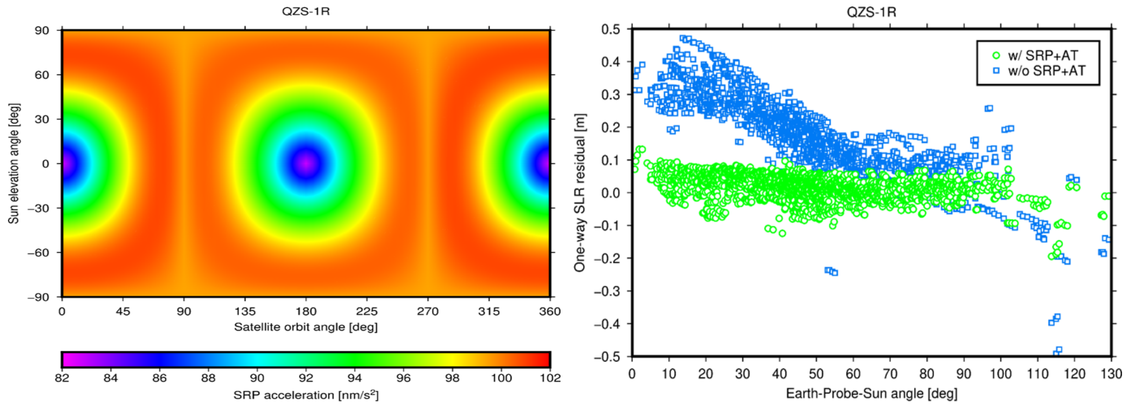
ESA/ESOC continues to provide a full complement of RINEX 3, and soon RINEX 4, data covering all signals and all satellites in view in daily, hourly and high-rate modes, plus real-time data streams, to the IGS from 10 of its public stations; VILL, CEBR, FAA1, KIRU, KOUR, MAS1, MAL2, NNOR, REDU and MGUE.

In the near future we will upgrade our Asian receivers to track the new L1 NAViC frequency, to be able to support dual frequency NAViC POD activities. Additionally, in the next few years worldwide coverage is planned to be further enhanced, with on-going negotiations with third parties in the US, Fiji, Brazil and Bermuda.

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

4 ESA-JAXA Collaboration

In early 2015, a collaboration was initiated between the European Space Agency's (ESA) Navigation Support Office and the Japan Aerospace Exploration Agency (JAXA), (Gini, 2024). At its core, the ESA-JAXA collaboration is designed to cross validate Japan's Quasi-Zenith Satellite System (QZSS) Precise Orbit Determination (POD) results and share expertise to improve the POD accuracy of QZSS. The cross-validation of the QZSS POD performance was implemented by jointly analyzing QZSS observations and validating the POD results of the QZSS satellites. As a result of this joint activity, ESA and JAXA have significantly improved the robustness and accuracy of their respective POD products. An important milestone in this collaboration was ESA's role in supporting the In-Orbit Testing (IOT) activities for QZS-1R towards the end of 2021. The successful execution of these tests demonstrated the practical results of the ESA-JAXA partnership and further solidified the commitment of both agencies to enhance their capabilities for QZSS POD and associated products. Notable achievements include the revision of metadata for the QZSS constellation, such as the optical properties of the QZS-1 solar arrays, which have been refined and improved through shared expertise, while simultaneously releasing the satellite mass and attitude mode history in a machine-readable file format for easy access and adoption by the users. One comparison involved the Solar Radiation Pressure (SRP) model results produced by both organizations. Figure 2 shows the accelerations in satellite-Sun frame computed by ESA's SRP model. The comparison of the computed SRP accelerations in different reference frames, spacecraft-fixed and inertial, showed excellent agreement with differences of less than 0.1 nm/s^2 Analysis of Satellite Laser Ranging (SLR) data from seven stations of the International Laser Ranging Service (ILRS), (Dilßner, 2019) suggests a radial RMS accuracy of the generated orbital trajectories of about 4 centimeters. Without applying the analytical models for SRP and other non-gravitational perturbation forces, such as antenna thrust (AT), the RMS accuracy decreases by a factor of five (Figure 2).



(a) Solar Radiation Pressure in satellite-Sun frame (b) Satellite Laser Ranging range residuals

Figure 2: ESA's QZS-1R Solar Radiation Pressure (SRP) model output in satellite-Sun frame (left). One-way Satellite Laser Ranging (SLR) range residuals calculated with respect to QZS-1R orbits generated with (green) and without (blue) a-priori radiation force models and displayed as function of the Earth-Probe-Sun angle (right).

5 Outlook

5.1 CHAMP

The Navigation Support Office at the European Space Agency (ESA) has developed a novel GNSS processing concept called CHAMP which stands for Consolidated High Accuracy Multi-GNSS Processing. Based on constellation-wise data processing and normal equation stacking, the method is used to efficiently generate GNSS products for all five global navigation systems (GPS, Galileo, GLONASS, BeiDou, QZSS). CHAMP's modular design, conseptionally shown in Figure 3, allows the different projects within the Navigation Support Office to combine the necessary constellation results, leading to substantial savings in CPU power and storage requirements Datum consistency is ensured by aligning satellite orbits and station coordinates to IGN's latest cumulative IGS2020 realization of the ITRF2020. ESA's data processing for the IGS is among the activities benefiting from CHAMP. As the transition to the new setup approaches in the coming months, ESA, as a long-standing IGS Analysis Center (AC), will routinely deliver Final products encompassing, for the very first time, all GNSS. The ESA AC Ionosphere final and rapid products have already transitioned to CHAMP.

Tree	Levels	Description	Example
	Leaves	Product generation and advanced processes (orchids).	IONO, DCBIAS
	Branches	NEQ-Stacking of individual constellation solutions, No-net rotation, BAHN (Code+Phase, 30s-clock solution).	MGNSS
	Trunk	Core processing: Broadcast Fit, GnssObs (Code-only solution), BAHN (Code+Phase, float solution), AmbFix (Ambiguity fixing), BAHN (Code+Phase, fixed solution).	DAILY
	Roots	Input data from ESOC NAVOPS Navigation Data archive.	dcd, brdc, ATX, EOP

Figure 3: ESA/ESOC CHAMP Concept

5.2 Observation Specific Signal Bias SINEX product

ESOC is working on a new Bias SINEX product. The aim is to provide long-term OSB estimates for all signals from all constellations in a stable "bias reference frame (BREF)". The product will be published on the webpage of the ESA Navigation Support Office in the second half of 2024. The ultimate goal is to enable interoperability between all signal combination.

6 Summary

The Navigation Support Office at the European Space Operations Centre (ESOC) of the European Space Agency (ESA) is improving continuously its capabilities and associated services and products (Enderle, 2022). As a consequence, the Analysis Center continues to produce *best in class* products for the IGS. All products are generated using the Navigation Package for Earth Orbiting Satellites (NAPEOS) software, (Springer, 2009). When we switch to our CHAMP based processing we will also switch to the new ESA Precised Navigation Software (EPNS). EPNS is the new Navigation software which combines the legacy NAPEOS capabilities with our newly developed RAW method. NAPEOS as well as EPNS are state of the art software packages that are highly accurate, very efficient, robust and reliable. They enables ESA/ESOC to deliver the high quality products as required for the IGS but also for the other space geodetic techniques DORIS, SLR and VLBI. This is important because besides being an IGS Analysis Centre, ESA/ESOC is also an Analysis Centre of the IDS and the ILRS and soon also the IVS.

In the coming year our main focus will be on further improving the orbit modelling for the different GNSS constellations. We need to improve our (a priori) box-wing models for the GPS IIF, III, BeiDou and GLONASS-K satellites. We will continue to improve and enhance our ESA tracking network.

References

Francesco Gini, Erik Schönemann, Florian Dilßner, Tim Springer, Werner Enderle, Satoshi Kogure, Research Report: Advancing precision in navigation May 20, 2024,

Florian Dilßner, Tim Springer, Francesco Gini, Erik Schönemann, Werner Enderle, New type on the block: Generating high-precision orbits for GPS III satellites May 15, 2023,

Enderle W., F. Gini, E.Schoenemann, R. Zandbergen and F. Zimmermann, The ESA Navigation Facility at the European Space Operations Cente - Independent Services and Reference Products for Precise Navigation and Timing, Presentation at the POSNAV 2022 - Positioning and Navigation for Intelligent Transport Systems, Organised by the German Institute of Navigation DGON, November 3 - 4, 2022, Berlin, Available at: http://navigation-office.esa.int/Publications.html

Dr. Tim Springer, Dr. Rene Zandbergen, Alberto Águeda Maté, NAPEOS Mathematical Models and Algorithms, *DOPS-SYS-TN-0100-OPS-GN*, Issue 1.0, Nov 2009, Available at: http://navigation-office.esa.int/Publications.html

Florian Dilßner, Erik Schönemann, Voker Mayer, Tim Springer, Francisco Gonzalez, Werner Enderle, M. Steindorfer, *Benefits of SLR Tracking for Galileo Orbit and Attitude Determination.* ILRS workshop 2019, Stuttgart, Germany.

GFZ Analysis Center
Technical Report 2023

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

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

1 Summary

During 2023, the standard IGS product generation was continued with minor changes in the processing software EPOS.P8. The GNSS observation modeling follows the repro3 (3rd IGS Reprocessing campaign) settings. Operational products cover GPS, GLONASS, and Galileo. The multi-GNSS processing was continued routinely during 2023 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.

3 Operational Data Processing and Latest Changes

Our EPOS.P8 processing software is following the IERS Conventions 2010 (Petit and Luzum, 2010) and the repro3 standards, changes in the processing lines are reported in Table 2. Operational processing lines cover approximately 140, 120, and 70 sites for IGS final, rapid and ultra-rapid chains, respectively. 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

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	Clocks for stations (5min) and satellites (30sec)
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	Troposphere estimates (1h ZPD, 24h gradients)
GFZ0OPSFIN_YD_01D_02H_ION.IOX	Ionosphere product, IONEX format
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	Clocks for stations (5min) and satellites (30sec)
GFZ0OPSRAP_YD_01D_01D_ERP.ERP	Daily Earth rotation parameters
GFZ0OPSRAP_YD_01D_01D_DSC.SUM	Summary file
GFZ0OPSRAP_YD_01D_02H_ION.IOX	Ionosphere product, IONEX format
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	Clocks for stations (5min) and satellites (30sec)
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_DCB.BSX	Bias file: differential code and inter-system biases
GBM0MGXRAP_YD_01D_01D_ATT.OBX	Attitude quaternions

Table 2: Recent processing changes

Date	IGS	IGR	IGU	Change
2023-08-05	-	w2274.1	w2274.0:12	switch to igs20_2272.atx
2023-08-09	w2273	w2274.5	w2274.5:00	switch to igs20_2274.atx
2023-09-18	w2279	w2280.3	w2280.2:12	switch to igs20_2280.atx
2023-10-30	w2286	w2287.3	w2287.2:18	switch to igs20_2287.atx
2023-12-01	w2289	w2290.5	w2290.4:12	switch to igs20_2290.atx

- Männel, B., Brandt, A., Nischan, T., Brack, A., Sakic, P., Bradke, M. (2020): GFZ ultra-rapid product series for the International GNSS Service (IGS). GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2020.004

4 Multi-GNSS data processing

The rapid multi-GNSS product GFZMGX was continued in 2023. The GFZMGX solution cover five GNSS constellations, namely GPS, GLONASS, Galileo, BeiDou2/3, and QZSS. The number of processed stations and satellites are about 140 and 130, respectively.

All GFZ MGEX products are available at DC CDDIS, IGN and GFZ own ftp server: ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

5 Multi-GNSS Combination

In 2023, we continued our efforts in developing a multi-GNSS orbit and clock combination, leading to the Satellite Precise Orbit and Clock Combination (SPOCC) software. The main focus was on extending the functionality and facilitating its usability, in particular in preparation for a possible operational use.

SPOCC can handle all available constellations and is based on a well-defined unified least-squares framework, using variance component estimation (VCE) to determine the weights. A main objective is to support multi-GNSS precise point positioning (PPP) users. The combination workflow consists of quality checks such as outlier detection, alignments harmonizing the AC products, and a weighted averaging. For the orbit combination, the optional alignments consist of Helmert transformations. The clock alignments consist of radial corrections and a removal of the impact of different reference clocks and reference inter-system biases (ISB) in the AC solutions. The combination can be configured for different weighting schemes, ranging from AC specific to satellite type or even satellite specific weights, and the alignments can be based on different sets of satellite orbits.

SPOCC's combination strategies and results were discussed in the IGS Combination Task Force, which aims at providing the next ACC software.

More information is availabe at:

- Mansur, G., Sakic, P., Brack, A., Männel, B., Schuh, H. (2022) Combination of GNSS orbits using least-squares variance component estimation. Journal of Geodesy, 96(11):92. https://doi.org/10.1007/s00190-022-01685-y
- Mansur, G., Sakic, P., Brack, A., Männel, B., Schuh, H. (2024) Utilizing Least Squares Variance Component Estimation to Combine Multi-GNSS Clock Offsets. GPS Solutions, https://doi.org/10.1007/s10291-023-01604-4.

6 Operational ionosphere products

The rapid and final global ionosphere map (GIM) products were continued in 2023 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

7 Operational GFZ Stations

The global GNSS station network operated by GFZ performed quite well in 2023 without major issues. In JOG2 (Yogyakarta/Indonesia) we exchanged hardware from Javad (Receiver: `JAVAD TRE_G3TH DELTA`, Antenna: `JAV_RINGANT_G3T NONE`) to Septentrio (Receiver: `SEPT POLARX5`, Antenna: `SEPCHOKE_B3E6 NONE`) to allow for full constellation tracking.

GFZ contributed to the ERC grant "Tectovision" (https://cordis.europa.eu/project/id/101042674) providing the necessary hardware, technical support, and data management services. In total 80 GFZ developed receiver/data logger units of two different types

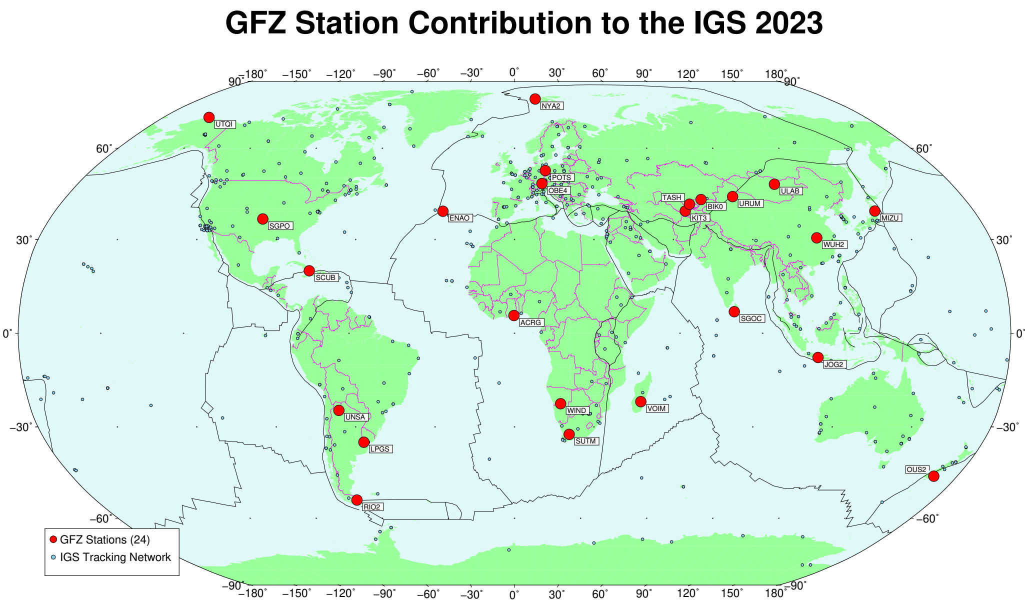


Figure 1: GNSS stations operated by GFZ (as of January 2024).

(MCGS, tinyBlack) will be installed in Greece to monitor surface deformations. Deployment of these receivers has started and by end of 2023 half of the 80 receivers are already providing data.

Additional information and quality indicators (e.g., data availability, latency, completeness) can be accessed through our GNSS portal `gnss.gfz-potsdam.de`. This portal also serves as the landing page for our RINEX toolbox **gfzrnx**.

References

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

CNES-CLS Analysis Center Technical Report 2023

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

[1] Centre National d'Etudes Spatiales,18 av. Edouard Belin 31400 Toulouse, France
[2] Collecte Localisation Satellite, 8-10 rue Hermès 31520 Ramonville St-Agne, France
[3] Geoscience Environnement Toulouse, 14 av. Edouard Belin 31400 Toulouse, France

E-Mail: igs-ac@groupcls.com

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 driven by the finalization of our participation to the REPRO3 campaign and the preparation of the post-ITRF2020 products (see IGSMAIL #8191) whose official delivery began on gps week 2238 (alongside with the others ACs). The main evolutions that happened in 2022 and 2023 are summarized in Table 1 .

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

The year 2023 was partly dedicated to the upgrade of the processing facilities (with the installation of our processing chains on a new cluster). Meanwhile, we enhanced the quality/operationality of our rapid/ultra products and at the end of 2023 we also started the delivery of our 4-constellations products (under MGX names) including Beidou satellites. The list of all the GRG products delivered today is summarized in Table 2 .

Table 1: Main GRG-AC events in 2022 and 2023

Date	GPS week	Change
2022/11/27	2238	Adoption of new standards corresponding to the post ITRF2020 switch
2022/11/27	2238	Start of delivery of Rapid and Ultra products
2023/01/07	2243	Rapid/Ultra EOP estimates & predictions improved
2023/09/24	2281	Switch to the new cluster facilities
2023/11/12	2288	Start of delivery of 4-constellation final products (including Beidou) under MGX names.
2023/11/28	2290	Inclusion of BDS-3 satellites on the Rapid and Ultra products

2 Progress in Rapid and Ultra-Rapid products

Since the end of the year 2022, we deliver rapid (GRR) and ultra-rapid (GRU) products for GPS and Galileo constellations. We made continuous efforts in 2023 to improve the quality of our products, the iterative process and the automatizations (for example, EOP estimates and predictions have been improved at the end of gps week 2243 by adding iterations to be less sensitive to erroneous a priori values). This progress is illustrated on Figure 1 for the WRMS of the GPS orbits that reaches $7-8$ mm with regard to IGS Rapid combination as of today. Note that since GPS week 2290 (DOY 330 2023) Beidou BDS-3 satellites are included in our Rapid and Ultra-Rapid products.

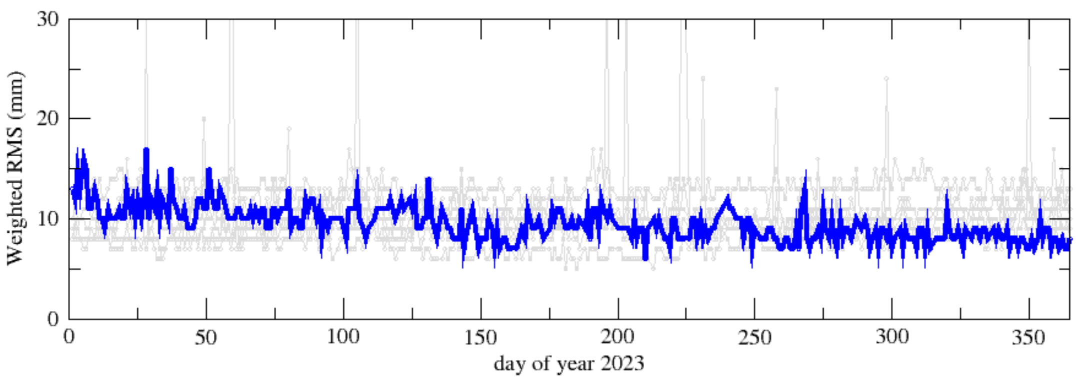


Figure 1: GPS GRG rapid orbits solutions (in blue, others AC in grey) compared to IGS rapid official combination over the full year 2023 (from IGS-ACC).

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
MGEX PRODUCTS: GPS, GLONASS, GALILEO & BEIDOU (since week 2288) Updated weekly		
GRG0MGXFIN_YYYYDDD0000_01D_30S_ATT.OBX	Satellites attitudes	30 seconds
GRG0MGXFIN_YYYYDDD0000_01D_01D_OSB.BIA	Observable specific biases	1 set/day
GRG0MGXFIN_YYYYDDD0000_01D_05M_ORB.SP3	Satellites ephemeris	5 minutes
GRG0MGXFIN_YYYYDDD0000_01D_30S_CLK.CLK	Satellites clocks	30 seconds
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

3 Inclusion of Beidou satellites in the Multi-GNSS processing (submitted to MGEX)

Satellites of the Beidou constellation were included in our products at the end of 2023. As of today, this 4-constellation parallel solution is delivered as MGX products (Multi-GNSS-Experiment). We obtain cm level orbit quality for BDS-3 satellites for which the ambiguities are fixed to integer values on phase measurements while BDS-2 satellite measurements are left unfixed (see Figure 2).

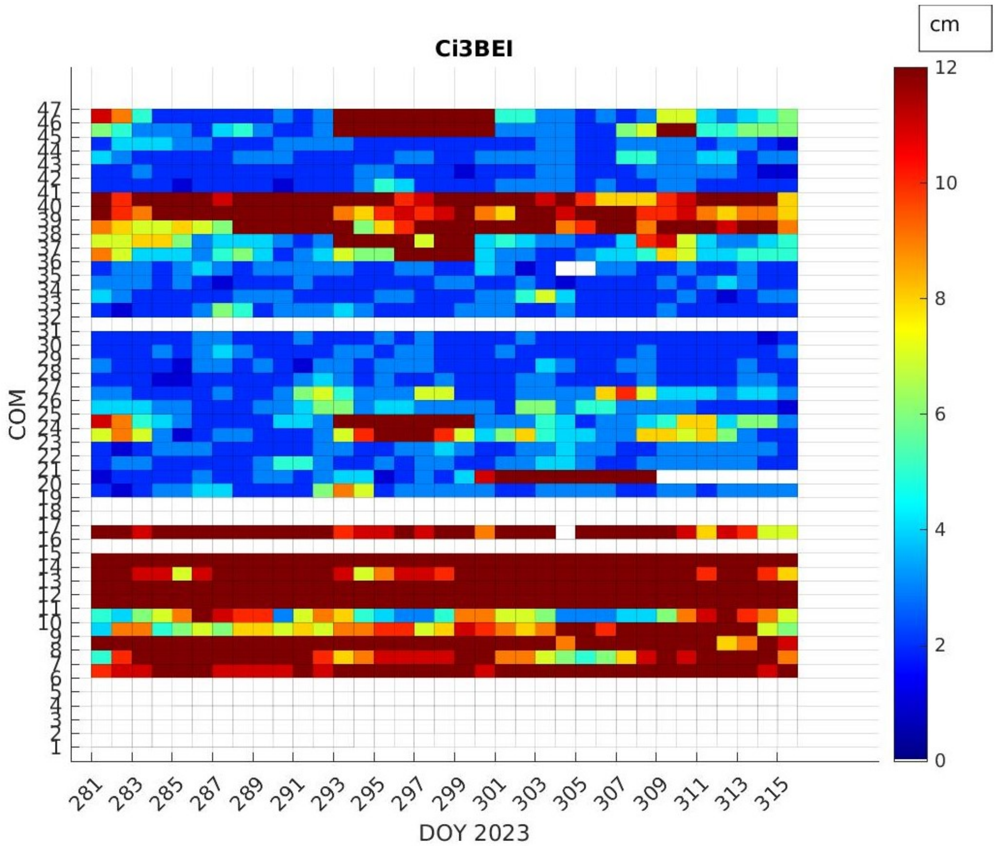


Figure 2: Internal overlaps of Beidou satellites (by PRN number) over a one-month period (BDS-2 and IGSO measurements unfixed)

The inclusion of the Beidou observations, even downweighed, still affect the station position solutions, up to few millimeters, as it is shown on Figure 3, with larger differences centered around Indonesia. One possible cause for this could be the incompatibility of phase-center-offsets of Beidou satellites (from igs20.atx ANTEX file) with the other constellations. Corrected PCO values will be available next year following an IGS-AC dedicated campaign that would aim at incorporating the "missing" constellations (BDS-3 and QZSS) into the IGS operational processing.

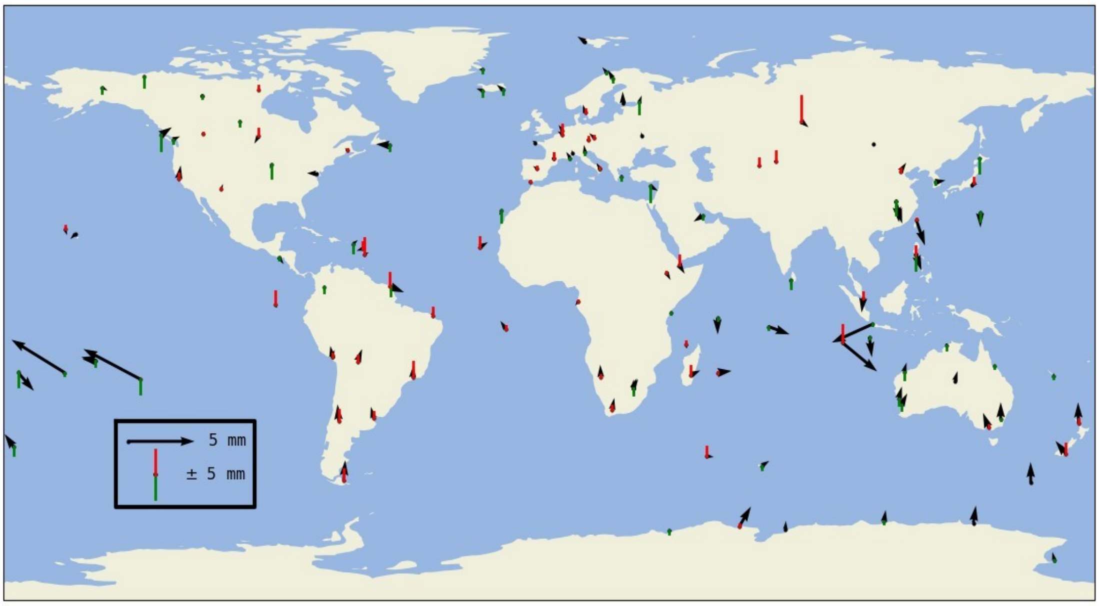


Figure 3: An example of daily differences between station position estimates "with" and "without" Beidou observations (Figure from P. Rebischung).

4 References

Saquet, E., S. Loyer, A. Mezerette, A. Couhert, F. Mercier, A. Santamaria Gomez. CNES/CLS IGS Analysis Center: BeiDou products. AGU2024, Session G44A.

Katsigianni G., S. Loyer, F. Perosanz, F. Mercier, R. Zajdel, K. Sosnica. Improving Galileo orbit determination using zero-difference ambiguity fixing in a Multi-GNSS processing. Advances in Space Research, Vol. 63(9), pp 2952–2963, 2019. doi: 10.1016/j.asr.2018.08.035

Loyer, S., H. Capdeville, A. Mezerette, G. Katsigianni, E. Saquet, A. Banos-Garcia. Exploitation de localisation géodésique. Rapport de juin 2023, CLS-GEO-NT-23-0330

Loyer, S., H. Capdeville, A. Mezerette, G. Katsigianni, E. Saquet, A. Banos-Garcia. Exploitation de localisation géodésique. Rapport de décembre 2023, CLS-GEO-NT-23-0659

Loyer S., F. Perosanz, F. Mercier, H. Capdeville, J. C. Marty. Zero-difference GPS ambiguity resolution at CNES–CLS IGS Analysis Center. Journal of Geodesy. Vol. 86, pp 991-–1003, 2012. doi: 10.1007/s00190-012-0559-2

Saquet, E., S. Loyer, A. Mezerette, A. Couhert, F. Mercier, A. Santamaria Gomez. CNES/CLS IGS Analysis Center: BeiDou products. AGU2023, Session G44A.

Geospatial Information Authority of Japan (GSI) and Japan Aerospace Exploration Agency (JAXA) Analysis Center Technical Report 2023

K. Akiyama[1], K. Ohno[2], N. Takamatsu[2], K. Kawate[1], Y. Igarashi[1], T. Sasaki[1], H. Takiguchi[1], M. Okeya[1], S. Kogure[1], C. Shodai[2], T. Wakasugi[2], B. Miyahara[2]

[1] Japan Aerospace Exploration Agency (JAXA), Tsukuba, Japan
[2] Geospatial Information Authority of Japan (GSI), Tsukuba, Japan

1 Introduction

The Geospatial Information Authority of Japan (GSI) and Japan Aerospace Exploration Agency (JAXA) is jointly working as a IGS analysis center to provide the GNSS orbit, clock, ERP, and SINEX products identified with the acronym "JGX". The JGX products are generated using our original software MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis) developed by JAXA (Kawate et al., 2023). JAXA is responsible for improving the software and the GSI uses the software to generate the JGX products and manages the quality of the products. Our contributions to IGS community are as follows.

Our contributions

1. Provide independent results from other ACs via our original analysis software MADOCA.
2. Provide precise multi-GNSS products, e.g., GPS, GLONASS, Galileo, BDS and QZSS.

3. Provide more detailed information regarding the POD for QZSS.
4. Provide a stable supply of products through years of experience in product generation.

2 Participation Process for new IGS ACs

Our operational products "JGX" launched on July 2023 (GPS Week 2269) and have been incorporated into IGS combination process since December 2023 after being approved as a new analysis center at the 65th IGS Governing Board Meeting. Since 2014, JAXA had been publishing their final, rapid and ultra-rapid products for GPS, GLONASS and QZSS generated using the MADOCA on the following website. The final products have been also provided for the IGS MGEX pilot project.

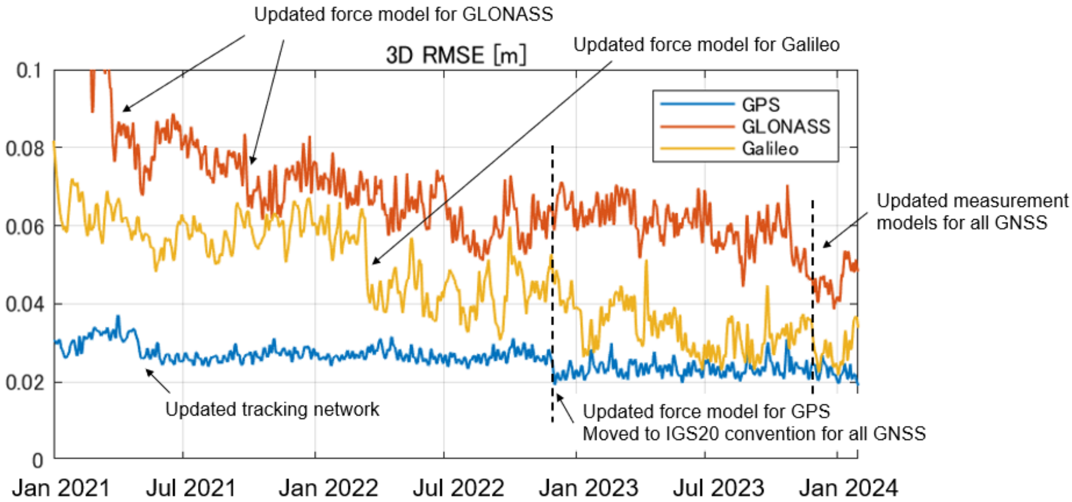
Project Web:
`https://mgmds01.tksc.jaxa.jp/`

Products:
`ftp://mgmds01.tksc.jaxa.jp/`

To further increase the contribution of these products to the IGS, we proposed to the IGS ACC and the reference frame coordinator in July 2021 to establish a new analysis center in Japan. To this point, the IGS ACC and the reference frame coordinator first evaluated the consistency of the products published on the MADOCA website with the IGS products. As a result of the evaluation, it became clear that the products at that time did not reach the same level of quality as other ACs and that the products did not satisfy requirements for an IGS analysis center. Therefore, we updated the following items and improved the model:

- Improved satellite dynamic models (i.e., SRP, Earth albedo and Antenna thrust etc.).
- Applied the minimum constrains (i.e., No-Net-Rotation) for reference frame alignment.
- Fixed SINEX format issues.

In December 2022, the quality evaluation of the products was conducted again by the IGS ACC and the reference frame coordinator. In this evaluation, we generated products under settings which are consistent with the `IGSR3/igsR3.atx` framework adopted by IGS Repro3 and checked the consistency with Repro3 products generated by other ACs. The results showed that the consistency of our orbit and clock products with those of other ACs had improved compared to the first evaluation, while scale bias in station positions was revealed. It was later found that this problem was due to the lack of a Shapiro time delay model in MADOCA software. Subsequently, the following operational changes were



*Reference products:
IGS rapid for GPS, IGS final for GLONASS, GFZ rapid (~2022) / CODE rapid (2023~) for Galileo

Figure 1: 3D RMS error of JAXA final orbit products generated using MADOCA. The software version was 1.0.1 as of January 2021 and 2.1.0 as of January 2024.

made prior to the release of JGX products in July 2023:

- Applied the `IGS20/igs20.atx` framework.
- Galileo incorporation, followed by GPS and GLONASS.

Then, in July 2023, JGX products will be launched, and these products were initially included in the IGS final orbit/clock and SINEX combinations for comparison only.

Here, the 3D RMS error of JAXA final orbit products compared with the IGS final orbits for the period from January 2021 to January 2024 is shown in Fig. 1. The consistency of GPS, GLONASS, and Galileo orbit has greatly improved over the past three years due to the updates of force and measurement models.

3 JGX Core Products

The list of JGX products provided by GSI and JAXA to IGS is summarized in Table 1. The ultra-rapid product is currently under preparation.

The JGX final and rapid products will also be available at the following URL with registration starting from the end of March 2024:
https://jgxnet.gsi.go.jp/en/top/

Table 1: List of JGX products provided by GSI and JAXA to IGS.

JGX Final (weekly updates) GPS, GLONASS and Galileo	
`JGX0OPSFIN_YD_01D_05M_ORB.SP3`	Daily GPS, GLONASS and Galileo orbits and clocks with 5 min intervals
`JGX0OPSFIN_YD_01D_30S_CLK.CLK`	Daily GNSS satellite and station clocks with 30 sec intervals
`JGX0OPSFIN_YD_01D_01D_SOL.SNX`	Daily station coordinates and ERPs in SINEX format
`JGX0OPSFIN_YD_01D_01D_ERP.ERP`	Daily Earth rotation parameters
`JGX0OPSFIN_YD_01D_07D_DSC.SUM`	Analysis summary for each processing
JGX Rapid (daily updates) GPS, GLONASS and Galileo	
`JGX0OPSRAP_YD_01D_05M_ORB.SP3`	Daily GPS, GLONASS and Galileo orbits and clocks with 5 min intervals
`JGX0OPSRAP_YD_01D_30S_CLK.CLK`	Daily GNSS satellite and station clocks with 30 sec intervals
`JGX0OPSRAP_YD_01D_01D_ERP.ERP`	Daily Earth rotation parameters
`JGX0OPSRAP_YD_01D_01D_DSC.SUM`	Analysis summary for each processing

4 Processing Software and Latest Changes

The JGX products are generated using our POD software named “MADOCA” which has been developed by JAXA since 2011. MADOCA supports Multi-GNSS (GPS, GLONASS, Galileo, BDS, and QZSS) and has adopted force and measurement models compliant with the International Earth Rotation and Reference Systems Service (IERS) conventions 2010 [2]. The estimations could be made in both post-processing with iterative weighted least squares and real-time processing with extended Kalman filter (EKF) using the methods to reduce memory usage and processing time and to improve process stabilization. JAXA continues to improve the performance mainly focusing on non-gravitational force models. The details of POD algorithm are shown in our paper Kawate et al. (2023).

Followings are the changes that have been made since JGX products became available. With these changes, the JGX products are now compliant with all models used in Repro3.

1. Application of second order ionospheric corrections (Kedar et al., 2003).
2. Application of Subdaily polar motion libration terms (Petit et al., 2010).
3. Application of Subdaily EOP model (IERS EOP, 2023).
4. Application of new secular pole model (IERS Chapter 7, 2023).

5 Operational Data Processing

Our operational products "JGX" launched on July 2023 (GPS week 2269) and have been incorporated into IGS combination process since December 2023. The JGX operational analysis for IGS final and rapid products uses the MADOCA software version 2.1.0. The network of stations processed in 2023 is shown in Figure 2. For the JGX final and rapid products, approximately 150 and 110 IGS sites are used, respectively. The IGS20/igs20.atx framework applied as a reference frame using minimum constraints with no-net-rotation. The fiducial sites are adjusted daily so that the geometric center of the fiducial site placement does not deviate from the origin of the reference coordinates, and approximately 50 fiducial sites are selected from the IGS20 core sites.

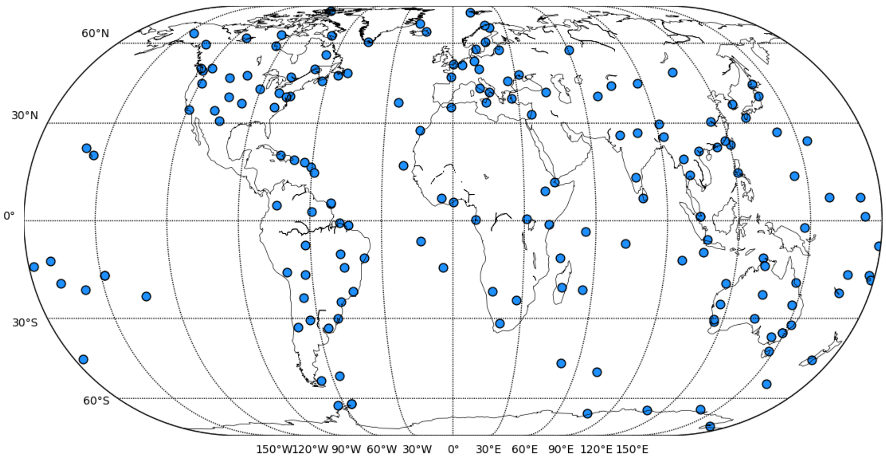


Figure 2: Station network used for JGX processing in 2023.

JGX final and rapid products for GPS, GLONASS, and Galileo have been routinely submitted to the IGS since GPS week 2269.The final products (SP3, CLK, SNX, ERP, SUM) have a latency of 5 days and are uploaded every Thursday of the week. The rapid products (SP3, CLK, ERP, SUM) have a latency of 1 day and are uploaded daily. When errors are detected in the internal quality assessment of the final product, they are manually adjusted before uploading. In addition, we have launched a website to publish our products.

Several issues identified in the preliminary evaluation prior to AC participation were resolved. All these updates are already implemented into the products generated after December 2023 that have been incorporated into the IGS combination process.

- Resolved issue regarding the satellite-specific GPS clock bias since GPS week 2323. We updated the DCB file policy and modified the handling of signal types in RINEX ver. 3.

- Measurement model was updated to be fully compliant with the Repro 3 since GPS week 2341. In particular, we have initiated second-order term corrections in the ionosphere, which has improved the consistency of station locations in the UD direction.

The 3D RMS evaluation of satellite orbit in 2023 is shown in Figure 3. No Helmert transformation is adopted in the plot. The quality is comparable among ACs. A pressing issue for JGX operational products is the stability of clock products. This is due to the clock reference station selection process. Stability has been improving since March 2024 due to the modification of the Quality Check process, which determines the effective epoch of the observation data. JGX will continue to address the issues of clock accuracy and stability.

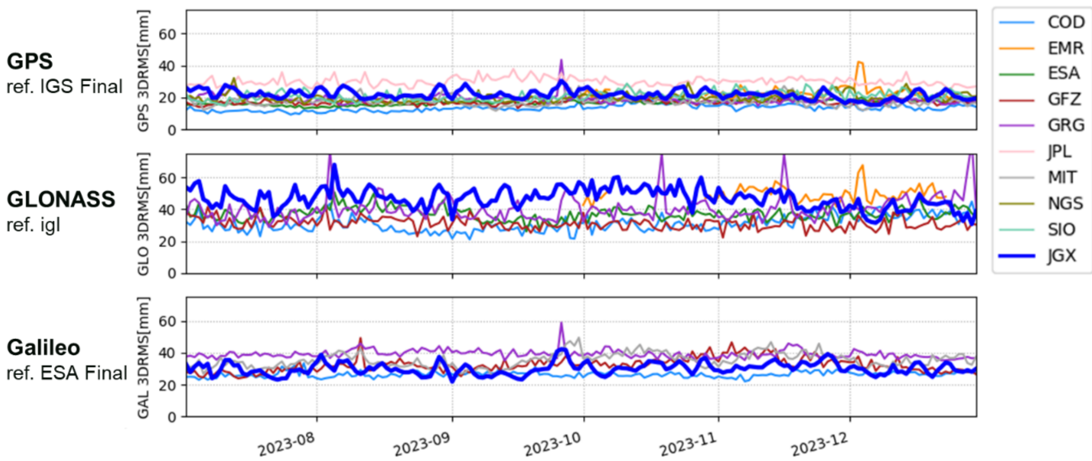


Figure 3: 3D RMS error w.r.t. IGS final (GPS, GLONASS) and ESA final (Galileo) from July to December 2023.

References

K. Kawate, Y. Igarashi, H. Yamada, K. Akiyama, M. Okeya, H. Takiguchi, M. Murata, T. Sasaki, S. Matsushita, S. Miyoshi, M. Miyoshi, and S. Kogure 2023 MADOCA: Japanese precise orbit and clock determination tool for GNSS. *Advances in Space Research*, 71(10), p.3927-3950. Surv Geophys, doi: https://doi.org/10.1016/j.asr.2023.01.060.

Petit and Luzum, 2010, IERS Conventions 2010.

Kedar, Sharon, et al. The effect of the second order GPS ionospheric correction on receiver positions. *Geophysical research letters* 30.16 (2003).

IERS EOP: IERS Working Group on Diurnal and Semi-diurnal EOP Variations https://ivscc.gsfc.nasa.gov/hfeop_wg/

IERS Chapter 7: IERS Conventions Centre, Chapter 7 (Updated): Displacement of reference points https://iers-conventions.obspm.fr/chapter7.php

Jet Propulsion Laboratory Analysis Center Technical Report 2023

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

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

1 Introduction

In 2023, 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 2023.

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

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

Product	Description	Rapid/Final
JPL0OPSFIN_YYYYJJJHHMM_01D_05M_ORB.SP3	GPS orbits and clocks	Rapid & Final
JPL0OPSFIN_YYYYJJJHHMM_01D_30S_CLK.CLK	GPS and station clocks	Rapid & Final
JPL0OPSFIN_YYYYJJJHHMM_01D_30S_TRO.TRO	Tropospheric estimates	Rapid & Final
JPL0OPSFIN_YYYYJJJHHMM_01W_01D_ERP.ERP	Earth rotation parameters	Rapid(01D), Final(01W)
JPL0OPSFIN_YYYYJJJHHMM_01D_30S_ATT.OBX	Satellite attitude quaternions	Rapid & Final
JPL0OPSFIN_YYYYJJJHHMM_01D_01D_SOL.SNX	Daily SINEX file	Final
JPL0OPSFIN_YYYYJJJHHMM_01W_00U_SUM.SUM	Weekly solution summary	Final

without applying any constraints between solutions. High-rate (30-second) Final GPS clock products are available from 2000-05-04 onwards.

The JPL IGS AC also generates Ultra-Rapid orbit and clock products for the GPS constellation. These products are generated with a latency of less than 2.5 hours and are updated hourly (Bertiger et al., 2020). Although not submitted to the IGS, our Ultra-Rapid products are available in native GipsyX formats at:

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

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).

The frame for Finals and Rapids was updated to IGb14 during week 2107 on 2020-05-24 and 2020-05-26 respectively. Our Rapid frame was updated to IGS20 during week 2238 (2022-11-28). Our Finals remain on IGb14 until we can complete a consistent reprocessing of IGS20 back to at least 2002 but we expect to transition these to IGS20 sometime in 2024.

Our IGS20 Rapid operations and our ongoing Final IGS20 reprocessing campaign adopted several new models, some from repro3 and some from our own choices:

1. Use of center of mass seasonals for reference site positions.
2. Data weighting based on optimization testing.
3. Troposphere randomwalk parameter optimized based on external (Young et al., 2022) and internal research.
4. VMF1 (Boehm etal., 2006) troposphere models and mapping functions instead of GPT2 for better station positioning (Martens and Simons , 2023).
5. Sub-daily EOP model (Desai and Sibois , 2016).
6. Time varying-gravity model.
7. Antenna thrust models per IGS recommendations.
8. Modern ocean tide loading, using GOT4.8 (Ray, 2013).
9. IGS20 antenna calibrations.

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

GipsyX has been the sole operational software at the JPL IGS Analysis center, replacing GIPSY-OASIS since January 2017.

GipsyX 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 simultaneous GNSS, SLR, and VLBI data processing at the measurement level.
5. DORIS data processing is also supported.
6. Multi-processor and multi-threaded capability.
7. Single rtgx executable replaces multiple GIPSY executables: model/oi, filter, smoother, ambiguity resolution.
8. Versatile PPP tool (gd2e) to replace GIPSY's gd2p.
9. Similar but not identical file formats to current GIPSY.
10. Runs under Linux and Mac OS.
11. First GipsyX beta-version released to the GIPSY user community in December 2016.
12. GipsyX-1.0 released 2019-01-28.
13. Most recent release was GipsyX-2.2 on 2023-09-05.
14. 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 2022-12-08.
- Started reprocessing campaign in IGS20 that will eventually go back to 1992 (Peidou et al. (2023)).
- 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.

  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.
- Switched from 5 minutes to 30s operational GPS+GALILEO rapid products in JPL-format on 2023-09-20:

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

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, replacing our current GPS-only processes. Furthermore, processing of SLR and geodetic data has been added to GipsyX and VLBI is under development and testing.

6 Acknowledgments

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

References

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

Boehm, J., B. Werl, and H. Schuh (2006), Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data, *J. Geophys. Res.*, 111, B02406, doi:10.1029/2005JB003629.

Desai, S. D., and A. E. Sibois (2016), Evaluating predicted diurnal and semidiurnal tidal variations in polar motion with GPS-based observations, *J. Geophys. Res. Solid Earth*, 121, 5237-5256, doi:10.1002/2016JB013125

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

Haines B, W. Bertiger, S Desai, M Heflin, D Kuang, M Miller, A Peidou, P. Ries, and X. Wu, A New Terrestrial Reference Frame: Combining SLR and GPS at the Observation Level Using Space Ties on the GRACE and Jason Missions, 2022 Fall AGU meeting, Chigago Il, December 12-16.

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

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

H R Martens, M Simons, A comparison of predicted and observed ocean tidal loading in Alaska, *Geophysical Journal International*, Volume 223, Issue 1, October 2020, Pages 454-470, https://doi.org/10.1093/gji/ggaa323

Peidou A, Komanduru A, Ries PA, Bertiger W, Heflin MB, Hemberger D, Moore A, Murphy DW, Sibthorpe A. JPL's IGS20 reprocessing campaign. AGU23. 2023 Dec 13.

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

Ries, P., ITRF2020 Seasonal Signals. 2022 UAW workshop, Thessaloniki, Greece, October 21-23, https://doi.org/10.5281/zenodo.7245437

Ries, P., W. Bertiger, M. Heflin, D. Hemberger, A. Komanduru. D. Murphy, and A Peidou, Exploring different ITRF2020 seasonals for a reprocessing campaign. 2022 Fall AGU meeting, Chigago Il, December 12-16.

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

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

Young, Z., Blewitt, G., and Kreemer, C. (2022) Application of Variable Random Walk Process Noise to Improve GPS Tropospheric Path Delay Estimation and Positioning at Local and Global Scales. *AGU Fall Meeting 2022*. G13A-01.

MIT Analysis Center Technical Report 2023

T. Herring

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

1 Introduction

In this report, we discuss results generated by the MIT analysis center (AC) both for submissions of weekly final IGS solutions and our weekly combination of SINEX files from MIT and the other eight IGS analysis centers that submit final SINEX files. We present here an analysis of the networks we process and a comparison between our position estimates and those from other IGS analysis centers. For repro3 and our IGS20 submissions, we use combined GPS and Galileo solutions; we also examine the differences between GPS-only and Galileo-only solutions.

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 2022 MIT Analysis Center report (see Herring, 2023).

In addition to weekly final processing, we also generate combined SINEX processing from the combination of up to 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 the IGS20 system. In Tables 1 and 2, we list the products submitted by MIT in our AC and AAC roles. Our operational processing continues to be a combined GPS+Galileo solution with 5-minute tabular points in the SP3 orbit files to accommodate the high eccentricity Galileo satellites.

Table 1: MIT products submitted for weekly finals analysis.

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

YYYY year, DDS DOY Start, DOE DOY End.

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

Long File Name	Description
MIT0OPSSNX_YYYYDDD0000_01D_01D_SUM.SUM	Summary file
MIT0OPSSNX_YYYYDDD0000_01D_01D_SOL.SNX	Combined SINEX file from all available analysis centers
MIT0OPSSNX_YYYYDDD0000_01D_01D_RES.SUM	File of the individual AC position estimates residuals to the combined solution for the week

YYYY year, DDD DOY for each day of week.

The network of stations processed by MIT in 2023 is shown in Figure 1. The figure shows the weighted root-mean-square (WRMS) scatter of the horizontal coordinates of nearly all of the stations included in the MIT finals processing. Stations that were used just a few times (6 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 removing linear trends from the time series. The median WRMS scatters of the 435 sites, measured more than five times, included in the statistics are 1.5, 1.5 mm in North and East and 5.5 mm in height. No annual signals were removed. The station selection in 2023 was based on the station selection list for the third reprocessing campaign (Repro3). This list was based on the priority order list for Repro3 (http://acc.igs.org/repro3/repro3_station_priority_list.pdf).

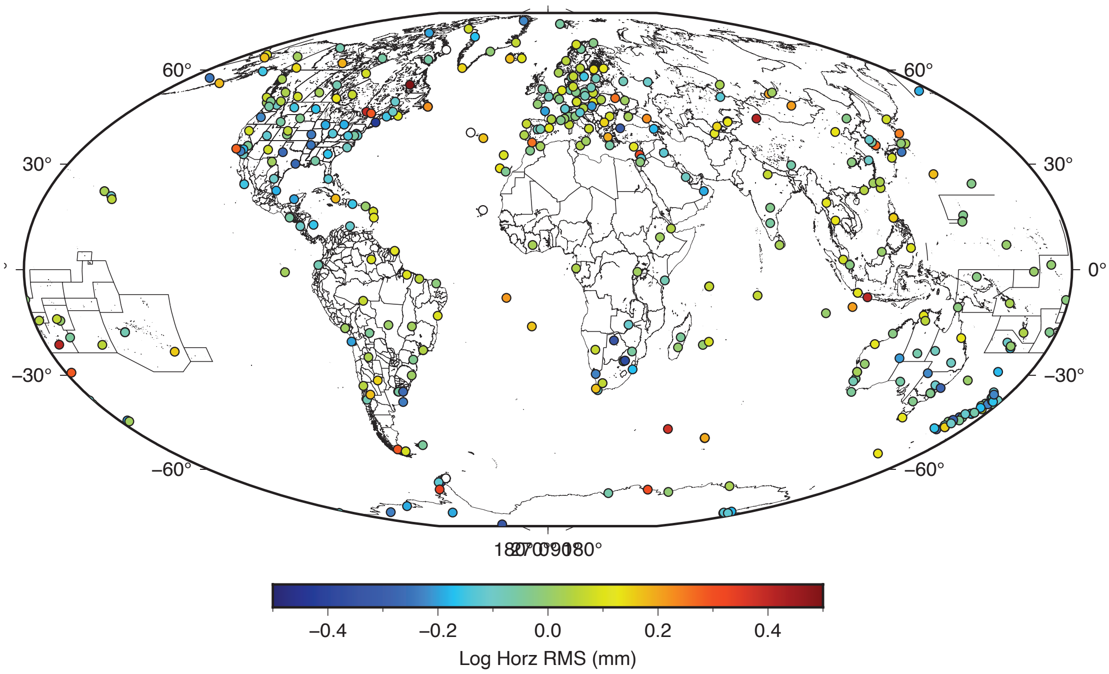


Figure 1: Log (base 10) of the RMS scatter of the horizontal position estimates from the network of 429 stations, six less than the total number, processed more than five times by MIT in 2022. Each daily network has 350 stations, and the networks evolve with time depending on data availability and geometry. Of the 435 stations, 256 have more 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 ALGO (5.17), SCH2 (5.32), FLRS (5.75), JCTW (5.79), RAUL (6.28), CPVG (6.59), KZN2 (7.47), TONG (9.35), QIKI (9.94) and OHI3 (10.88) mm. The sites with the largest height RMS scatters (mm) are OHI3 (9.96), REDU (9.98), NVSK (10.23), ULAB (10.73), POVE (10.76), JPLM (12.04), TONG (12.29), URUM (13.83), WES2 (14.55) and KZN2 (14.60) mm.

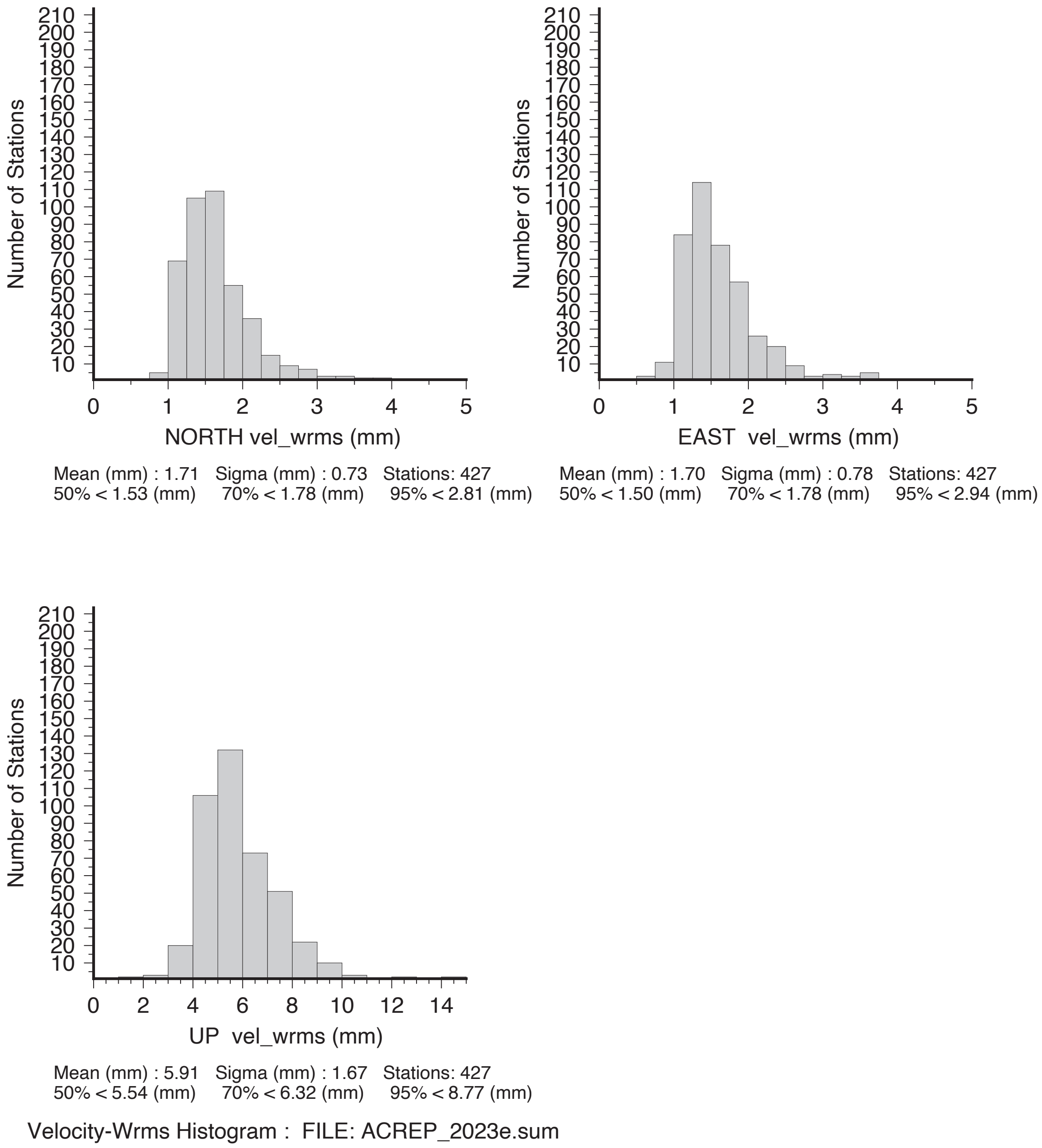


Figure 2: Histogram of the weighted root-mean-square (WRMS) scatter of daily position estimates of sites used more than five times for 2023 after removing linear trends and eliminating gross outliers (5 times WRMS scatter). The median scatters are similar to last year, with 1.5, 1.5 mm horizontal, and 5.5 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 MIT0OPSSNX combined solution is used for comparison with the official IGS combination performed at IGN and generally matches the IGN solution at the level of $0.1 - 0.2$ mm in north and east (NE) and $0.7 - 1.0$ mm in height (U). The two analyses use different methods to determine AC weighting and different selections of sites. In Figure 3, we show the WRMS scatter of the daily fits to ≈ 40 IGS20/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 the combination of the other ACs. There is good consistency between the ACs. Figure 4 shows the WRMS scatter between the AC and either IGS20 (until week 2137) or IGS20 (after 2138). 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 to IGS20 and 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 3.3 mm WRMS in height. We also compute the chi-squared per degree of the fits, and all ACs have similar chi-squared values, indicating that no one center dominates the combination.

Table 3: Comparison of the fits to the IGS20 reference frame (RF) and daily combined solutions for RF sites in the MIT and other AC daily final SINEX files. Typically, 50 sites are used in the comparison to IGS20.

Center		IGb14			Combined	
	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
MIT	2.74	2.90	7.52	0.98	0.90	3.29
COD	2.61	2.87	7.18	1.30	1.23	3.95
EMR	2.46	2.89	6.73	1.26	1.74	4.08
ESA	2.57	2.81	6.75	0.99	0.82	3.83
GFZ	2.38	2.71	8.05	0.90	1.09	4.11
GRG	2.31	2.41	6.34	1.03	0.87	3.07
JPL	2.67	3.04	8.80	1.51	1.78	5.71
NGS	2.68	3.43	7.69	1.37	1.66	4.33
SIO	2.94	3.15	8.30	1.58	1.78	4.68

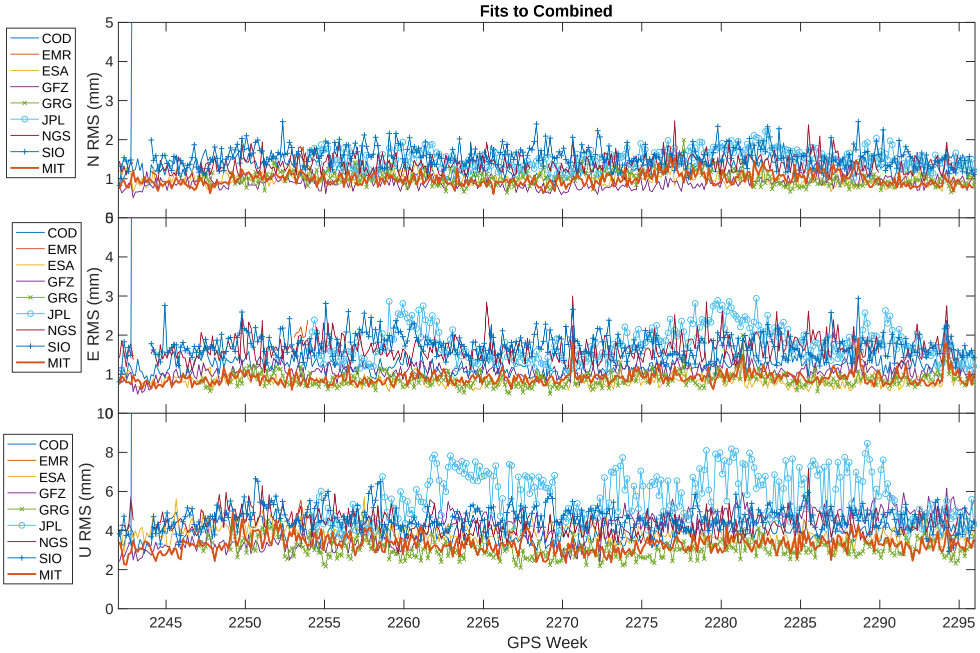


Figure 3: RMS scatters of the fits of the different IGS ACs to the MIT0OPSGLB combined solution for 2023. Not all centers had adopted the IGS20 system for the whole year.

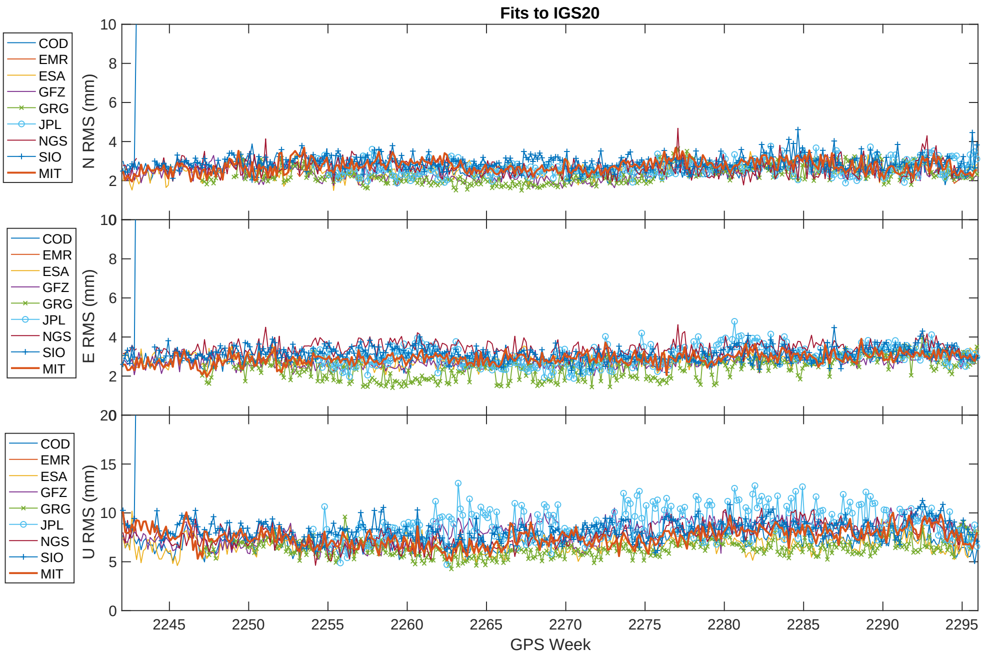


Figure 4: RMS scatters of the fits to the IGS20 system using typically 45−50 stations. Not all centers used the IGS20 system for the whole year. Note the scales here are twice those used in Figure 3.

4 Comparison between GPS-only, Galileo-only, and combined solutions

The MIT contribution to the final IGS20 orbit and reference frame products is a combination of the GPS and Galileo solutions. We also process each system separately so that we can compare the mean differences between the solutions and the RMS differences of the time series of each system and the combination after removing linear trends. The network of sites used for the Galileo processing is formed from the 350 sites used daily for the GPS network and includes all sites with Galileo data and that don't have AOAO DM antennas. Analyses for the repro3 processing showed large differences between GPS and Galileo analyses for sites using these types of antennas. Only L1 and L2 phase calibration are available, and the differences indicate that the L5 phase models likely deviate by large amounts from the L2 values. Generally, there are about 250 sites in the Galileo network.

Table 4 gives the median and worst WRMS scatters of the site common to all three solution types. This table shows that Galileo-alone solutions have higher WRMS scatter than GPS-only solutions but that the combined GPS+Galileo solution has the lowest WRMS scatter in all components for both median and worst values. When the differences between the GPS-only and Galileo-only solutions are analyzed, there are systematic mean differences at some sites. The ten largest positive and negative differences for each component are given in Table 5. The table has three blocks for Height, North, and East differences. Not all of the antennas analyzed have full Galileo calibrations, but the lack of L5 calibration does not seem to introduce systematic differences except for the AOAD/M_T and B antennas, where the height differences are all positive and range from 4.8 to 22 mm. Our operational products no longer use sites with these antenna types. (The 111 days of data used here were from the interval when the IGS20 was being evaluated before the official start of IGS20 at the start of GPS week 2238 (2022/11/27).

The differences between the L1/L2 and L1/L5 GPS and Galileo solution with fully calibrated antennas indicate that the phase center model to be used at individual sites is likely to depend critically on the in-situ environment in which the antenna is installed. The histogram of the differences for all sites, shown in Figure 5, shows very small mean

Table 4: Median and Worst WRMS scatters of the 249 sites common to the GPS, Galileo, and combined solutions. All units are mm.

	Median			Worse		
Solution	N WRMS	E WRMS	U WRMS	N WRMS	E WRMS	U WRMS
Galileo	2.04	2.01	6.81	8.64	7.23	41.57
GPS	1.65	1.64	5.89	9.32	8.57	17.81
Combined	1.55	1.44	5.65	8.81	7.15	13.83

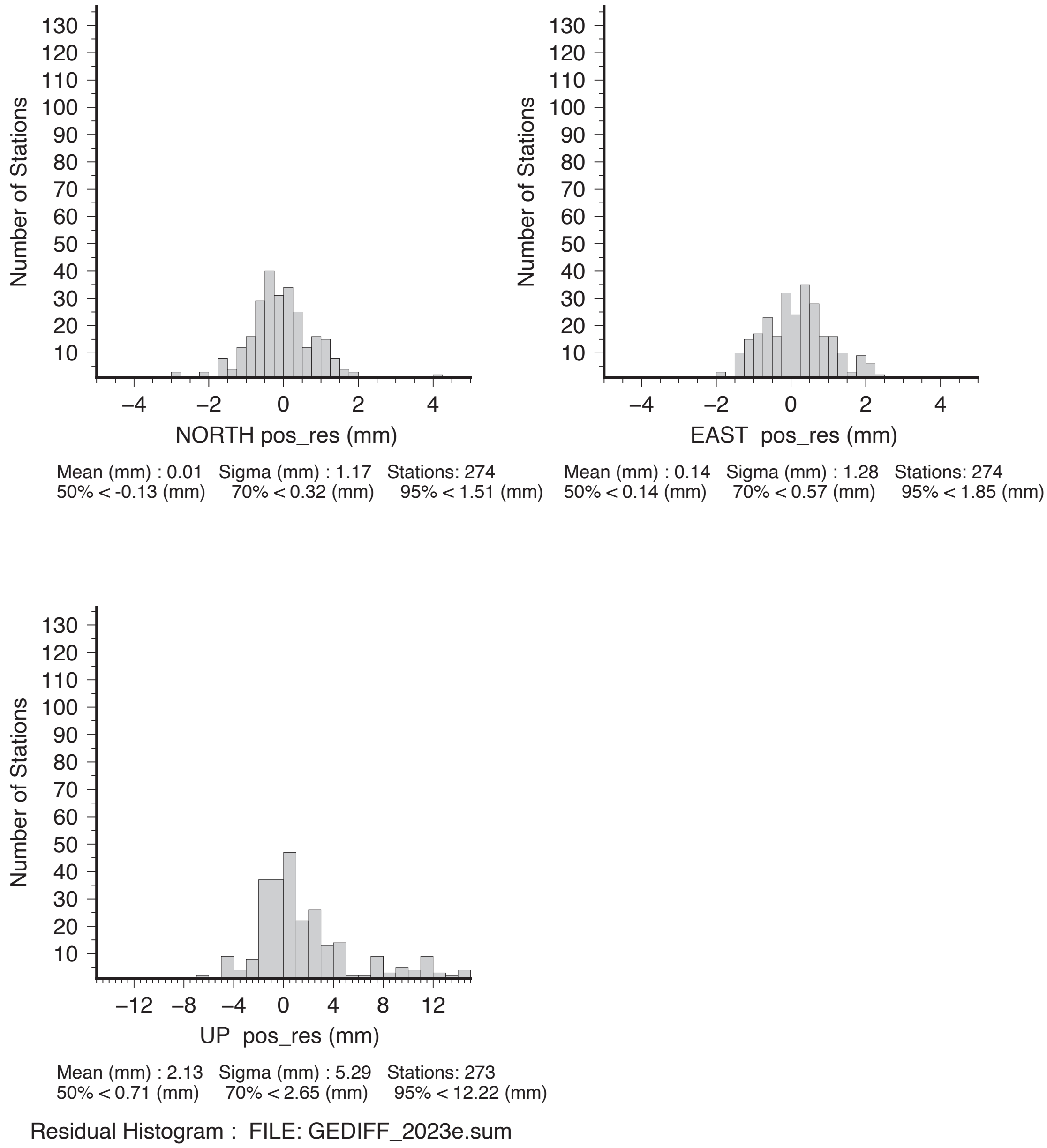


Figure 5: Histograms of the mean differences in North, East and Height between GPS-only and Galileo-only analyses. The mean differences are small and the slight positive mean difference in the height component is due to the AOAD/M_T and B antennas (bins between 8 and 14 mm). The mean and median when using just the 254 sites without AOAD/M_T and B antennas are 1.42 and 0.51 mm.

and median differences in north and east, and a positive difference in height, which is related to including sites with AOAD/T_M and B antennas. When these sites are removed, the mean and median of the mean differences reduce to 1.42 and 0.51 mm.

Table 5: Sites with the largest differences between GPS-only and Galileo-only solutions. In this table, # is the number of days of data used; DP is the difference in position, either height, north or east, depending on the block in the table; ± is the standard deviation of the mean difference assuming white noise; WRMS is the weighted RMS scatter about the mean; c is a shorthand notation for the square-root of chi-squared per degrees of freedom and it would be close to one if the standard deviation of the differences were consistent with the scatter; Receiver is the receiver type; Antenna is the antenna and radome type; and F is the GPS (G) and Galileo (E) frequency calibrations available (other available calibration frequencies are not shown.)

Height

Site	#	DP	± (mm)	WRMS (mm)	c	Receiver	Antenna		F
THTI	341	−14.01	2.29	42.21	0.53	TRIMBLE NETR9	ASH701945E_M	NONE	G01 E01 G02 G05 E05
PGEN	367	−10.26	0.42	8.11	0.70	LEICA GR50	LEIAR25	LEIT	G01 G02
MARS	515	−9.53	0.30	6.71	0.57	LEICA GR50	TRM57971.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
SCUB	427	−7.04	0.42	8.70	0.72	JAVAD TRE_G3TH DELTA	JAV_RINGANT_G3T	NONE	E01 E05 E06 E07 E08 G01 G02 G05
PPPC	100	−6.91	0.90	8.98	0.84	LEICA GR50	LEIAR25	LEIT	G01 G02
ABMF	521	−6.62	0.38	8.70	0.68	SEPT POLARX5	TRM57971.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
BRST	522	−5.94	0.19	4.41	0.55	TRIMBLE ALLOY	TRM57971.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
TUC2	452	−4.44	0.52	11.00	0.59	LEICA GRX1200+GNSS	LEIAR25.R3	NONE	G01 E01 G02 G05 E05 E06 E07
THTG	525	−4.27	0.35	8.00	0.69	SEPT POLARX5TR	LEIAR25.R3	LEIT	G01 E01 G02 G05 E05 E06 E07 E08
GLSV	416	−4.19	0.19	3.88	0.60	TRIMBLE NETR9	TRM115000.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
ABPO	389	14.03	0.36	7.19	0.60	SEPT POLARX5	ASH701945G_M	SCIT	G01 G02
GODE	111	14.45	0.47	4.94	0.60	SEPT POLARX5TR	AOAD/M_T	JPLA	
NYA1	525	14.51	0.33	7.46	0.72	TRIMBLE NETR9	ASH701073.1	SNOW	G01 G02
KOKB	516	14.93	0.32	7.27	0.67	SEPT POLARX5TR	ASH701945G_M	NONE	G01 G02
YAR2	111	15.63	0.38	4.03	0.58	TRIMBLE ALLOY	AOAD/M_T	NONE	G01 G02
BREW	514	16.77	0.40	8.97	0.48	SEPT POLARX5TR	ASH701945C_M	SCIT	G01 G02
SYDN	419	17.32	1.18	24.10	0.59	SEPT POLARX5TR	ASH701945C_M	NONE	G01 E01 G02 G05 E05 E06 E07 E08
USUD	110	21.92	0.88	9.19	0.62	SEPT POLARX5	AOAD/M_T	JPLA	
ANTC	110	22.62	0.77	8.08	0.38	SEPT POLARX5	ASH700936D_M	SNOW	G01 G02
KERG	516	28.75	0.43	9.66	0.66	TRIMBLE ALLOY	ASH701945E_M	SNOW	G01 G02

Table 5: Continuation.

North									
Site	#	DP	± (mm)	WRMS (mm)	c	Receiver	Antenna		F
GOLD	110	−3.07	0.17	1.81	0.65	JAVAD TRE_G3TH DELTA	AOAD/M_T	NONE	G01 G02
KGNI	38	−2.98	0.54	3.31	0.54	JAVAD TRE_G3TH DELTA	JAVRINGANT_DM	SCIS	G01 E01 G02 G05 E05 E06 E07
JPLM	111	−2.91	0.16	1.66	0.61	SEPT POLARX5	AOAD/M_T	NONE	G01 G02
FTNA	335	−2.77	0.14	2.63	0.65	TRIMBLE ALLOY	TRM59800.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
SGOC	524	−2.43	0.10	2.33	0.68	JAVAD TRE_3	JAVRINGANT_G5T	NONE	G01 E01 G02 G05 E05
MEDI	525	−2.24	0.08	1.93	0.63	LEICA GR10	LEIAR20	LEIM	G01 E01 G02 G05 E05 E06 E07 E08
USUD	110	−2.12	0.22	2.27	0.61	SEPT POLARX5	AOAD/M_T	JPLA	
GODE	111	−2.10	0.14	1.52	0.54	SEPT POLARX5TR	AOAD/M_T	JPLA	
SEYG	524	−1.81	0.10	2.19	0.63	SEPT POLARX5	TRM59800.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
CRO1	521	−1.75	0.08	1.88	0.65	SEPT POLARX5TR	JAVRINGANT_DM	SCIS	G01 E01 G02 G05 E05 E06 E07
ANTC	110	1.85	0.23	2.37	0.53	SEPT POLARX5	ASH700936D_M	SNOW	G01 G02
UNSA	516	1.93	0.08	1.80	0.59	SEPT ASTERX4	SEPCHOKE_B3E6	NONE	G01 E01 G02 G05 E05
FALK	521	2.30	0.10	2.23	0.66	SEPT POLARX5	ASH701945E_M	SCIT	G01 E01 G02 G05 E05 E06 E07 E08
CORD	9	2.67	0.84	0.86	0.34	SEPT POLARX5	TPSCR.G3	NONE	G01 E01 G02 G05 E05 E06 E07 E08
URUM	525	2.81	0.20	4.68	1.54	JAVAD TRE_3	JAVRINGANT_G5T	NONE	G01 E01 G02 G05 E05
SCH2	523	3.20	0.09	1.97	0.72	JAVAD TRE_3N DELTA	ASH701945E_M	NONE	G01 E01 G02 G05 E05
GRAS	496	3.93	0.08	1.83	0.58	TRIMBLE NETR9	ASH701945E_M	NONE	G01 E01 G02 G05 E05
THTI	395	4.05	0.17	3.43	0.55	TRIMBLE NETR9	ASH701945E_M	NONE	G01 E01 G02 G05 E05
CMUM	515	4.10	0.11	2.56	0.59	TRIMBLE NETR9	JAV_GRANT-G3T	NONE	G01 E01 G02 G05 E05 E06 E07 E08
JOG2	496	9.24	0.23	5.01	1.55	SEPT POLARX5	SEPCHOKE_B3E6	NONE	G01 E01 G02 G05 E05

Table 5: Continuation.

East									
Site	#	DP	± (mm)	WRMS (mm)	c	Receiver	Antenna		F
JOG2	496	−8.66	0.23	5.17	1.31	SEPT POLARX5	SEPCHOKE_B3E6	NONE	G01 E01 G02 G05 E05
URUM	525	−7.67	0.15	3.53	1.18	JAVAD TRE_3	JAVRINGANT_G5T	NONE	G01 E01 G02 G05 E05
SGOC	524	−3.34	0.13	2.93	0.70	JAVAD TRE_3	JAVRINGANT_G5T	NONE	G01 E01 G02 G05 E05
GOLD	110	−2.19	0.20	2.07	0.69	JAVAD TRE_G3TH DELTA	AOAD/M_T	NONE	G01 G02
FAIR	500	−1.99	0.09	1.93	0.69	SEPT POLARX5	ASH701945G_M	JPLA	
GODN	508	−1.83	0.08	1.70	0.65	JAVAD TRE_3 DELTA	TPSCR.G3	SCIS	G01 E01 G02 G05 E05 E06 E07 E08
PIE1	513	−1.83	0.09	2.07	0.76	JAVAD TRE_3 DELTA	ASH701945E_M	NONE	G01 E01 G02 G05 E05
JFNG	395	−1.49	0.11	2.15	0.66	TRIMBLE ALLOY	TRM59800.00	NONE	G01 E01 G02 G05 E05 E06 E07 E08
MATE	524	−1.48	0.08	1.89	0.67	LEICA GR30	LEIAR20	NONE	G01 E01 G02 G05 E05 E06 E07 E08
OHI2	303	−1.47	0.12	2.02	0.77	JAVAD TRE_G3TH DELTA	LEIAR25.R4	LEIT	G01 E01 G02 G05 E05 E06 E07 E08
BAUT	84	2.13	0.22	2.04	0.68	JAVAD TRE_3 DELTA	LEIAR25.R3	LEIT	G01 E01 G02 G05 E05 E06 E07 E08
YARR	521	2.15	0.08	1.86	0.72	SEPT POLARX5	LEIAT504	NONE	G01 E01 G02 G05 E05
TRO1	525	2.20	0.07	1.71	0.60	TRIMBLE NETR9	TRM59800.00	SCIS	G01 E01 G02 G05 E05 E06 E07 E08
VARS	504	2.28	0.07	1.61	0.53	TRIMBLE NETR9	TRM59800.00	SCIS	G01 E01 G02 G05 E05 E06 E07 E08
BSHM	434	2.36	0.09	1.81	0.61	SEPT POLARX5	TRM59800.00	SCIS	G01 E01 G02 G05 E05 E06 E07 E08
SAMO	500	2.70	0.14	3.23	0.63	SEPT POLARX5	JAVRINGANT_DM	NONE	G01 E01 G02 G05 E05 E06 E07 E08
NYAL	111	2.78	0.13	1.39	0.65	TRIMBLE NETR9	AOAD/M_B	DOME	
HRAO	516	4.40	0.09	2.05	0.63	SEPT POLARX5TR	ASH701945E_M	NONE	G01 E01 G02 G05 E05
CMUM	515	5.06	0.16	3.73	0.71	TRIMBLE NETR9	JAV_GRANT-G3T	NONE	G01 E01 G02 G05 E05 E06 E07 E08
ULAB	513	5.47	0.11	2.39	0.95	JAVAD TRE_3	JAVRINGANT_G5T	NONE	G01 E01 G02 G05 E05

References

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

Herring, T. MIT Analysis center: IGS Technical Report 2022. In R. Dach and E. Brockmann, editors, *International GNSS Service: Technical Report 2022*, pages 91–98. IGS Central Bureau, May 2023. doi: 110.48350/10.48350/179297.

NGS Analysis Center Technical Report 2023

J. Jones[1], P. McFarland[1], R. Bennet[1]

[1] National Geodetic Survey,
1315 East-West Highway, SSMC3
Silver Spring, MD 20910, USA
E-Mail: josh.jones@noaa.gov

1 Introduction

In 2023, NGS continued to serve as an IGS analysis center and a regional data center. This report summarizes the routine analysis and data center activities conducted at the National Geodetic Survey (NGS), and all significant changes that occurred since the last contribution to the IGS Report.

2 Core Analysis Center Products

The NGS analysis center currently focuses on producing the rapid and file products presented in Table 1. Starting Nov 18, 2022, we began to provide updated solutions to the IGS aligning with the ITRF2020 frame. We also updated our file names accordingly, matching the new IGS standards for long file names. With these changes, we continue to provide rapid products on a daily basis and now include a daily ERP file instead of only one a week. There were no changes in providing final products on a weekly basis except for the before mentioned file names. We are currently not providing ultra-rapid products, but new software under development at NGS, should include the additional capabilities necessary to help generate them. Combination statistics for NGS can be found at the IGS Analysis Coordinator website http://acc.igs.org.

Table 1: NGS Analysis Center Products

Pre-Wk 2237 Products	
ngswwwd.sp3	GPS only orbit solution
ngswwwd.snx	PAGES software position/velocity solution
ngswww7.erp	Earth Rotation Parameters
Current Products	
NGS0OPSRAP_YYYYDDD0000_01D_15M_ORB.SP3.gz	Rapid GPS orbit solution
NGS0OPSRAP_YYYYDDD0000_01D_01D_ERP.ERP.gz	Rapid Earth Rotation Parameters
NGS0OPSRAP_YYYYDDD0000_01D_01D_SUM.SUM.gz	Rapid GPS combination summary
NGS0OPSFIN_YYYYDDD0000_01D_15M_ORB.SP3.gz	Final GPS orbit solution
NGS0OPSFIN_YYYYDDD0000_01D_01D_ERP.ERP.gz	Final Earth Rotation Parameters
NGS0OPSFIN_YYYYDDD0000_01D_07D_SUM.SUM.gz	Final GPS combination summary
NGS0OPSFIN_YYYYDDD0000_01D_01D_SOL.SNX.gz	Final PAGES software position/velocity solution

3 Analysis Center Processing Software and Strategies

The NGS Analysis Center uses an in-house software package, Program for the Adjustment of GPS Ephemerides (PAGES), to estimate station baselines, orbits, and EOPs from double-differenced GPS phase observables. NGS computes solutions from small regional clusters of stations and combines the regions, at the normal equation level, into a global solution using the software package GPSCOM with no-net-rotation constraints. NGS is currently delivering products to the IGS computed using repro2/ITRF2020 models and standards.

For details about the models and strategies used, please refer to the https://itrf.ign.fr/docs/solutions/itrf2020/IGS-contribution-to-ITRF2020.pdf (Altamimi et al. (2023)). A Key updates in the models and strategies to the processing software include:

- Solar radiation pressure model in use is ECOM2 for all GPS satellites except Block IIF which uses ECOM1.
- Ocean loading model in use is FES2014.

Table 2: Sites contributed to the IGS network during 2023

Site	Location	Lat.	Long.	Receiver Type	System
ASPA00USA	Pago Pago, American Samoa	-14.33	-170.72	SEPT POLARX5	GPS+GLO+GAL
BRFT00BRA	Eusebio, Brazil	-3.88	-38.43	SEPT POLARX5	GPS+GLO+GAL
CNMR00USA	Saipan, CNMI, USA	15.23	145.74	TRIMBLE NETR9	GPS+GLO+GAL
GUUG00USA	Mangilao, Guam, USA	13.43	144.80	TRIMBLE ALLOY	GPS+GLO+GAL
HNPT00USA	Cambridge, MD, USA	38.59	-76.13	LEICA GR50	GPS+GLO+GAL
WES200USA	Westford, MA, USA	42.61	-71.49	TRIMBLE ALLOY	GPS+GLO+GAL

Table 3: Sites where NGS is facilitating data flow during 2023

Site	Location	Lat.	Long.	Receiver Type	System
GUAT00GTM	Guatemala City, Guatemala	14.59	-90.52	LEICA GRX1200GGPRO	GPS+GLO
ISBA00IRQ	Baghdad, Iraq	33.34	44.44	TRIMBLE NETR5	GPS+GLO
WUHN00CHN	Wuhan, China	30.53	114.36	TRIMBLE NETR9	GPS+GLO+BDS

4 Regional Data Center Core Products

During 2023, NGS contributed data from the sites listed in Table 2 to the IGS Network. As a Regional Data Center, NGS also facilitated data flow for the sites given in Table 3 as a Regional Data Center. NGS has updated the site names to the new 9 character ID format since the last submitted report (Yoon et al. (2023)). Please refer to the IGS Network website http://igs.org/network for site logs, photos, and data statistics for the sites serviced by the NGS regional data center.

5 Acknowledgements

The analysis and data center teams wish to express our gratitude to NGS management: Director Juliana Blackwell, Deputy Director Brad Kearse, and Division Chief Dan Gillins for their support of this work as fundamental activities of NGS. For information about how these activities fit into NGS plans, see the https://geodesy.noaa.gov/web/about_ngs/info/documents/ngs-research-plan-2024-final.pdf.

6 References

Altamimi, Z., Rebischung, P., Collilieux, X., Métivier, L., Chanard, K. (2023): ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. *Journal of Geodesy, 97(47)*. doi: https://doi.org/10.1007/s00190-023-01738-w

Yoon, S., J. Saleh, P. McFarland, B. Stressler, J. Heck, S. Hilla, and M. Schenewerk. (2020): NGS IGS Analysis Center Technical Report 2019. In R. Dach, and Y. Jean, editors, *IGS 2019 Technical Reports*, pages 95-98, 2020. IGS Central Bureau and University of Bern; Bern Open Publishing DOI doi: 10.7892/boris.144003

NRCan Analysis Center Technical Report 2023

S. Elson, R. Ghoddousi-Fard, O. Kamali, P. Lamothe, E. Maia Y. Mireault, T. Nikolaidou

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

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 2023 (products labelled 'EMR*'). Furthermore, it includes an outline of the changes to the stations and services managed by NRCan. 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 are being generated using GipsyX (v2 with in-house developments). The GNSS Rapid and Ultra-Rapid products continued to be generated using the Bernese software version 5.2 (Dach et al., 2015). IGS20/Repro3 standards have been implemented for all products. The products available from the NRCan-AC are summarized in Table 2. The 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 (EMR0OPSFIN_[yyyy][ddd]0000_01D_01H_GIM.INX.gz), and include GPS and GLONASS differential code biases (DCBs). They are available at CDDIS with a latency of less than 2 days. Staring DoY 64, 2023 they are available in long filename. 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 Ghoddousi-Fard (2023a,b) .

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 2023 and these are listed in Table 1. Figure 1 shows a map of the NRCan's publicly available GNSS network as of January 2024. 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 and ftp://cacsb.nrcan.gc.ca/gps

Figure 1: NRCan Public GNSS Stations (CGS-CACS, CGS-RACS, CHIS-WCDA).

Table 1: NRCan-IGS Station upgrades in 2023.

Station	Date	Remarks
STJO00CAN	2023-05-25	Station receiver upgraded to SEPT POLARX5
BAKE00CAN	2023-07-21	Station receiver upgraded to SEPT POLARX5
NAIN00CAN	2023-11-02	Station receiver upgraded to SEPT POLARX5S

References

Alfonsi L., N. Bergeot, P. J. Cilliers, G. De Franceschi, L. Baddeley, E. Correia, D. Di Mauro, C. Enell, M. Engebretson, R. Ghoddousi-Fard, I. Häggström, et al. (2022). Review of Environmental Monitoring by Means of Radio Waves in the Polar Regions: From Atmosphere to Geospace Surv Geophys, doi: 10.1007/s10712-022-09734-z.

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

Ghoddousi-Fard R. (2023). GNSS carrier phase irregularities during 2022 over Canadian high latitudes DASP 2023, Canadian Space Agency, Saint-Hubert, QC, Feb 20-24, 2023.

Ghoddousi-Fard R. (2023). Multi GNSS carrier phase irregularities in response to magnetic field perturbations over Canada URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023.

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):	
EMR0OPSFIN_yyyydoy0000_01D_15M_ORB.SP3 EMR0OPSFIN_yyyydoy0000_01D_01D_SOL.SNX EMR0OPSFIN_yyyydoy0000_01D_30S_CLK.CLK EMR0OPSFIN_yyyydoy0000_07D_01D_ERP.ERP EMR0OPSFIN_yyyydoy0000_07D_01D_SUM.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

USNO Analysis Center Technical Report 2023

S. Byram, J. Crefton, E. Lovegrove, J. Rohde

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

1 Introduction

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

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

The USNO AC is hosted in the GPS Analysis Division (GPSAD) of the USNO Earth Orientation Department. USNO AC activities, chairing the IGS TWG, and serving on the IGS Governing Board are overseen by Dr. Sharyl Byram who also oversees production of the IGS Final Troposphere Estimates. All GPSAD members, including Mr. Jeffrey Crefton, 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, 2023

Figures 1-4 show the 2023 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 25 mm with respect to (wrt) the IGS rapid combined orbits. The USNO Ultra-rapid orbits had median WRMSs of 25 mm (24-h post-processed segment) and 46 mm (6-h predict) wrt the IGS rapid combined orbits. USNO rapid (post-processed) and Ultra-rapid 6-h predicted clocks had median 155 ps and 975 ps RMSs wrt IGS combined rapid clocks.

USNO rapid polar motion estimates had (x, y) 25 and 32 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 296 and 644 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 454 and 704 microarcsec, respectively.

All USNO AC official products were generated with the Bernese GNSS Software, Version 5.2 in 2023 and were produced using the IGS20 reference frame.

References

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

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

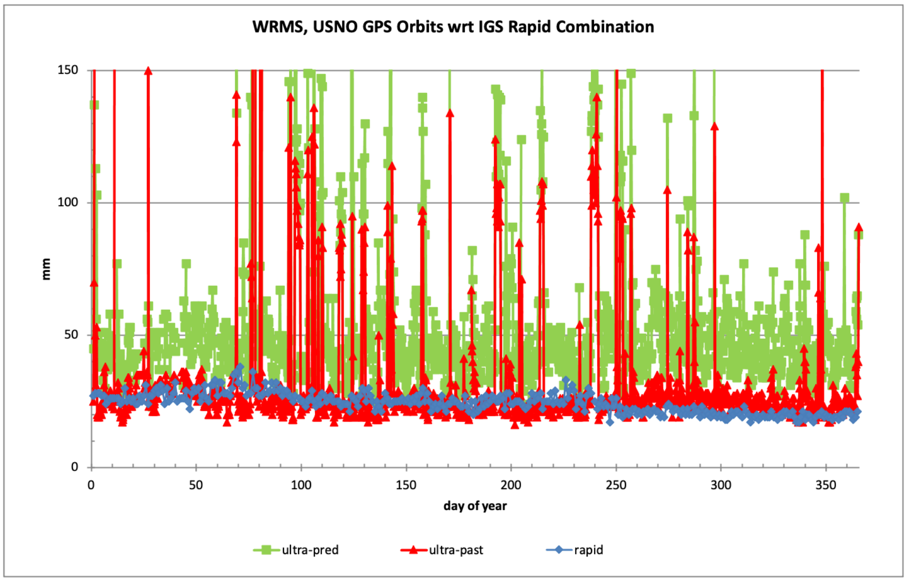


Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2023. “Ultra-past” refers to 24-hour post-processed section of USNO Ultra-rapid orbits. “Ultra-pred” refers to first six hours of Ultra-rapid orbit prediction.

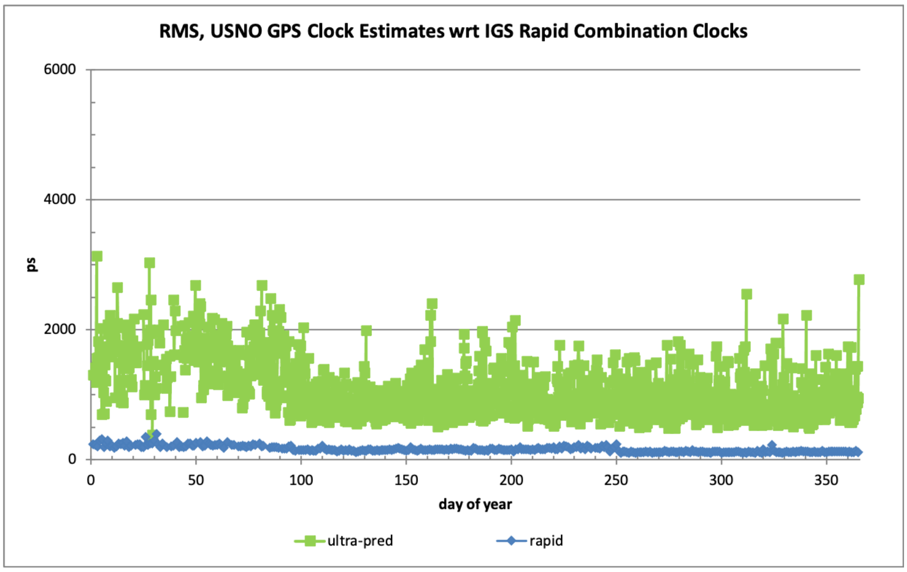


Figure 2: RMS of USNO GPS Rapid clock estimates and Ultra-rapid clock predictions with respect to IGS Rapid Combination, 2023.

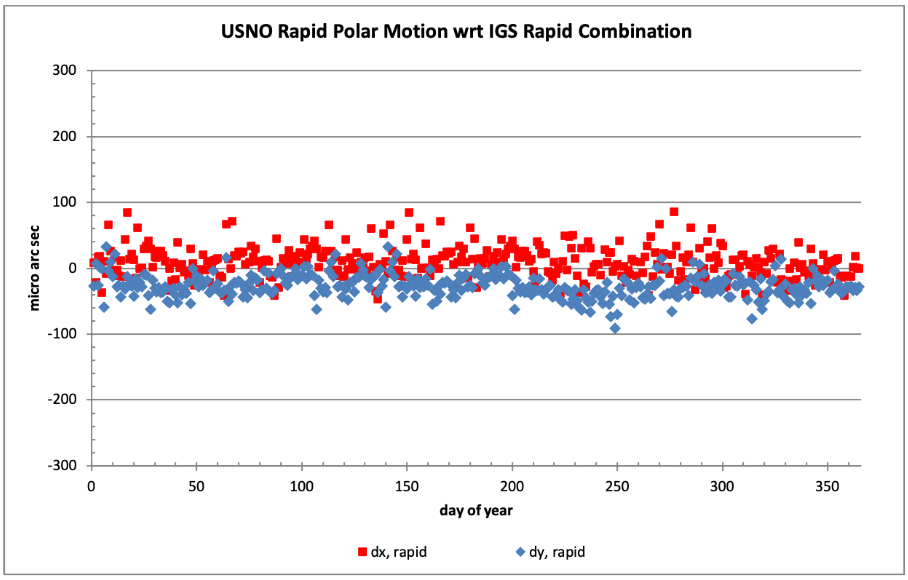


Figure 3: USNO Rapid Polar Motion estimates differenced with IGS Rapid Combination values, 2023.

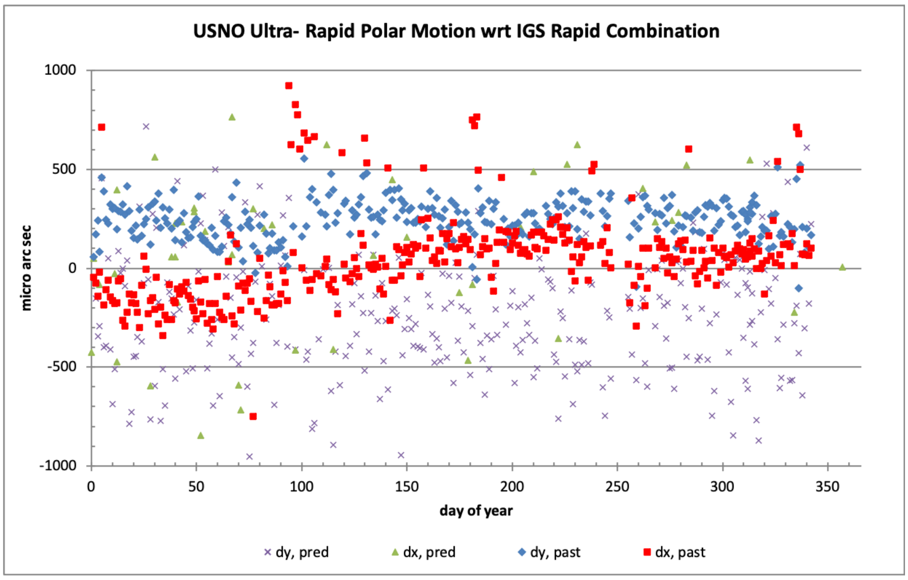


Figure 4: USNO Ultra-rapid Polar Motion estimates differenced IGS Rapid Combination values, 2023. "pred" denotes predicted and "past" denotes post processed.

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		
1/1/2023 – 12/31/2023	25	25	46	25	32	296	644	454	704	155	975

Wuhan University Analysis Center Technical Report 2023

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

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

1 Introduction

The IGS Analysis Center of Wuhan University (WHU) has contributed to the International GNSS Service (IGS) since 2012 with a regular determination of the precise 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 2023, WHU participated in the generation of Galileo Ultra-rapid products, and updated the global ionosphere modeling method, which includes the consideration of the GLONASS receiver inter-frequency differential code bias and the adoption of the inequality-constrained least squares method. We also investigated the system time offset of different satellite navigation systems.

2 WHU Analysis Products

The products provided by WHU are summarized in Table 1.

3 Ionosphere Activities

Since Wuhan University (WHU) was recognized as one of the members of the IGS IAACs in 2016. The daily rapid and final GIM products have been generated by the software

Table 1: List of products provided by WHU.

WHU rapid GNSS products	
WHU0OPSRAP_YYYYDDDHH00_01D_15M_ORB.SP3	Orbits for GPS/GLONASS/Galileo satellites
WHU0OPSRAP_YYYYDDDHH00_01D_05M_CLK.CLK	5-min clocks for stations and GPS/GLONASS/Galileo satellites
WHU0OPSRAP_YYYYDDDHH00_01D_01D_ERP.ERP	ERPs
WHU ultra-rapid GNSS products	
WHU0OPSULT_YYYYDDDHH00_02D_15M_ORB.SP3	Orbits for GPS/GLONASS/Galileo satellites, provided to IGS every 6 hours
WHU0OPSULT_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

named GNSS Ionosphere Monitoring and Analysis Software (GIMAS). The WHU RT GIM was published and updated in 2020 and 2021, respectively (Zhang et al., 2019).

During 2023, WHU updated the global ionosphere modeling method by considering the GLONASS receiver inter-frequency differential code bias (IFDCB). WHU ionosphere ROTI products have been released since August in 2023. The WHU ROTI map can be accessible via Wuhan Data Center (ftp://igs.gnsswhu.cn/pub/whu/MGEX/ROTI).

WHU take the GLONASS data to global ionosphere mapping based on Spherical Harmonic Expansion (SHE) model, this method considers the GLONASS receiver inter-frequency differential code bias (IFDCB) exists in the dual-frequency geometry-free combination observable. The investigation indicated that the GLONASS IFDCB is distinguishable from the leveling error induced by the "carrier-to-code leveling" method and this error can not be ignored in the modeling process. By estimating the individual GLONASS receiver IFDCB for each satellite at one station, and adopting a modified model for combined GPS and GLONASS global ionosphere mapping method. The GLONASS satellite plus receiver DCB for each satellite-receiver link can be obtained through the parameter estimation (Zhang et al., 2023).

The negative values exist in the global ionosphere map with the SHE model is unreasonable from physical point of view. The investigation showed that the occurrence of the negative values is attributed to the deficiency of the SHE modeling method when the vertical total electron content (VTEC) is small (Zhang et al., 2019). By adopting the inequality-constrained least squares method, the negative VTEC can be eliminated efficiently and, which is more important, it has nearly no influence on the positive VTEC values. This method can also improve the receiver DCB estimation and the precision of the GIM.

In addition, we also published global ionosphere ROTI map products since 2023, the products can be obtained via Wuhan Data Center. The ROTI calculated with a time window in 5 minutes can show the distribution of the global ionosphere irregularities effectively.

4 Real-time clock estimation aiming at multi-GNSS time interoperability

The combined use of multi-GNSS constellations can improve the accuracy and availability of PNT solutions. However, this requires a degree of interoperability, notably time interoperability. The inter-system bias (ISB) is the key issue for time interoperability, which contains two portions: the receiver hardware delay difference and the system time offset (STO) between different constellations. Although users can add unknowns to account for the ISB, this requires more visible satellites and probably provides no solutions under poor satellite visibility. To alleviate this problem, fixing the ISB to known values is a popular approach, which needs a prerequisite, i.e., known hardware delay difference and STO values.

The receiver hardware delay difference between different constellations is stable over a long time. Consequently, receiver calibration is a common approach to determine the value and difference of hardware delays. As for the STO, it is induced by multi-GNSS satellite clock products and generally exhibits slow variations. As a result, it is vital to determine STO values for fixing the ISB. To solve the STO problem of real-time multi-GNSS clocks, we proposed a real-time clock estimation method with STO maintenance, which can generate multi-GNSS clocks with stable STO values. Based on the multi-GNSS clocks, users are easy to fix the ISB with pre-estimated values.

Comparing with the conventional method, the STO maintenance method has not harmed the accuracy of satellite clocks. The clocks generated with the two methods respectively use the notation of CONV clocks and STOM clocks hereafter. The ISB estimation with static PPP is adopted to validate stable STO values of STOM clocks. Figure 1 shows the ISB series of several stations for dozens of days. For comparison, ISB results estimated using broadcast ephemerides (BRDC) and the CONV clocks are shown as well. The STO maintenance method is based on ISB reference values (ISBREF), which are also given in Figure 1. It is clear that the ISB results of the STOM clocks are rather stable for a long-term period and show great consistency with the ISBREF values with a RMS value better than 1 ns. Additionally, kinematic PPP solutions using the STOM clocks

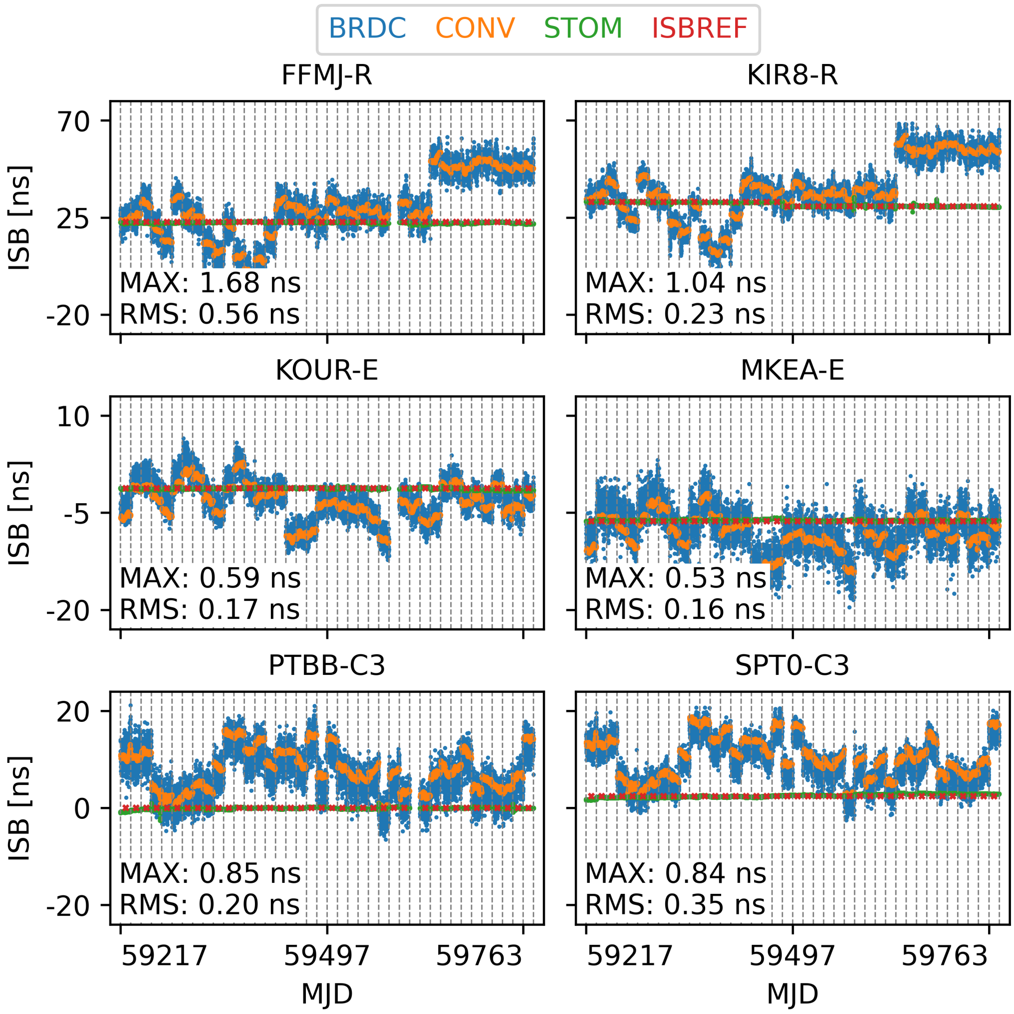


Figure 1: ISB series obtained with various clock products (BRDC: blue, CONV: orange, STOM: green) and ISB reference values (ISBREF: red), where the grey dashed lines indicate the boundaries of the solutions. The maximum and RMS of the difference between STOM and ISBREF are reported in the bottom left corner of each subplot.

indicate that compared with estimating the ISB, fixing the ISB can significantly improve the convergence speed, accuracy, and availability for cutoff elevation angles greater than 45°.

References

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

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

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

Zhang Q., J. Tao, X. Liu., Z. Hu, and Q. Zhao Combined GPS/GLONASS global ionosphere mapping considering the GLONASS inter-frequency differential code bias. *GPS Solut.* 27, 101, 2023.

Mao F., X. Gong, S. Gu, F. Zheng, Y. Lou, and C. Shi Real-time clock estimation using system time offset maintenance aiming at multi-GNSS time interoperability, *Measurement*, doi: https://doi.org/10.1016/j.measurement.2023.113929,2024.

EUREF Permanent Network Regional Network Associate Analysis Centre Technical Report 2023

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

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

1 Introduction

The International Association of Geodesy Regional Reference Frame sub-commission for Europe, EUREF, defines, maintains, and provides access to the European Terrestrial Reference System (ETRS89). This is done through the EUREF Permanent GNSS Network (EPN). EPN observation data as well as the precise coordinates and the zenith total delay (ZTD) parameters of all EPN stations are publicly available. The EPN cooperates closely with the International GNSS Service (IGS); EUREF members are e.g. involved in the IGS Governing Board, the IGS Reference Frame Working Group, the RINEX Working Group, the IGS Real-Time Working Group, the IGS Antenna Working Group, the IGS Troposphere Working Group, the IGS Infrastructure Committee, and the IGS Multi-GNSS Working Group and Multi-GNSS Extension Pilot Project (MGEX). This paper provides an overview of the main changes in the EPN during the year 2023.

In 2023, EUREF's multi-GNSS Working Group and European dense velocity Working Group were closed, mainly due to a personal change (E. Brockmann retired from the EUREF GB at the EUREF symposium in Gothenburg (May 2023)). Moreover, the task of monitoring the official national coordinates of the EU Countries, which has been established since 2009, has been taken over by the reference frame coordinator.

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 availability, correctness of metadata, and data quality. In 2023, the EPN Central Bureau (CB, https://epncb.oma.be/) added 17 new stations to the EPN (indicated in green in Figure 1) and adapted its routines to process RINEX 4 data. End of 2023, 3 EPN stations were providing RINEX 4 data. 97%, 90%, and 81% of the EPN stations were providing respectively GLONASS, Galileo, and BeiDou observations.

To move towards FAIR-aligned GNSS data (as recommended by Resolution No 2 of the 2021 EUREF symposium), the latest version of M3G (https://gnss-metadata.eu) allows now to insert the Digital Object Identifiers (DOI) associated with the dataset of a GNSS station. The EPN CB also offers EPN station mangers help to assign a DOI to the dataset of their EPN stations.

Encouraged by Resolution No 2 of the 2019 EUREF symposium in Tallinn, 87% (an increase of 20% wrt 2022) of the EPN stations are sharing their daily RINEX data with the European Plate Observing System (EPOS). These EPN data are available from the EPOS data portal (https://www.epos-eu.org/dataportal) through the ROB-EUREF EPOS data node built on top of the historical EPN data centre managed by the ROB.

3 Data Products

3.1 Positions

The EPN Analysis Centres (ACs) operationally process GNSS observations collected at EPN stations. In 2023, 15 of 17 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 combined by the Analysis Centre Coordinator (ACC). Details of the various combinations done by the ACC are given on http://www.epnacc.wat.edu.pl/epnacc/final/. In 2023, 19 new EPN stations have been included in AC and combined coordinate solutions.

In 2023 the EPN Analysis Centres Coordinator (ACC) worked on operational combinations of Analysis Centres (AC) solutions provided in the IGS20 framework. After the introduction of IGS20 reference frame (November 27, 2023; GPS week 2238), the creation of EPN combined coordinate solutions was stopped, because most of the EPN AC solutions could not provide their solutions according to IGS20 standards on time (e.g., due to necessary transition to the new version of the Bernese GNSS Software, lack of manpower). Finally, in September 15 of 17 ACs could regularly provide their solutions and the creation of combined solutions could be resumed. Because not all ACs were able to provide their

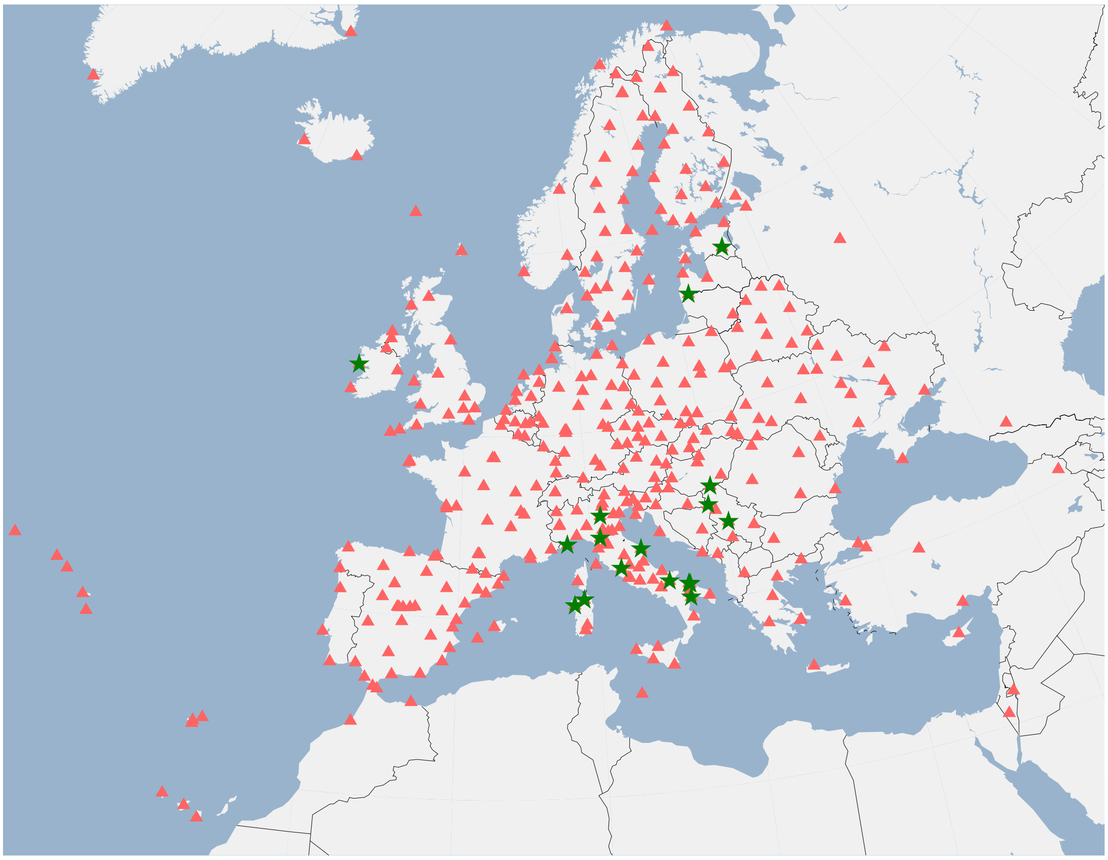


Figure 1: 17 new GNSS stations (in green) integrated in the EPN in 2023. The new EPN station THU200GRL is outside of the map.

solutions, small changes were done to the AC networks so that each station would be processed by at least 3 ACs (the requirement used in the EPN). The combined solutions for GPS weeks 2238-2276 were completed in October and November, and the regular creation of operational combined solutions started in December. The combination of AC coordinate solutions is done in Bernese GNSS Software version 5.4. The combined solutions in IGS20 include also the solutions from GFZ, the new EPN analysis centre which was established in 2022. Also, with the change to the IGS20 standards, including the usage of new long filenames for AC (and combined) solutions, the abbreviation for CODE EPN analysis centre was changed from “COE” to “COD”. The comparisons of AC solutions can be found at the ACC website: http://www.epnacc.wat.edu.pl/epnacc/final/.

In addition, the strategy for a combination of AC solutions was slightly enhanced. It now includes also the preliminary stacking of AC solutions into long-term solutions. This additional step allows to detect potential issues in individual AC solutions and outliers in station positions. The preliminary daily combined solutions are also stacked into long-

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 2023), 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	112 (15/1)	GipsyX-2.1	GRE
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	134 (2/1)	BSW 5.4	GRE
BEV	Federal Office of Metrology and Surveying, Austria	WD	178 (1/0)	BSW 5.4	GRE
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRN	155 (2/0)	BSW 5.4	GRE
COD	Center for Orbit Determination in Europe, Switzerland	WD	39 (0/0)	BSW 5.5	GRE
GFZ	GeoForschungsZentrum, Germany	WD	114 (1/0)	EPOS.P8	GRE
IGE	Instituto Geografico Nacional, Spain	WDR	100 (1/0)	BSW 5.4	GRE
IGN	Institut Géographique National de L'information Geographique et Forestiére, France	—	62 (0/0)	—	—
LPT	Federal Office of Topography swisstopo, Switzerland	WDRN	60 (1/0)	BSW 5.3	GRE
MUT	Military University of Technology, Poland	DR	160 (1/0)	GG 10.71	GE
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WDR	107 (3/0)	BSW 5.4	GRE
RGA	Republic Geodetic Authority, Serbia	-–	68 (5/1)	-–	-–
ROB	Royal Observatory of Belgium, Belgium	DR	114 (1/0)	BSW 5.4	GRE
SGO	Lechner Knowledge Center, Hungary	WDR	64 (0/0)	BSW 5.4	GRE
SUT	Slovak University of Technology, Slovakia	DRN	94 (13/0)	BSW 5.4	GRE
UPA	University of Padova, Italy	WDR	115 (15/1)	BSW 5.4	GRE
WUT	Warsaw University of Technology, Poland	WDR	156 (2/0)	BSW 5.4	GRE

term solutions and the resulting position time series are checked. The outliers found in AC and combined solutions position time series are excluded from AC solutions before the final combination. The stacking of AC and combined solutions into long-term solutions is done using CATREF software.

In 2023, ACC and ACs also worked on the new Guidelines for EPN Analysis Centres. The new guidelines describe the present strategy for GNSS observations processing in EPN within the IGS20 framework. The guidelines are available at the EPN Central Bureau website: https://epncb.oma.be/_documentation/guidelines/guidelines_analysis_centres.pdf. The new guidelines are consistent with the IGS20 standards. The main changes in the EPN analysis include the usage of the new EPN antenna model (based almost exclusively on the IGS type-mean model), the correction of antennas not oriented to true north, exclusion of GNSS observations without receiver antenna calibrations, the usage of new ocean tide model (FES2014b), and the new long filenames for the EPN products.

3.2 Troposphere

Due to the transition to IGS20 standards occurred on November 27th, 2022 (GPS week 2238) tropospheric final operational combination stopped because of the lack of input solutions from the EPN ACs. As of today, 15 EPN ACs delivered final tropospheric operational products conformed to IGS20 standards. The final tropospheric operational combination for past weeks (since 2238 to present) was completed and made available at the EPN data centres in December when the regular creation of operational combined solutions resumed.

In 2023, the 14 new EPN stations were successfully included in the tropospheric combined solution. ZTD combined estimates are available, on average, for 397 EPN stations (compared to the 368 in 2022). For each combined EPN station Integrated Water Vapour (IWV) is provided along with ZTD. Tropospheric products are disseminated only 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/troposphere/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 till GPS week 2237 and 15 ACs from 2238 afterwards. In addition, the operational individual AC solutions are not cleaned before the computation of the mean bias and standard deviation. In both cases, gross errors (i.e. ZPD with formal standard deviation $>$ 15 mm) and outliers, detected during the combination process, are removed thus not affecting the combined value.

In 2023 it was recommended to the EPN ACs to submit rapid operational tropospheric estimates (namely ZTDs and horizontal gradients) obtained as a by-product of the rapid analysis for the EPN stations included in their sub-network. As of today, 9 ACs are providing these rapid products with a deadline for the submission of 22 hours after the end of observations of the analysed day. This allowed a rapid operational combination that is currently under evaluation.

3.3 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. The Reference Frame Coordinator (RFC) computes these EPN multi-year solutions with the CATREF software (Altamimi et al., 2007). Exceptionally in 2023, only one Reference Frame Solution has been published in January (C2235, https://doi.org/10.24414/ROB-EUREF-C2235). The EPN reference frame solution C2235 was the last solution in IGb14, it provides the positions and velocities for 389 EPN stations and covers the period from the 1^{st} of January 1996 to 12^{th} of November 2022, when the IGS switched to IGS20.

The EPN multi-year product includes SINEX files in IGb14 and ETRF2014, a discontinuity list and the associated residual position time series which are all available from https://epncb.eu/ftp/product/cumulative/latest/. The archive of the previous EPN multi-year products is available from https://epncb.oma.be/pub/product/cumulative/.

The next release of the EPN Reference Frame Product will be expressed in IGS20. It will be based on the daily EPN Repro3 solutions and the operational EPN final daily solutions, both provided in IGS20.

In the meantime, for monitoring purposes, rapid timeseries of the EUREF permanent stations are generated daily with 2-day delay and based on a mix of IGb14 final daily solutions (until Nov. 12^{th} 2022) and IGS20 final and rapid daily solutions (after Nov. 12^{th} 2022), for example https://epncb.oma.be/_productsservices/timeseries/index.php?station=ADAR00GBR&update.

Together with the quality checks provided by the EPN CB, these quick updates allow to monitor the behaviour of the EPN stations and to react promptly in case of problems.

4 Working Groups

4.1 EPN reprocessing

Numerous analysis centres of the EPN are currently busy reprocessing all the available GNSS data of the EPN network to provide their products in the latest reference frame IGS20. Unfortunately, work on this project called EPN-Repro3 has been delayed several times, as more time than expected was needed to implement updates to the analysis software and provide the necessary computer resources. After all, more than 25 years of data from well over 350 stations must be reprocessed in different subnetworks of the EPN, which will tie up considerable resources at the individual analysis centres. In contrast to the original plan to start reprocessing in spring 2023, several analysis centres could not begin reprocessing before the end of 2023. It is expected that the ACs will have completed their work by early 2024 and that homogeneous EPN products (coordinates, velocities and ZTDs) can then be computed based on these new available products and made available over a period of more than 25 years.

4.2 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 (D2237) is expressed in IGS14 and covers the period from October 2008 to November 2022 (GPS week 1500-2237) using inputs expressed in IGS14. The complete solution includes 31 networks with positions and velocities of 3800 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 to generate a unique reference velocity model for referencing the EGMS (European Ground Motion Service) InSAR ground motion model. A new EPND combination is only to be expected, after the EPN-Repro3 and the national scale reprocessing solutions are ready.

5 Stream and Product Dissemination

End of 2023, 237 EPN stations (i.e., mount-points) provided real-time data (219 end of 2022) which corresponds to 55.5% (almost same percentage as in 2022) of the EPN stations. RTCM 3.x, x=1, 2, 3, messages are available from the three EPN broadcasters; four stations still providing RTCM 2.3 are no longer available. 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.) remains at 66 whereas the MSM7 (message types 1077 etc.) increased again significantly from 127 to 145 data streams. Hence, the stations providing the old "legacy" messages 1004 (GPS) and 1012 (GLONASS) further reduced from 20 to 17. 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). 239 data streams are operationally monitored, 98% 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, complemented by the broadcast ephemerides BCEP00BKG0.

References

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

Bruyninx, C., J. Legrand, A. Fabian, and E. Pottiaux. GNSS metadata and data validation in the EUREF Permanent Network. GPS Solutions, 23:106, 2019. https://doi.org/10.1007/s10291-019-0880-9A.

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

Legrand J. EPN multi-year position and velocity solution C2235, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-C2235

Steffen R., J. Legrand, J. Agren, H. Steffen, and M. Lidberg. HV-LSC-ex2: Velocity field interpolation using extended least-squares collocation. Journal of Geodesy 96, 15, 2022, https://doi.org/10.1007/s00190-022-01601-4

Part III

Data Centers

Infrastructure Committee Technical Report 2023

M. Bradke[1], R. Ruddick[2], D. Maggert[3], W. Söhne[4], E. D'Anastasio[5]

[1] GFZ Potsdam, Germany
E–mail: markus.bradke@gfz-potsdam.de
[2] Geoscience Australia, Australia
[3] EarthScope Consortium, United States
[4] BKG, Germany
[5] GNS Science, New Zealand

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 which 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 is composed of ex-officio members, who hold 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. In February 2023, an updated charter[1] was published to facilitate the creation of a vice coordinator role, and Ryan Ruddick was approved as the new vice coordinator. Meanwhile, Markus Bradke will continue in the coordinator role for another four-year term, concluding at the end of 2027.

As of December 31, 2023, Table 1 provides a snapshot of the current membership.

[1] https://files.igs.org/pub/resource/ic/IGS_IC_Charter_February_2023.pdf

Table 1: List of IGS Infrastructure Committee Members (as of December 31, 2023)

Member	Affiliation	Role
Leadership (2):		
Bradke, Markus	GFZ	Infrastructure Committee Coordinator (ICC)
Ruddick, Ryan	GA	Infrastructure Committee Vice Coordinator IGS Network Representative
Current Members (5):		
Bruyninx, Carine	ROB	EPN Network Coordinator
D'Anastasio, Elisabetta	GNS	IERS Representative
Elson, Stuart	NRCan	NRCan Network Representative
Fernandes, Rui	UBI/SEGAL	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
Gini, Francesco	ESA/ESOC	IGS/RTCM RINEX Working Group Chair
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)
Rebischung, Paul	IGN	IGS Reference Frame Coordinator (RFWG)
Rülke, Axel	BKG	IGS Real-Time Working Group Chair (RTWG)
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 2023

Throughout 2023, the IC actively assisted the Network Coordinator in responding to inquiries from IGS product and data users. The Station Proposal Committee (SPC) added 6 multi-GNSS stations to the network and removed 6 long-term absent stations from the network, as detailed in Table 2. The SPC 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 leadership of the IC has participated in several IGS Working Group teleconferences throughout 2023 to ensure the coordination in terms of station needs and infrastructure across all the different IGS activities.

The IC is working towards the recommendations from the 2022 IGS Virtual Workshop[2] that are summarised below.

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.

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

Table 2: List of approved and decommissioned Stations in the IGS Network in 2023

Station	Location	Systems	Real-Time	Agency
Approved Stations (6):				
CUIB00BRA	Cuiaba, Brazil	GRECS	Yes	IBGE
MSGR00BRA	Campo Grande, Brazil	GRECS	Yes	IBGE
NAUS00BRA	Manaus, Brazil	GRES	Yes	IBGE
OAFA00ARG	Ciudad de San Juan, Argentina	GREC	Yes	IGN-Ar
TEJA00CHL	Isla Teja - Valdivia, Chile	GREC	Yes	UACh
WUTH00NOR	Hornsund, Norway	GRECJIS	No	WUT
Decommissioned Stations (6):				
ATRU00KAZ	Atyrau, Kazakhstan	GRES	-	JSC
HUEG00DEU	Huegelheim, Germany	GRECS	-	BKG
LCK300IND	Lucknow, India	GRECJIS	-	ISRO
LLAG00ESP	La Laguna, Spain	GRECIS	-	DLR
KOST00KAZ	Kostanay, Kazakhstan	GREC	-	JSC
SEME00KAZ	Semey, Kazakhstan	GREC	-	JSC

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

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 has taken steps towards implementing Recommendation 1 by releasing revised guidelines for CORS. The document titled "Guidelines for Continuously Operating Reference Stations in the IGS"[4] is now accessible, providing valuable support to station owners and operators in the planning and maintenance of CORS. Furthermore, an updated process for proposing new IGS stations has been specified in the "Procedure for Becoming an IGS Station"[5] document. This revision aims to provide clarity on the responsibilities of contributing organisations in the station proposal process.

In 2023, the IC conducted a survey across IGS data centres to gather information on various aspects of their IT infrastructure, encompassing data management and information security. The significant findings were presented to the Governing Board (GB) during the July meeting in Potsdam. The GB recognized the pivotal role played by data centres in the service chain and identified the need for a comprehensive overhaul, focusing on standards for quality checks, data provenance, data synchronisation, data discoverability, and information security. Subsequently, a task team was initiated to draft a high-level document titled "Global Data Centre", outlining the requirements for an elevated tier of data centre (Recommendation 4).

Another task team within the IC is working on the promotion of GeodesyML[6] as a recognised standard to maintain the metadata of GNSS stations in our community (see recommendation 3). 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[7]. The IC supported the IGS Central Bureau in successfully launching the new CORS metadata management system (SLM 2.0[8]), which marks an essential step forward in promoting GeodesyML as a metadata exchange format.

Additionally, members of the IC are actively exploring an alternative to RINEX as the storage and access format for GNSS data. Several prototypes utilising TileDB have been

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

[4] https://files.igs.org/pub/resource/guidelines/Guidelines_for_Continuously_Operating_Reference_Stations_in_the_IGS_v1.0.pdf

[5] https://files.igs.org/pub/resource/guidelines/Procedure_for_Becoming_an_IGS_Station_v1.0.pdf

[6] http://geodesyml.org

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

[8] https://github.com/International-GNSS-Service/SLM

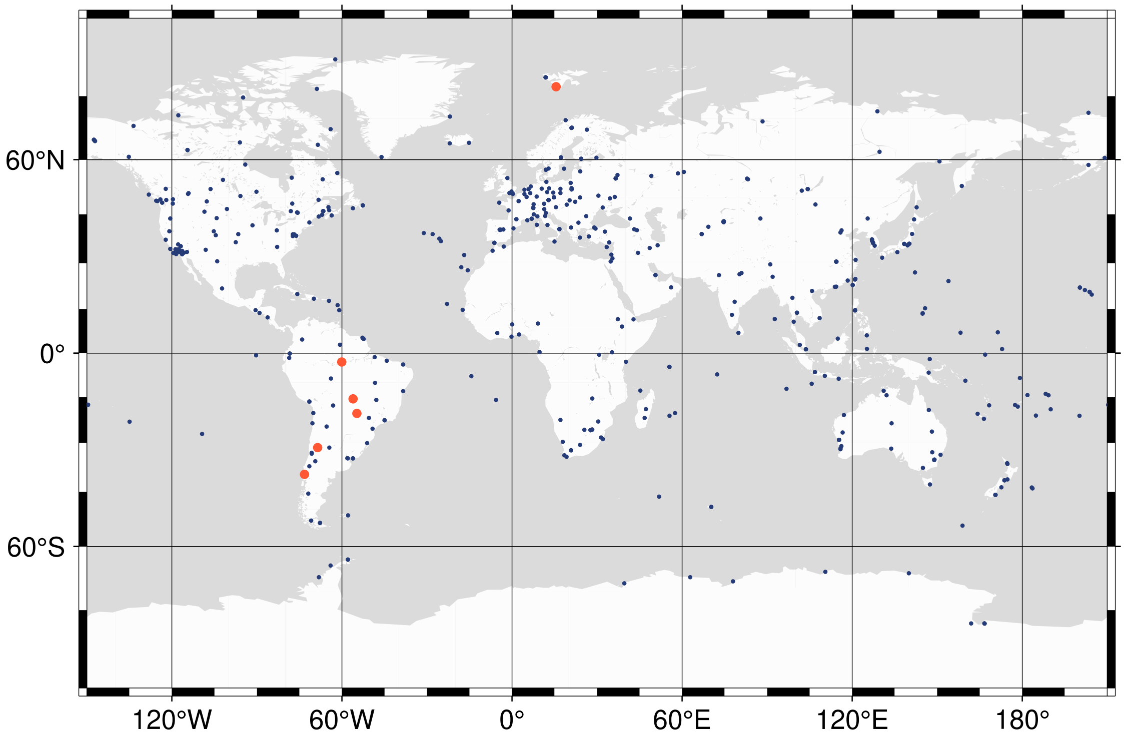


Figure 1: A Map of the IGS Network in 2023 with the newly added stations highlighted in red.

developed. However, further feasibility studies and benchmark tests are required to evaluate the practicality and performance of TileDB[9] in an operational environment. This initiative reflects the ongoing efforts to enhance and optimise data storage and access methods in the GNSS community.

4 Current and planned Activities

In 2024, the Committee aims to work on all recommendations from the IGS Workshop listed in section 3 .

The initiative's objective is to boost the number of Multi-GNSS and Real-Time stations through active outreach efforts. Particular attention will be given to regions with limited representation in the IGS, such as Africa and the Middle East. The plan involves offering assistance to station operators in these targeted regions to enhance their capacity and capabilities.

As part of the strategy, the organisation intends to participate in the upcoming FIG

[9] https://tiledb.com/

Working Week[10] in Accra, Ghana. The aim is to establish connections with local station and network operators and advocate for the IGS infrastructure.

The committee has set the goal to integrate the ISO-3166 “Alpha-3 code” for geographic descriptions in the IGS site log files in early 2024. We will ensure a seamless transition by maintaining parallel support for both old and new formats for a period of at least 6 months. With this implementation we are also able to phase out the 4-character station IDs.

We are targeting to initiate web-based systems to make station and satellite metadata more discoverable. With the new SLM operational, the IC will work on solutions for an automated exchange of metadata between different IT systems. We will further explore the full potential of TileDB as a data storage and access format.

We plan to advance the idea of a “Global Archive” through the formulation of a comprehensive concept, the compilation of requirements, and the preparation of a feasibility analysis. Our primary emphasis will be on addressing key aspects such as data storage, data access, metadata collection, quality checks, security standards, and the absence of synchronisation methods between data centres. While Information Security is an integral part of the concept, its scope extends beyond data centres. Generally, the significance of this subject is often underestimated, impacting every aspect from receiver infrastructure to analysis and data centres. As part of our efforts, we aim to create promotional materials to advocate for the importance of Information Security across all components of the IGS.

Furthermore, the Committee is planning to assemble a comprehensive program for the plenary infrastructure session of the IGS Workshop that will be held in Bern, Switzerland in July 2024.

[10] https://www.fig.net/fig2024/

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
IGBE	Instituto Brasileiro de Geografia e Estatística
IGN	Institut national de l'information géographique et forestière
IGN-Ar	Instituto Geográfico Nacional de Argentina
ISRO	Indian Space Research Organisation
JPL	Jet Propulsion Laboratory
JSC	JSC National Company Kazakhstan Gharysh Sapary
KASI	Korea Astronomy and Space Science Institute
MIT	Massachusetts Institute of Technology
NRCan	Natural Resources Canada
NRL	United States Naval Research Laboratory
ROB	Royal Observatory of Belgium
SEGAL	Space & Earth Geodetic Analysis Laboratory
SIO	Scripps Institution of Oceanography
UACh	Universidad Austral de Chile
UBI	University of Beira Interior
WHU	Wuhan University
WUT	Warsaw University of Technology

CDDIS Global Data Center Technical Report 2023

R. Lamb, R. Bagwell

NASA Goddard Space Flight Center, Code 61A
Greenbelt, MD 20771 USA
Rivers.Lamb@nasa.gov
Ross.Bagwell@nasa.gov

1 Introduction

The Crustal Dynamics Data Information System (CDDIS) is one of NASA's Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs) (see https://earthdata.nasa.gov). CDDIS supports the international space geodesy community. For over 40 years, CDDIS has provided continuous, long-term, public access to Global Navigation Satellite System (GNSS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) data and derived products required for a diverse variety of scientific studies, including the determination of a global terrestrial reference frame, and geodetic studies in plate tectonics, earthquake displacements, volcano monitoring, Earth orientation, and atmospheric angular momentum, among others. EOSDIS DAACs serve a diverse user community and are tasked to provide facilities that enable the discovery and access of science data and products. CDDIS is also a regular member of the International Council for Science (ICSU) World Data System (WDS, https://www.icsu-wds.org) and the Earth Science Information Partners (ESIP, https://www.esipfed.org).

CDDIS is funded by NASA but cooperates extensively with the international community in support of Earth science research. CDDIS serves as one of the primary data centers and core components for the geodetic services established under the International Association of Geodesy (IAG). In particular, the system has supported the International GNSS Service (IGS) as a global data center since 1992. CDDIS activities within the IGS during 2023 are summarized below. This report also includes any recent changes or enhancements made to CDDIS.

2 Archive Contents

As a global data center for the IGS, CDDIS is responsible for archiving and providing access to GNSS data from the global IGS network, as well as the products derived from the analyses of these data in support of both operational and working group/pilot project activities. CDDIS archive is approximately 77 TBytes in size (over 417 million files) of which nearly 90 % is devoted to GNSS data (52 TBytes) and GNSS products (7.1 TBytes). All these GNSS data and derived products are accessible through subdirectories at https://cddis.nasa.gov/archive/gnss.

CDDIS archive of IGS data and products are globally accessible through secure ftp (FTPS/FTP-SSL, address: ftp://gdc.cddis.eosdis.nasa.gov) and through web-based archive access (https://cddis.nasa.gov/archive). CDDIS is located at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and is available to users 24 hours per day, seven days per week.

2.1 GNSS Data

2.1.1 Main Data Archive

The user community has access to GNSS data and derived products available through the on-line global data center archives of the IGS. Nearly 50 operational and regional IGS data centers and station operators make data available in RINEX format to CDDIS from receivers on a daily, hourly, and sub-hourly basis. CDDIS also accesses the archives of other IGS global data centers (GDCs) to retrieve (or receive) data holdings not routinely transmitted to CDDIS by an operational or regional data center. However, this is not a formal mirroring of the other GDCs, and as such it is possible that GDCs are not in a one-for-one agreement on holdings. Table 1 summarizes the types of IGS GNSS data sets available at CDDIS in the operational, non-campaign directories of the GNSS archive.

The main GNSS data archive (https://cddis.nasa.gov/archive/gnss/data) at CDDIS contains GPS and GPS+GLONASS data in RINEX V2 format and multi-GNSS data in RINEX V3 format. Since January 2016, RINEX V3 data, using the V3 "long" filename specification, have been made available here along with the RINEX V2 data. The availability of RINEX V3 data into the operational, main archives at the IGS GDCs (and detailed in the "RINEX V3 Transition Plan") addressed a key recommendation from the IGS 2014 Workshop: "one network one archive" and provided for the better integration of multi-GNSS data into the entire IGS infrastructure. Starting in 2015, stations began submitting RINEX V3 data using the format's "long" filename specification. The transition plan specified that RINEX V3 data from IGS network sites using the V3 filename structure should be archived in the same directories as the RINEX V2 data. Therefore, starting on January 1, 2016, all daily, hourly, and high-rate data submitted to CDDIS in RINEX V3 format and using the long, V3 filename specification have been archived

Table 1: GNSS Data Type Summary

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

Table 2: GNSS Data Archive Summary for 2023

Data Type	Number of sites				Vol.	# files	Directory
	V2	V3	V2+V3	Unique			
Daily	281	438	160	558	1729 GB	1.3 M	`/gnss/data/daily`
Hourly	171	359	133	397	713 GB	14.6 M	`/gnss/data/hourly`
High-rate	118	307	109	316	20 TB	34.2 M	`/gnss/data/highrate`

in the same directories as the RINEX V2 data (which use the 8.3.Z filename for daily and hourly files and the 10.3.Z filename format for high-rate files). In addition, these RINEX V3 files are compressed in gzip (.gz) format; files in RINEX V2 format now use gzip (.gz) as of 1 December 2020. These data in RINEX V3 format include all available multi-GNSS signals (e.g., Galileo, QZSS, SBAS, BeiDou, and IRNSS) in addition to GPS and GLONASS. Figure **??** shows the network of IGS sites providing daily data in RINEX V2 and/or V3 formats.

CDDIS archives three major types/formats of GNSS data, daily, hourly, and high-rate sub-hourly, all in RINEX format, as described in Table 1. Nearly 235K daily station days from 558 distinct GNSS receivers were archived at CDDIS during 2023 of these sites, 160 sites supplied both RINEX V2 and V3 data (see Table 2). A complete list of daily, hourly, and high-rate sites archived in CDDIS can be found in the yearly summary reports at URL `https://cddis.nasa.gov/archive/reports/gnss`. All incoming files for CDDIS archive are now checked for conformance to basic rules, such as valid file type, non-empty file, correct compression usage, consistency between filename and contents, correct file naming convention usage, and other logic checks. After incoming files pass these initial checks, content metadata are extracted and the files undergo further processing based on data type and format.

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

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

2.1.2 RINEX V4 Data

In late 2021, the RINEX 4.00 format, which follows the V3 "long" filename specification, was officially accepted by the IGS Governing Board. The Infrastructure Committee developed a transition plan for the new format. More information on this transition plan is available in IGSMail 8207 sent in May 2022.

In mid-2022, CDDIS began receiving RINEX V4 daily files from the GFZ analysis center. In the future, we expect to receive daily files from additional sources along with hourly and high-rate sub-hourly data. In the testing phase, these data are archived in the directory structure `/gnss/data/campaign/rinex4/daily/YYYY`.

2.1.3 Broadcast Navigation Files

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

CDDIS also generates daily RINEX V3 concatenated broadcast ephemeris files. The files are archived in the yearly brdc subdirectory (https://cddis.nasa.gov/archive/gnss/data/daily/YYYY/brdc) with a filename of the form `BRDC00IGS_R_YYYYDDDHHMM_01D_MN.rnx.gz`. The procedure for generating these files, using the software provided by the chair of the IGS Infrastructure Committee, is similar to the V2 procedure in that site-specific, mixed V3 ephemeris data files are merged into to a single file that contains the orbit information for all GNSS satellites for the day. Users can thus download these single, daily (or hourly) files (in both RINEX V2 and V3 formats) to obtain unique navigation messages, rather than downloading multiple broadcast ephemeris files from the individual stations.

CDDIS also archives a merged, multi-GNSS broadcast ephemeris file containing GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS ephemerides. This file, generate by colleagues at the Technical University in Munich (TUM) and Deutsches Zentrum für Luft- und Raumfahrt (DLR) from real-time streams, contains all the unique broadcast navigation messages for the day. The file, named `BRDM00DLR_S_YYYYDDD0000_01D_MN.rnx.gz`, is stored in daily subdirectories within the archive (`/gnss/data//daily/YYYY/DDD/YYp`) and in a yearly top level subdirectory (`/gnss/data/daily/YYYY/brdc`). Creation of the merged GPS/QZSS LNAV and CNAV navigation file generated from real-time streams with the naming convention `BRDX00DLR_S_YYYYDDDHHMM_01D_MN.rnx.gz` ceased at the end of 2021. Archival of these files using the RINEX V2 naming convention which were stored in the MGEX campaign directories ended in the summer of 2020.

Beginning in 2022, the TUM/DLR team began providing to CDDIS a daily RINEX V4 broadcast ephemeris file. These files are archived in the yearly brdc subdirectory (https://cddis.nasa.gov/archive/gnss/data/daily/YYYY/brdc) with a filename of the form `BRD400DLR_S_YYYYDDHHMM_01D_MN.rnx.gz`.

2.1.4 Supporting Information

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

2.2 IGS Products

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

Table 3: GNSS Product Summary for 2023

Product Type	Number of ACs/AACs	Volume	Directory
Orbits, clocks, ERP positions	14+Combinations	3.9 GB/week	`/gnss/products/WWWW` (GPS, GPS+GLONASS) `/glonass/products/WWWW` (GLONASS only)
Troposphere	Combination	2.9 MB/day, 1 GB/year	`/gnss/products/troposphere/YYYY`
Ionosphere	7+Combination	15.2 MB/day, 5.6 GB/year	`/gnss/products/ionosphere/YYYY`
Real-time	Combinations	14.5 MB/week	`/gnss/products/rtpp/WWWW`
MGEX	6	86 MB/week	`/gnss/products/mgex/WWWW`

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

CDDIS also continues to archive combined troposphere estimates in directories by year and day of year. Global ionosphere maps of total electron content (TEC) from the IONosphere Map Exchange (IONEX) Associate Analysis Centers (AACs) are also archived in subdirectories by year and day of year. Real-time clock comparison products have been archived at CDDIS in support of the IGS Real-Time Pilot Project, and current IGS Real-Time Service, since 2009.

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

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

In late summer 2022, the IGS and the ACs began creating their GNSS products using the RINEX V3 file naming convention. From GPS week 2222 through GPS week 2237, these products were archived in the directory structure `/gnss/products/WWWW/igs20` for testing purposes. Starting with GPS week 2238 (November 27, 2022), CDDIS began archiving these files in the operational subdirectories (`/gnss/products/WWWW`). More information on this file name transition is available in IGSMail messages 8238 sent in July 2022 and

8274 sent in November 2022.

2.3 Real-Time Activities

CDDIS real-time caster has been operational since early 2015 in support of the IGS Real-Time Service (IGS RTS). By the end of 2022, CDDIS caster broadcasts 36 GNSS product and 375 data streams in real-time. The caster runs the NTRIP (Network Transport of RTCM via Internet Protocol) format. A full updated listing of all the streams CDDIS provides can be found at this URL - https://cddis.nasa.gov/Data_and_Derived_Products/Data_caster_streams.html.

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

CDDIS staff updated the caster to provide new 10-character mount point names for both data and derived product streams, as per direction of the IGS Real-Time Working Group (RTWG). The expanded mount point names align with the RINEX V3 naming convention utilized within the IGS to accommodate multi-constellation data. CDDIS caster configuration was also updated to relay data streams from upgraded hardware and improved BKG and Geoscience Australia casters. CDDIS staff also developed scripts to monitor and report GNSS data streams with unusually high mean latencies (greater than 10 seconds).

As stated previously, CDDIS utilizes the EOSDIS Earthdata Login, for authenticating file uploads to its incoming file server. Since the NTRIP-native registration/access software was not compatible with NASA policies, CDDIS developed software to interface the caster and the Earthdata Login within a generic Lightweight Directory Access Protocol (LDAP) framework. Access to CDDIS caster requires that new users complete two actions: 1) an Earthdata Login registration and 2) a CDDIS caster information form, providing the user's email, institution, and details on their planned use of the real-time data. Following completion, the information is submitted to CDDIS staff for the final steps to authorize access to CDDIS caster; this access is typically available to the user within 24 hours.

2.4 Supporting Information

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

Table 4: GNSS Data Retrieval Summary

Data Type	# of Files	Volume
Daily	191.0 M	143.3 TB
Highrate	260.2 M	80.6 TB
Hourly	608.6 M	29.2 TB
Products	160.8 M	21.7 GB

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

3 System Usage

Summarizing the retrieval of GNSS data and products from the online archive in 2023, Table 4 illustrates the number and volume of GNSS files retrieved by the user community during the past year, categorized by type (daily, hourly, high-rate, products). Over 1.5 billion files (over 350 TBytes) were transferred in 2023.

4 Recent Developments

4.1 Updates to Archive Access

CDDIS has a large international user community; over 22K unique hosts accessed the GNSS files in the system in 2023. Today, users access CDDIS archive through encrypted anonymous ftp and https. On 1 November 2020, unencrypted anonymous ftp was terminated at CDDIS as per US government regulations.

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

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

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

Examples on using these protocols, including help with the cURL and Wget commands, are available on CDDIS website; users are encouraged to consult the available documentation at: https://cddis.nasa.gov/About/CDDIS_File_Download_Documentation.html and examples documentation at: https://cddis.nasa.gov/Data_and_Derived_Products/CDDIS_Archive_Access.html. Various presentations on these updates to CDDIS archive access are also available (see Section 6 below and https://cddis.nasa.gov/Publications/Presentations.html).

4.2 Metadata Improvements

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

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

4.3 High-rate Archive Modifications

CDDIS staff put forward a recommendation at the 2018 IGS Workshop to consolidate the sub-hourly high-rate data files into a tar archive, one file per site per day. At this time, each site supplies up to 96 files per day; the bundling of the files into a single daily site-specific tar file simplifies downloads for the user as well as streamlines the directory structure at the data centers. In mid-2022, CDDIS enacted these modifications to the high-rate data archive starting with 2001 and working toward the present; the data from the past 6 months will remain in the standard, submitted 15-minute file format.

4.4 Repro3 Support

CDDIS provided support through the upload of files from the ACs and online archive of the IGS repro1 and repro2 campaigns (`/gnss/products/WWWW/repro[1,2]` and `/gnss/products/repro[1,2]/WWWW`). As such, repro3 will be archived similarly. Acceptance of repro3 data up through the end of 2021 concluded in late 2022.

5 Future Plans

5.1 RINEX V3 Data

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

5.2 Real-Time Activities

CDDIS will continue to add real-time data and product streams to its operational caster in support of the IGS RTS. CDDIS continues to review the implementation of software to capture real-time streams for generation of 15-minute high-rate files for archive. This capability requires further testing and coordination with the IGS Infrastructure Committee. CDDIS staff is also performing extensive testing to ensure the newest BKG Professional Caster configuration offers optimal performance given increasing volumes of new NTRIP caster user accounts (248 new user requests in 2023, an increase of 40% from 2022, the most requests CDDIS has had in a single year).

CDDIS staff members continue to investigate the use of DLR's ntripchecker software for updating the caster source table in real-time, maintaining stream record consistency among

CDDIS and regional casters.

6 Publications

CDDIS staff attended the 2023 Fall American Geophysical Union (AGU) meeting and presented the following:

J. Woo, B. P. Michael. The Crustal Dynamics Data Information System (CDDIS) – Updates and Future Developments, presented at the *2023 Fall AGU meeting*, San Francisco, CA, USA, December 2023.

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

7 Contact Information

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

Rivers Lamb, Email: Rivers.Lamb@nasa.gov
Manager (Interim), CDDIS

Ross Bagwell, Email: Ross.Bagwell@nasa.gov
Deputy Manager, CDDIS

web: https://cddis.nasa.gov
Code 61A
NASA GSFC
Greenbelt, MD 20771
Phone: (301) 614-5370
Fax: (301) 614-6015

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

8 Acknowledgments

Funding for CDDIS, and its support of the IAG, IGS, and other services, is provided by NASA through the Earth Science Data and Information System (ESDIS) project, which manages the EOSDIS science systems and DAACs. The authors would like to acknowledge the entire CDDIS staff. The success of CDDIS and its recognition in the many international

programs supported by the system can be directly attributed to the continued dedicated, consistent, professional, and timely support of its staff.

9 Additional Resources

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

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

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

GSSC Global Data Center Technical Report 2023

V. Navarro, J. Ventura-Traveset

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

1 Introduction

The GNSS Science Support Centre (GSSC[1]) is the GNSS Science Exploitation Platform provided by ESA's Navigation Science Office to consolidate a GNSS data preservation and exploitation environment in support of IGS and the overall GNSS scientific community.

As an IGS Global Data Center (GDC), the GSSC contributes to GNSS data storage and dissemination, and collaborates with other GDCs such as CDDIS to make IGS data and products available in a free, worldwide manner.

2 GSSC Overview

The GSSC hosts ESA's innovative Digital Platform for GNSS, GSSC Now[2] (see Figure 1), which integrates a large GNSS repository with cutting-edge features for data exploration and analysis. GSSC Now currently runs as a public beta version.

Whereas the original IGS GDC repository still lies at the heart of the GSSC, the content has been expanded to include datasets from supplementary ground networks, relevant scientific services, GNSS receivers on-board spacecrafts and ESA experiments. Public data and products in GSSC archive can be accessed through a traditional approach via anonymous SFTP and HTTPS[3]; nevertheless, the GSSC Now provides powerful features to navigate and refine searches through its vast array of GNSS Datasets[4].

Furthermore, GSSC Now Datalabs[5] (see Figure 2) provide web-based access to on-demand

[1] https://gssc.esa.int/
[2] https://gssc.esa.int/portal/
[3] https://gssc.esa.int/activities/ftp-and-web-access-to-gnss-repository/
[4] https://gssc.esa.int/portal/datasets
[5] https://gssc.esa.int/portal/datalabs

data analysis and visualisation tools, referred as Datalabs. A Datalab is a software component available for execution on GSSC Now's cloud infrastructure from the user's web browser. Beyond applications natively designed to run on a browser, GSSC Now Datalabs offer the possibility to containerise desktop-based applications as web-based ones. This capability, for example, enables the expansion of GSSC Now Datalabs catalogue with legacy data processing systems, ensuring their long-term preservation.

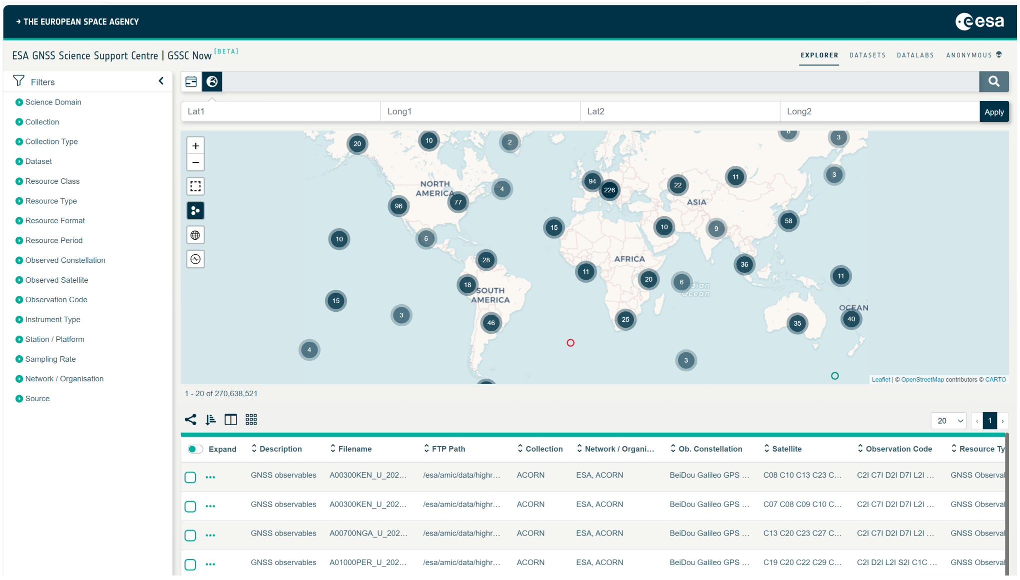


Figure 1: GSSC Now

During 2023, GSSC expanded its archive and more than 270 million of GNSS data and products are now stored and publicly available to the scientific community through GSSC Now.

As shown in Figures 3 and 4, the number of accesses to the IGS GDC hosted at GSSC, as well as the download volumes of IGS data and products, keeps growing steadily.

Apart from the extension of GSSC archive, in 2023 the GSSC also achieved the following objectives:

- **New GSSC Datasets**
  GSSC Now stores data from the following projects:
  - AMIC project, an ESA's TEC-EFW funded activity led by Rokubun which aims to densify areas with a lack of GNSS receivers by means of an Affordable Continuously Operating Reference Network (ACORN).
  - MONITOR project, which collected GNSS data during the peak of solar cycle 24 to assess GNSS behavior during periods of high solar activity.
- **New GSSC Datalabs**

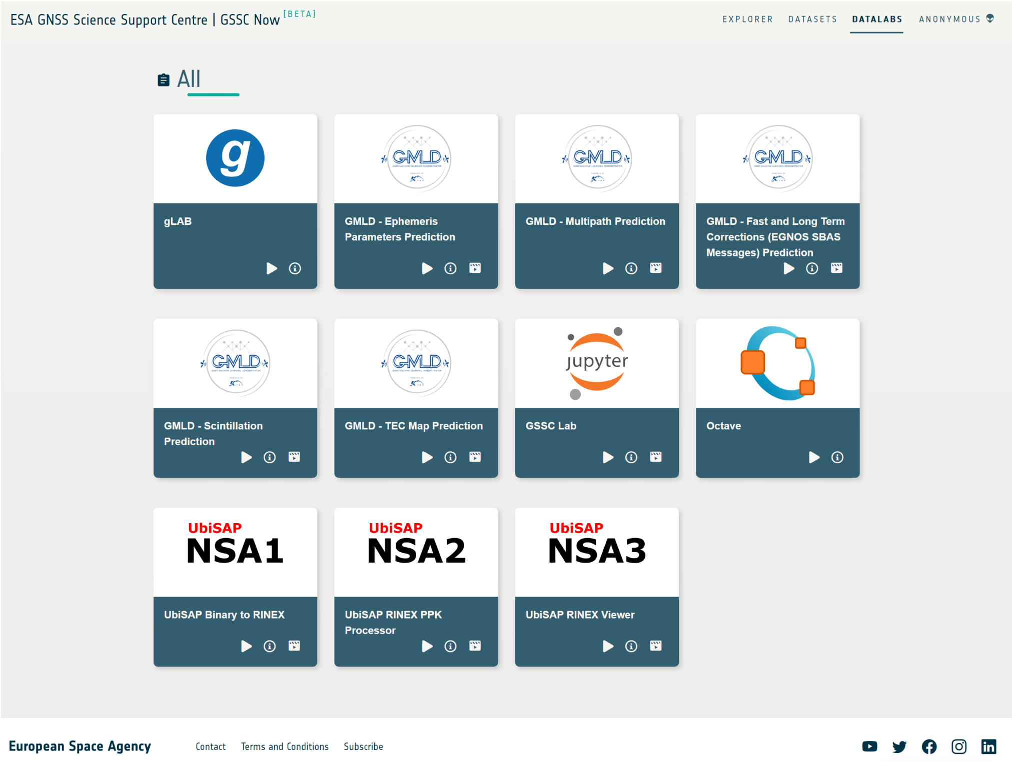
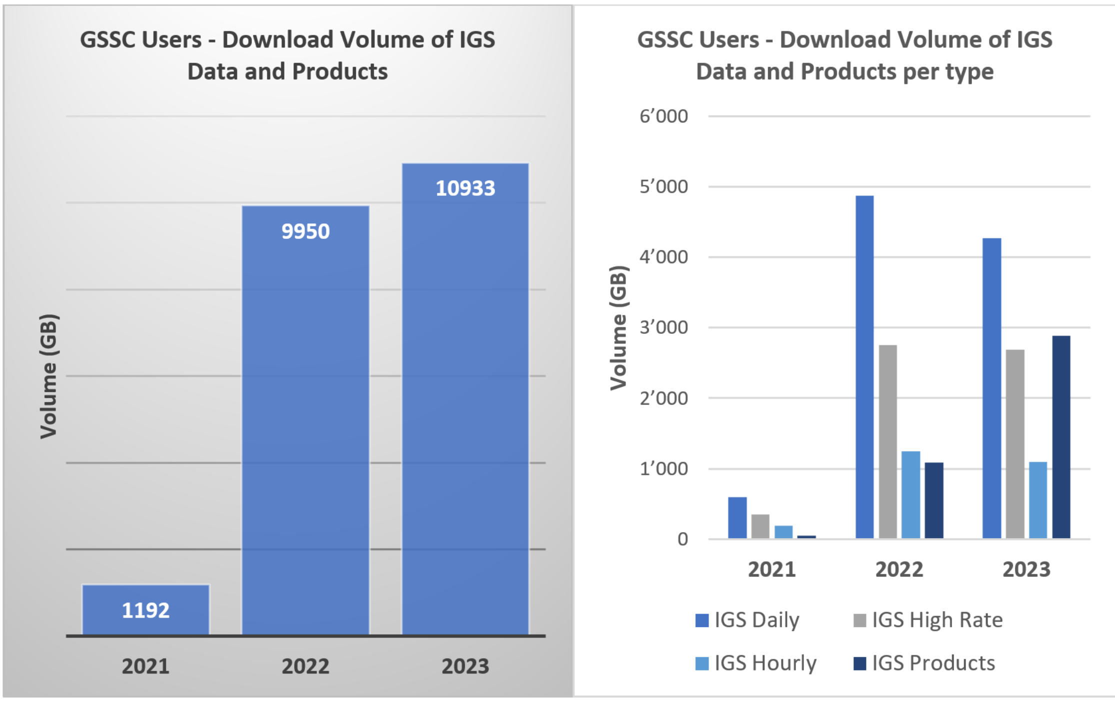


Figure 2: GSSC Datalabs

  - CAMALIOT Datalabs enable the characterization of the ionosphere and troposphere using raw GNSS data from smartphones by means of **machine learning** technology; datalabs are "Camaliot Ionosphere Prediction", "Spatial Interpolation of VTEC" and "Spatial Interpolation of ZWD".
  - GMLD datalabs use **machine learning** techniques to improve GNSS navigation message performance; datalabs are "SGMLD – Ephemeris Parameters Prediction", "SGMLD – Fast and Long-Term Corrections (EGNOS SBAS Messages) Prediction", "SGMLD – Scintillation Prediction" and "SGMLD – Multipath Prediction".

- **Redesigned GSSC Home**
  - Sleek design: the new portal brings a contemporary, user-friendly interface in line with ESA's corporate identity.
  - Enhanced accessibility of GNSS discovery and analysis services: a "Continue Working" section for a streamlined user experience, integrated video tutorial for each datalab, enhanced startup process for datalabs.
  - A friendlier, more responsive site that is easier to browse using mobile devices.
- **Enhanced filtering experience and readability**



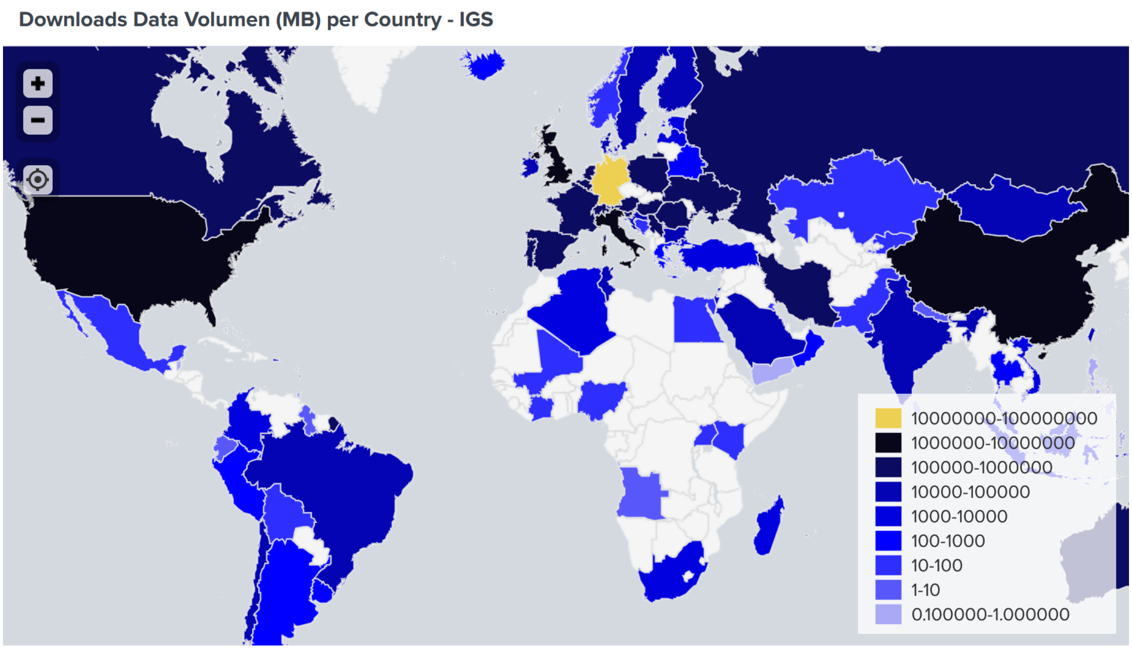


Figure 3: Downloads Data Volume (MB) per Country - IGS

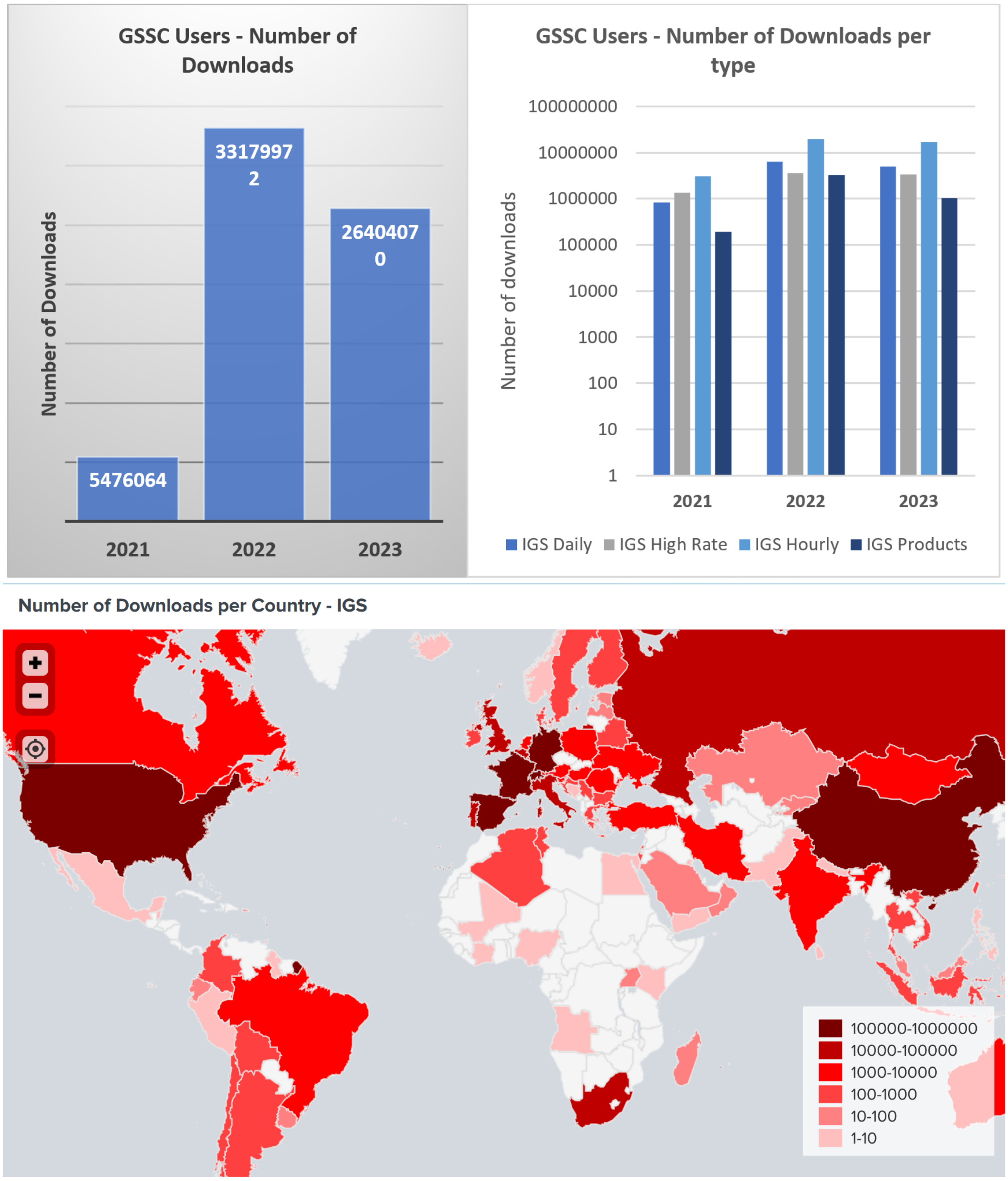


Figure 4: Number of Downloads per Country - IGS

  - A new feature to facilitate the discovery of Daily, Hourly and High-rate data.
  - Search functionality for GPS week and Day-Of-Year in Date Picker.
  - Enabled vertical scroll within the filter section in Explorer.
  - Improved Science Domains in Explorer.
  - Introduced station groupings on the world map to facilitate easier navigation.
  - Improved the zoom-out capability on the world map for easier station selection in Explorer.

- GSSC Now **performance optimizations, bug fixes, enhanced security, stability** and **accessibility**.
- GSSC Now **Users Survey** 2023.
- **DOI** minting process initiated by GSSC (e.g. DOI for GSSC public GREAT dataset[6])
- First GSSC Now Webinar: Exploring ESA's Navigation Digital Platform[7]
- Release of **scientific paper on GSSC Now**:
  - "Navarro, V., del Rio, S., Millán, M. del M., Messina, A., Ventura-Traveset, J. (2024). GSSC Now: ESA Thematic exploitation platform for navigation digital transformation. Enhancing GNSS scientific research. Advances in Space Research. https://doi.org/10.1016/j.asr.2024.02.016"

3 Planned 2024 Activities

Planned 2024 activities will include:

- Adaptive and evolutionary maintenance in line with IGS requirements.
- GSSC Now evolution in support to GENESIS FutureNAV's mission.
- Upgrade of SW and HW infrastructure to support an increased number of GSSC Now users.

[6] Further information on GSSC DOI for GREAT public dataset can be found in https://gssc.esa.int/news/gssc-starts-the-use-of-dois-to-identify-its-assets/

[7] Recordings and presentations can be accessed in https://gssc.esa.int/webftp/main.html?download&weblink=846f9fbfdb275351a611f1a7d6b537a9

Wuhan University Data Center Technical Report 2023

Q. Zhao[1], M. Li[1]

[1] GNSS Research Center, Wuhan University, Wuhan, China
E–mail: zhaoql@whu.edu.cn

1 Introduction

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

The activities of WHU DC within the IGS during 2023 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/).

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

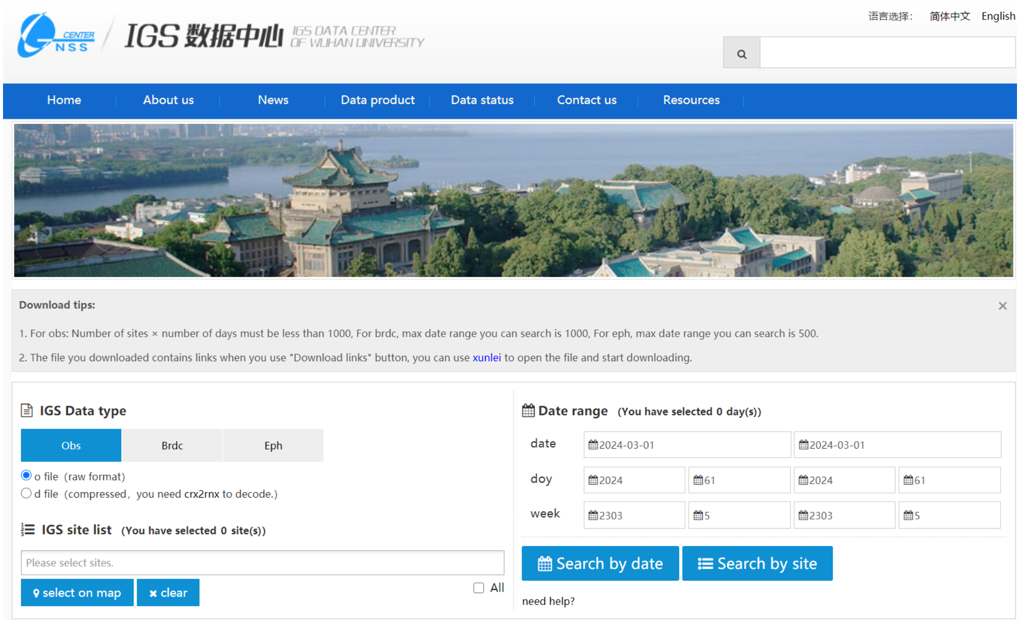


Figure 1: A snapshot of the website of WHU data center for data and products provision.

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.

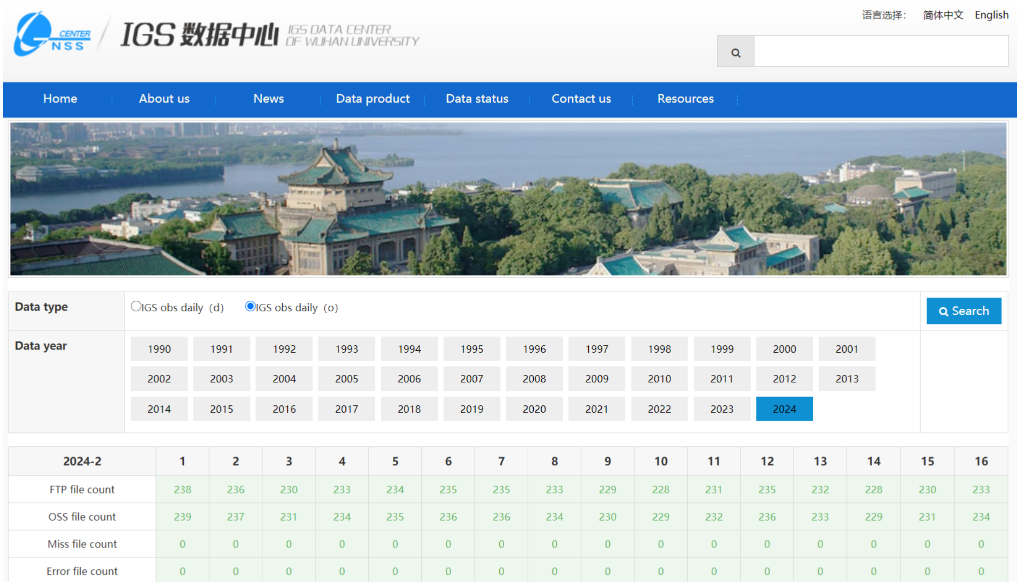


Figure 2: Data and products monitoring of WHU data center.

BKG Regional Data Center Technical Report 2023

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

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

1 Introduction

Since more than 25 years BKG is contributing to the IGS data center infrastructure operating a regional GNSS Data Center (GDC). BKG's GDC is also serving as a data center for the regional infrastructure of EUREF as well as for national infrastructure or for specific projects. Two types of data are handled in the GDC: file-based (Section 2) and real-time (Section 3) data. Since 2004, BKG is operating various entities for the global, regional and national real-time GNSS infrastructure. The development of the basic real-time components has been done independently from the existing file-based data center. The techniques behind, the user access etc. were completely different from the existing file-based structure. Moreover, operation of a real-time GNSS service demands a much higher level of monitoring than it is necessary in the post-processing world, where for example RINEX files can be reprocessed the next day in case of an error. 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), RINEX v3 (Rx3), and RINEX v4 (Rx4), daily, hourly and high-rate data of approximately 958 (with national stations 1335) 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.

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

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

20.9 million files are stored in the GDC at the end of 2023, with an overall archive size of 25.0 TB. We are facing with approx. 80.000 uploads and 700.000 downloads per day. There was no noteworthy difference in the number of downloaded files with respect to 2022. Approximately 1000 different users did visit the GDC websites per day.

2.6 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.

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. Similarly to 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.

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 2023):

- On the IGS caster (`http://igs-ip.net`) approx. 345 data streams in `RTCM3.0/1/2/3` format are provided. The majority is in 3.2/3.3 Multiple Signal Message (MSM) format. Moreover, most of the 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 (BOR100POL0, DAEJ00KOR0). All streams are provided with long mount-point names.
- On the EUREF caster (`http://euref-ip.net`) approx. 250 data streams in `RTCM3.`

0/1/2/3 format provided. There are still four streams available in the old RTCM 2.3 format (BOR100POL0, ROVE00ITA0, UNPG00ITA0, UNTR00ITA0).

- On the PRODUCTS caster (http://products.igs-ip.net) approx. 100 data streams in RTCM3.0/1/2 format as well as in the IGS-SSR format, provided from various organizations. Most of these streams are containing satellite clock & orbit corrections. Some of them are providing in addition Observable-specific Signal Biases (OSB) as well as VTEC information. Furthermore, there is a low number of product data streams containing ionosphere information only, and two product streams containing OSB information only. To provide real-time access to broadcast ephemeris, there are various streams available, which carry only ephemerides data sets. Therefore, incoming ephemerides are checked for errors and inconsistencies and then merged, encoded and uploaded to NTRIP broadcasters with a high repetition rate.
- There is still the old MGEX caster (http://mgex.igs-ip.net) running with real-time data of approx. 55 streams provided, mostly received in raw data format. Seven ephemeris data streams are generated with EuroNet software from raw data streams: one multi-GNSS and one each exclusively for BeiDou, Galileo, GLONASS, GPS, QZSS, and SBAS.

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.

The IGS RTS provides access to real-time precise products such as orbits, clocks, code and phase biases, which can be used as a substitute for ultra-rapid products in real-time applications. The true performance of these products can be monitored by the daily statistics derived from the comparison with IGS rapid products. The current RTS product monitoring is based on comparisons performed by the RTACC at BKG. In order to satisfy high demands on availability and reliability, the RTACC also provides two combined multi-GNSS product data streams: SSRA02IGS/SSRC02IGS (GPS, GLONASS, Galileo) and SSRA03IGS/SSRC03IGS (GPS, GLONASS, Galileo, BeiDou). As part of the Center for Orbit Determination in Europe (CODE) BKG has access to high resolution CODE rapid products, which can be processed to perform such comparisons. Hence, the IGS Analysis

Center CODE rapid products for GPS, Galileo and GLONASS with a time resolution of 30 seconds are used for monitoring and comparison purposes. Several monitoring results are delivered for the official RTS Web page https://igs.org/rts/monitoring/.

An indirect verification of the individual RT AC results as well as of the combination results is performed by their application to various precise point positioning strategies in real-time (https://igs.bkg.bund.de/ntrip/ppp).This is done e.g. using the GPS+GLONASS+Galileo+BDS observations of our GREF station FFMJ01DEU but with IGS stations as well.

3.5 Usage Statistics

While there is still 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, when starting with the registration on an operational basis, the request for registration for BKG' casters has been stable on a high level of more than 600 requests per year but increasing since the last years to more than 900 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 6000 from approx. 200 different users during a typical day. The data volume sent to the users is roughly 20 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 2023.

References

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

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

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

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

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

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

Part IV

Committees, Pilot Projects

Antenna Committee Technical Report 2023

A. Villiger

Swiss Federal Office of Topography (swisstopo)
Seftigenstrasse 264, CH3084 Wabern, Switzerland
E-mail: arturo.villiger@swisstopo.ch

1 Introduction

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

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

2 Updates and content of the antenna phase center model

Table 1 lists all updates of the `igs20_wwww.atx` in 2023. 15 new antenna/radom combinations have been added.

Table 1: Updates of the phase center model `igs20_wwww.atx` in 2023 (`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
2290	30. Nov 2023	`Added JAVRINGANT_DMT NONE`
		`JAVRINGANT_DMT SCIS`
		`TWI3972XF_CONE NONE`
2287	08. Nov 2023	`Added R803 (R26)`
		`Decommission date R801 (R26)`
		`Added LEIICG160 NONE`
2283	13. Oct 2023	`Added EML_REACH_RS3 NONE`
		`JAVTRIUMPH_1MPR NONE`
		`TPSHIPER0_CR NONE`
2280	19. Sep 2023	`Added I009 (I09) and I010 (I10)`
		`Added JAVGRANT_3L+GP JVSD`
		`JAVGRANT_3L NONE`
		`JAVGRANT_G5TLBI NONE`
		`JAVTRIUMPH_3NRA NONE`
2274	11. Aug 2023	`Added G044 (G22)`
		`Decommission date G041 (G22)`
2272	25. Jul 2023	`Added C231 (C62)`
		`Added TRMR580 NONE`
2270	14. Jul 2023	`Added STXSA1100 STXM`
		`TRM159900.00 SCIT`
		`TRMDA2 NONE`
2247	01. Feb 2023	`Added G079 (G28)`
		`Decommission date G049 (G28)`

3 Calibration status of the IGS network

Table 2 shows the percentage of IGS tracking stations with respect to certain calibration types. For this analysis, 513 IGS stations as contained in the file `logsum.txt` (available at `https://files.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 2023. The overall situation regarding the stations with state-of-the-art robot- and chamber-based calibrations is similar to the one from 2023. 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 94.7%.

The IGS20 is based on three GNSS systems (GPS, GLONASS, Galileo) while the prede-

Table 2: Calibration status of 5133 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%
JAN 2024	**igs20.atx:**	**94.7%**	**1.0%**	**4.3%**

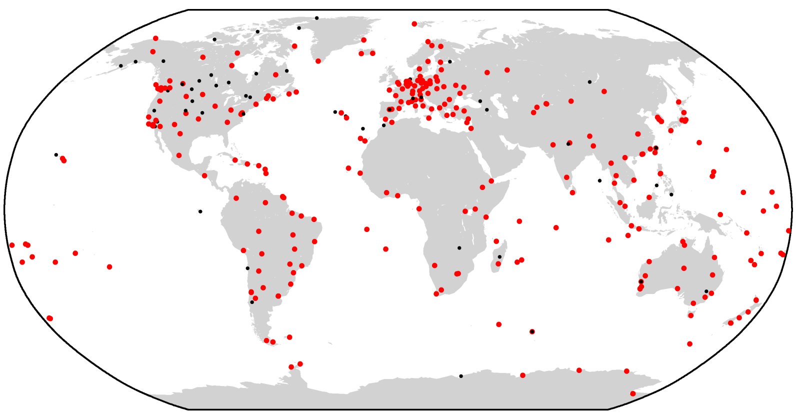


Figure 1: IGS stations tracking Galileo. Red dots: antennas with Galileo calibrations; Black dots: antennas without Galileo calibrations.

cessor 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 513 sites with antennas for which multi-GNSS calibrations are available. 384 IGS sites are currently tracking Galileo out of which 83% 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.

Bias and Calibration Committee Technical Report 2023

S. Schaer

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

1 Introduction

The IGS Bias and Calibration Committee 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 Bias and Calibration Committee (formerly Working Group, shortly 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 2023

- 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.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.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

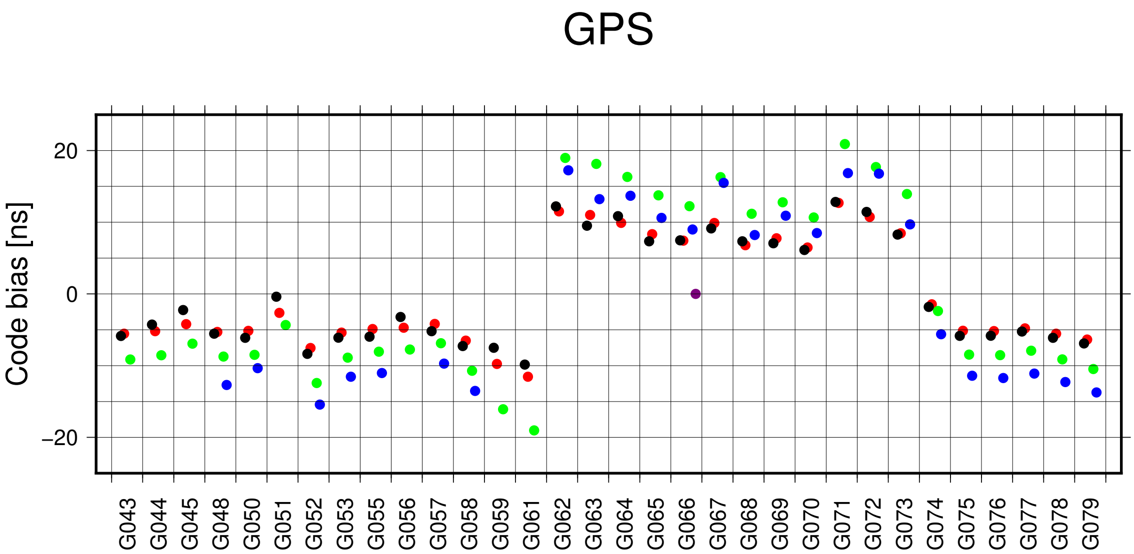


Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2024. Note that G043–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations and G074–G079 corresponds to Block IIIA. Legend: C1C (black), C1W (red), C2W (green), C2L/C2S (blue).

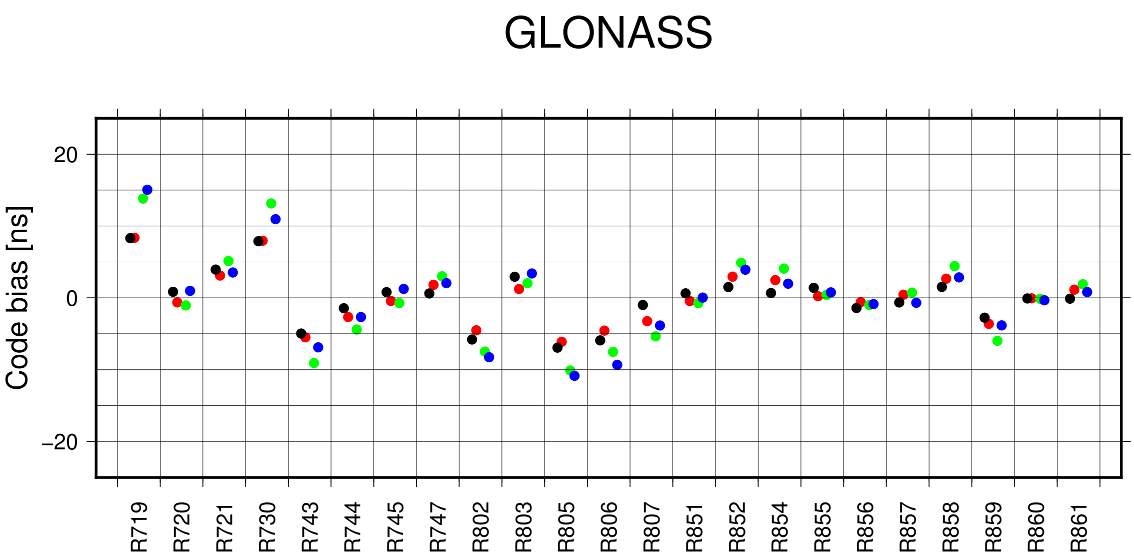


Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2024. Note that R719–R747 and R851–R861 correspond to GLONASS-M; R802 and R805–R807 correspond to GLONASS-K1 satellite generations; R803 represents the first GLONASS-K2 satellite. Legend: C1C (black), C1P (red), C2P (green), C2C (blue).

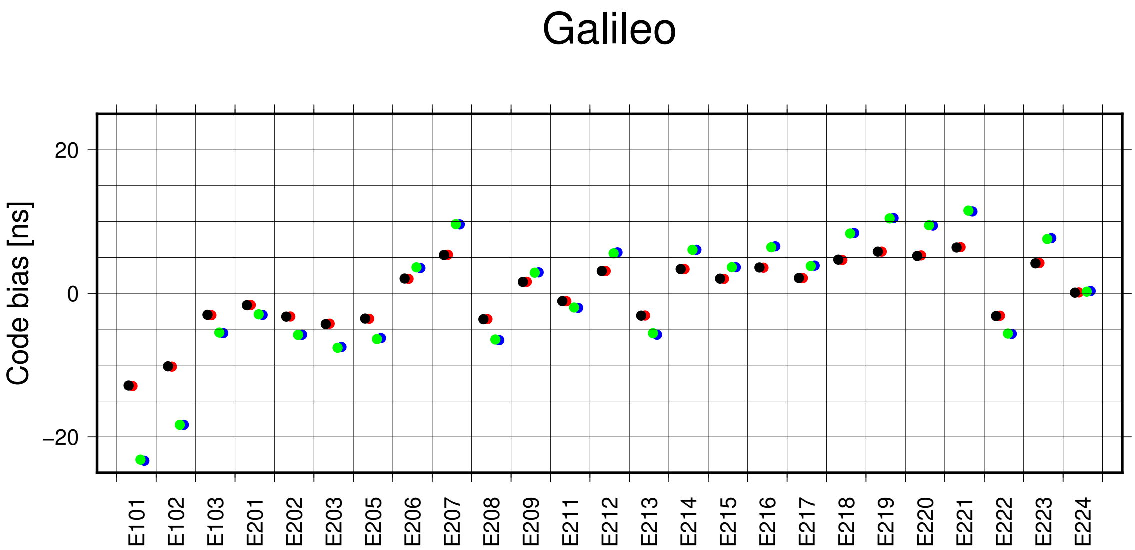


Figure 3: Observable-specific code bias (OSB) estimates for Galileo code observable types (using the RINEX3 nomenclature) and Galileo SV numbers, computed at CODE, for January 2024. Legend: C1X (black), C1C (red), C5Q (green), C5X (blue).

regard to the GPS satellit constellation, now covering all sampled code signals of L1 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 (and expanded to RINEX4). 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/y2023/odata2_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata2_d335_sat.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata3_gnss_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata3_gps_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata3_glonass_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata3_galileo_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata3_beidou_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/odata3_qzss_d335.txt
http://ftp.aiub.unibe.ch/igsdata/y2023/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, G28/G079). 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 CODE's Main Bias Product Files

It is strongly advised to consider bias files of the following list:
http://ftp.aiub.unibe.ch/CODE/CODE.BIA
http://ftp.aiub.unibe.ch/CODE/CODE_MONTHLY.BIA
https://cddis.nasa.gov/archive/gnss/products/bias/code.bia
https://cddis.nasa.gov/archive/gnss/products/bias/code_monthly.bia
These are in Bias-SINEX format, contain OSB values, labeled with RINEX3 observation codes, and time windows for validity. The first bias file contains values averaged over the

last 30 days; the second file contains a time series of monthly averages. It is extremely important that this bias product line is consistent with the corrections addressed in Section 4. Although OSB values are provided here, these may and should of course also be used for differential (DCB) applications. Any differentiation is permitted, for intra-frequency as well as inter-frequency observation combinations.

The use of existing DCB product files should be avoided. The end of production is foreseeable for corresponding product lines, such as:
http://ftp.aiub.unibe.ch/CODE/P1C1.DCB
http://ftp.aiub.unibe.ch/CODE/P1P2.DCB
http://ftp.aiub.unibe.ch/CODE/CODE.DCB
It must be clearly stated that these old bias products do not contain the correction required in Section 4. The influence of this particular correction is undone (effectively back-corrected), also to avoid problems for old application areas. This specifically applies to the P1P2.DCB output (also included in CODE.DCB).

6 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

References

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

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

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

Schaer, S. (2023): Bias and Calibration Working Group Technical Report 2022. In: R. Dach and E. Brockmann (eds.) (2023): *International GNSS Service Technical Report*

2022 (IGS Annual Report). IGS Central Bureau and University of Bern; Bern Open Publishing; DOI 10.48350/179297; pp. 167–173.

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

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

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

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

GNSS Monitoring Pilot Project Technical Report 2023

E. Schönemann

Navigation Support Office at ESA/ESOC
Robert-Bosch-Str. 5
64293 Darmstadt, Germany
erik.schoenemann@esa.int, +49 (0) 6151 90 2653

1 Introduction

The International Committee on GNSS (ICG) established the International GNSS Monitoring and Assessment (IGMA) Task Force at the ICG-6 meeting in Tokyo in 2011, tasked to facilitate cooperation and information between providers and scientific organizations that engage in open service signal quality monitoring. The International GNSS Service (IGS) is coordinating the operation of a global multi-GNSS network and is playing a key role in generating precise GNSS products since its inception in 1994.

The ICG recommended at the ICG-10 meeting in Boulder in 2015 that the IGMA Task Force and the IGS initiate a joint Trial Project to demonstrate a global GNSS Monitoring and Assessment capability, utilising existing resources and infrastructure and avoiding duplication. Participation from non-IGS analysis groups, networks, and data centres is invited to develop benchmarking between groups and to generate analysis products, cross-sharing between existing IGS functional streams and IGMA activities. Initially, it is proposed to initiate the activity with the monitoring of a limited number of parameters to demonstrate the service and exercise it operationally. This will be followed by a broader set of parameters to be monitored as the system approaches permanent operations.

The IGS Monitoring Working Group has been established to install, operate, and further develop the GNSS Monitoring and Assessment Trial Project jointly with ICG's IGMA Task Force, considering the Terms of Reference of the IGMA Task Force for the IGMA-IGS Joint Trial Project, utilizing existing resources and infrastructure, and creating publicly available, useful data products.

2 Membership

A second Call for Participation will be released in the beginning of 2024 to enlist the participants of the new IGS Monitoring Pilot Project and to solicit the participation of new institutions.

3 Summary of Activities in 2023

During the 64th IGS Governing Board Meeting, it was decided to restart the activities of the former IGS Monitoring Working Group in the form of a new Pilot Project called the IGS Monitoring Pilot Project.

In the following months a review of the ICG IGMA ToR has been performed.

In the 65^{th} IGS Governing Board Meeting, the IGS GB endorsed the updated ICG IGMA ToR and agreed to issue a second Call for Participation in the IGS Monitoring Pilot Project.

4 Planned 2024 Activities

The second Call for Participation in the IGS Monitoring Pilot Project is scheduled for the beginning of 2024.

Following the consolidation of the IGS Monitoring Pilot Project Members, it is planned to review the IGS Monitoring Pilot Project Charter and start implementing the Pilot Project.

The working group chair will represent the IGS Monitoring Pilot Project in the ICG IGMA.

Ionosphere Committee Technical Report 2023

A. Krankowski[1,*], L. Zishen[2] M. Hernández-Pajares[3], A. Froń[1], K. Kotulak[1], P. Flisek[1]

1 Space Radio-Diagnostics Research Centre
University of Warmia and Mazury in Olsztyn, Poland (SRRC/UWM)
2 Aerospace Information Research Institute,
Chinese Academy of Sciences (AIR/CAS), Beijing, China
3 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. Haixia Lyu (Wuhan University)
21. Léo Martire (JPL)
22. Angelyn Moore (JPL)
23. Raul Orus (ESTEC)
24. Michiel Otten, PosiTim (SA/ESOC)
25. Ola Ovstedal (UMB)
26. Vergados Panagiotis (JPL)
27. Ignacio Romero, CSC (ESA/ESOC)
28. Stefan Schaer (CODE)
29. Michael Schmidt (DGFI-TUM)
30. Tim Springer, PosiTim (ESA/ESOC)
31. David R. Themens (University of Birmingham)
32. M. Sithartha Muthu Vijayan (CSIR 4PI)
33. Ningbo Wang (CAS)
34. Rene Warnant (ULiège)
35. Robert Weber (TU Wien)
36. Pawel Wielgosz (UWM)
37. Brian Wilson (JPL)
38. Junchen Xue (CAS)
39. Yunbin Yuan (CAS)
40. Qile Zhao (WHU)

Zishen Li (CAS) has been elected for a vice-chair of the group for 2024-2027. Haixia Lyu (Wuhan University), Junchen Xue (CAS) and M. Sithartha Muthu Vijayan (CSIR 4PI) were introduced as new members introduced at the end of 2023 after acceptance by the IGS IONO WG members.

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 Draft version of the IGS real-time ionospheric services are available.

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.

The draft Real-Time combined product based on the four IAACs (prepared in cooperation with the Real-Time IGS WG) is also provided.

All information about validation, evaluation and combination of the products can be found at the Ionosphere Working Group webpage (see section 6 of this document).

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.

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.

5.3 Ionospheric products are available through CDDIS

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

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

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

together with their previous short names and new long names.

6 Ionosphere Working Group webpage

An IGS Iono Working Group webpage established at University of Warmia and Mazury in Olsztyn, Poland server allows 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.

Webpage can be found at: igsiono.uwm.edu.pl

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.

7 Advancements in IGS Iono WG and IRI Collaboration: Real-Time VTEC Maps for Enhanced Ionospheric Monitoring

In the past year, significant strides have been made in the collaboration between the IGS Ionosphere Working Group (IGS Iono WG) and the International Reference Ionosphere (IRI) group, particularly in the implementation of real-time Vertical Total Electron Content (VTEC) maps for the Ionospheric Real-Time Assimilative Mapping (IRTAM) and the Global Assimilative Model of Bottomside Ionosphere (GAMBIT). This collaborative effort, led by the University of Warmia and Mazury (UWM), Universitat Politècnica de Catalunya (UPC) and the Chinese Academy of Sciences (CAS), has resulted in substantial advancements in the use of GNSS-derived ionospheric observations in assimilative ionospheric models.

The integration of real-time VTEC maps into the IRTAM and GAMBIT systems, facilitated by the ARTEMIS service, which is a result of a joint project between the University of Warmia and Mazury in Olsztyn, Poland (UWM) and Chinese Academy of Sciences (CAS), has significantly advanced the capacity for accurate and timely ionospheric monitoring. This achievement has been instrumental in generating real-time VTEC maps tailored to meet the specific requirements of the IRI model.

The cooperation between IGS Iono WG and IRI lays a robust foundation for future advancements in ionospheric science. As we move forward, these goals not only promise to enhance our understanding and monitoring of the ionosphere but also to improve the resilience of global navigation, communication, and observation systems against the changes of space weather. The incorporation of real-time GNSS-derived TEC data in order to improve the representation of the ionosphere within the IRI model has been demonstrated in doctoral dissertation of Adam Froń, defended at UWM in November 2023. Fig. 1 represents the comparison of climate VTEC maps with IRI-derived NmF2.

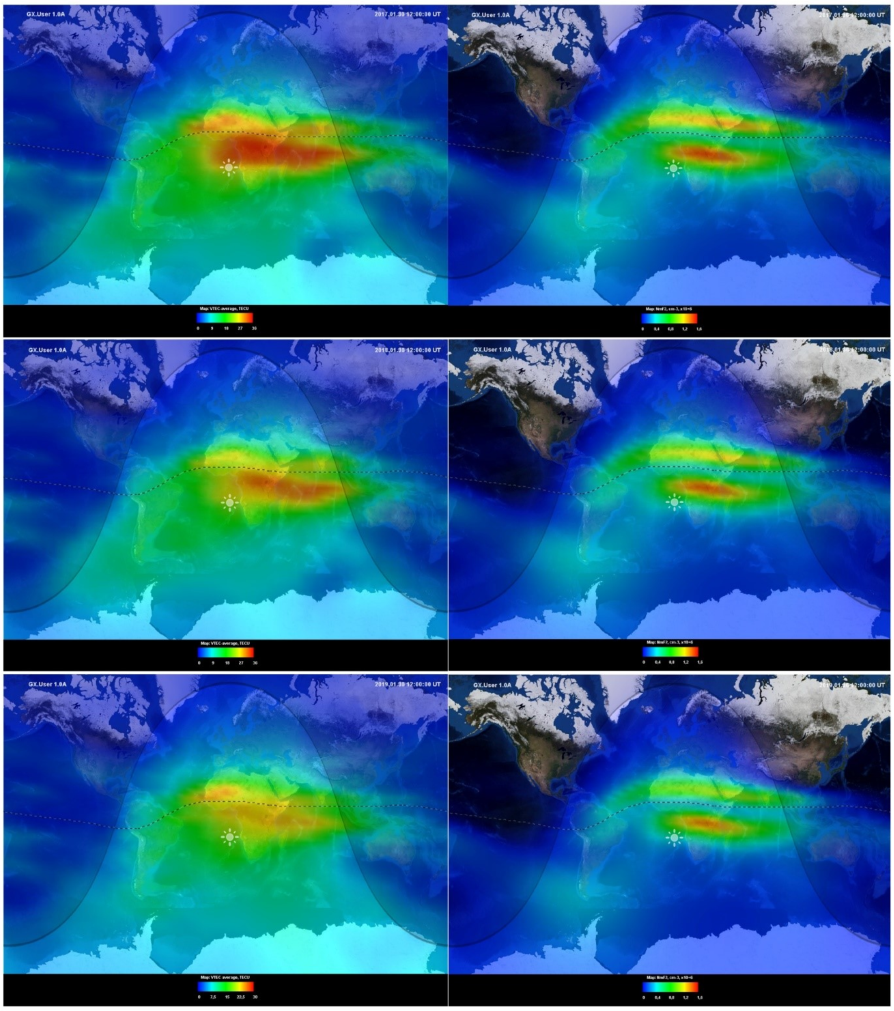


Figure 1: Comparison of the GMBT climate product (left column) with NmF2 values calculated using the IRI model (right column) in the GAMBIT Explorer window. The next rows show 12:00 UT on January 30 in 2017, 2018 and 2019, respectively.

Multi-GNSS Pilot Project Technical Report 2023

P. Steigenberger, O. Montenbruck

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

1 Introduction

In 2023, the IGS made further steps towards a full coverage of all GNSS in the IGS products: two MGEX ACs included additional constellations in their MGEX products. The Combination Task Force continued the development of a combined orbit and clock product, and with the latest generations of NavIC and GLONASS satellites, additional GNSS signals are on the air.

2 GNSS Evolution

Table 1 lists the GNSS satellite launches of the year 2023. GPS continued its modernization with the launch of the sixth GPS III satellite which was set healthy and available for use on February 16, 2023. China launched the fourth geostationary satellite of the BeiDou-3 system in May 2023. However, this satellite is not yet part of the operational constellation and still has the status *testing* as of early 2024. The latter is also true for the third BeiDou-3 GEO launched in June 2020. After a break of four years, a pair of BeiDou-3 MEO satellites transmitting as PRN C48 and C50 was launched at the end of 2023.

The first GLONASS K2 satellite was launched in August 2023 and started signal transmission on September 8, 2023 (IGS-ACS-MAIL #1599). In addition to the legacy L1 and L2 frequency division multiple access (FDMA) signals transmitted by all GLONASS satellites and the L3 code division multiple access (CDMA) signals of GLONASS M+ and K1 satellites, K2 adds CDMA signals in the L1 and L2 frequency band. As of early 2024, none of the IGS stations supports tracking of the new CDMA signals. Phase center offsets for the ionosphere-free linear combination of L1 and L2 FDMA signals by CODE, DLR and ESA have been added to the IGS antenna model in November 2023. A draft for the inclusion of L1OCd and L3OCd navigation messages in the RINEX 4.x navigation file format was prepared by the MGWG and is currently under discussion in the RINEX committee.

Table 1: GNSS satellite launches in 2023.

Date	Satellite	Type
18-Jan-2023	GPS III-6	MEO
17-May-2023	BeiDou-3	GEO
29-May-2023	NVS-01	GEO
07-Aug-2023	GLONASS K2	MEO
26-Dec-2023	BeiDou-3	MEO
26-Dec-2023	BeiDou-3	MEO

Launches of additional Galileo satellites are further delayed and now expected for 2024 following launching agreements with SpaceX. Several Galileo reference documents including interface control documents and service definitions have been updated or published in 2023 (European Union, 2023a,b,c,d).

The first generation of satellites of the Indian regional navigation system NavIC suffered from several failures of the onboard Rubidium clocks. Therefore, the Space Applications Centre (SAC) of the Indian Space Research Organisation (ISRO) developed its own Rubidium atomic frequency standard. This new type of clock is flown on NVS-01, the first second-generation NavIC satellite, launched in May 2023. NVS-01 started signal transmission on June 17, 2023 and was declared operational on July 4^{th} of the same year (IGS-ACS-MAIL #1599). In addition to the L5 and S-band signals of the first generation NavIC satellites, NVS-01 also transmits a new signal in the L1 band which was added to the most recent RINEX version 4.01 published in July 2023 (Gini, 2023). A draft for the NavIC L1 navigation message prepared by the MGWG is currently under discussion within the IGS RINEX committee. Recent Javad receivers support tracking of the NavIC L1 starting with firmware 4.3.00 published in December 2023. However, none of the Javad receivers of the IGS tracking network runs that firmware as of early 2024.

3 Network

As of January 2024, the IGS multi-GNSS tracking network comprises 403 stations, see Figs. 1 and 2. Compared to 2022, this is an increase of nine stations. Unfortunately, another nine stations are completely dormant and did not provide any observations in 2023.

After a trial period, the RINEX 4 format (Gini, 2023) for observation, navigation, and meteorologial files was introduced in the operational data archives on July 19, 2023 (IGS-MAIL #8349). However, the number of stations providing RINEX 4 data is still very limited. Examples are GOP600CZE in Pecny, Czech Republic, and UNBD00CAN in New Brunswick, Canada.

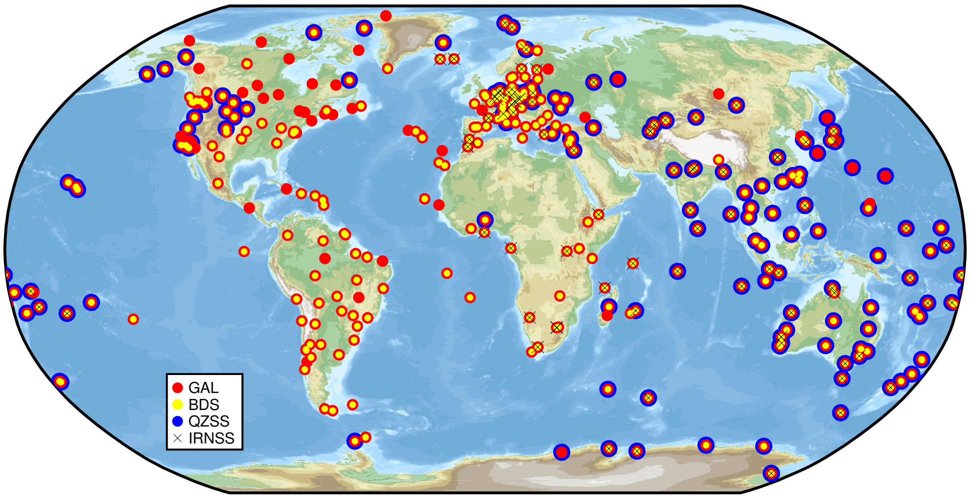


Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2024.

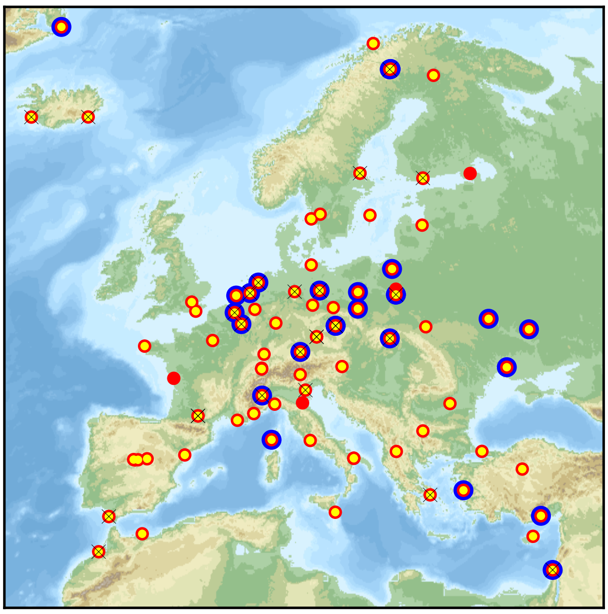


Figure 2: Distribution of European IGS multi-GNSS stations as of January 2024. See Fig. 1 for explanation of individual station labels.

4 Products

Table 2 lists the analysis centers (ACs) contributing orbit and clock products to the IGS Multi-GNSS Pilot Project. Two MGEX ACs made progress to cover more constellations in their products: JAXA started to include Galileo on 1 August 2023 and BeiDou is included in the CNES/CLS products since GPS Week 2288 (IGS-ACS-MAIL #1610).

Table 2: Analysis centers contributing to IGS MGEX as of December 2023.

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

Multi-GNSS differential code bias (DCB) products are generated by CAS and GFZ (daily rapid products) as well as DLR (quarterly final product). The transition of the MGEX DCB products to operational (OPS) IGS products was decided and prepared in late 2023 and is planned for 23 January 2024. Wuhan University started to provide a rapid MGEX phase bias product, for details see IGSMAIL #8409.

With support from the IGS Central Bureau, the analysis section of the MGEX website (`https://igs.org/mgex/analysis/`) was updated to cover all BDS-3 MEO satellites. Clock time series analysis is now based on one selected AC (currently GFZ).

5 SLR tracking of BeiDou-3 MEO satellites

Satellite laser ranging (SLR) is a valuable tool for the validation of GNSS orbits obtained from microwave observations (e.g., Sosnica et al., 2015). So far, SLR tracking of the BeiDou-3 constellation was limited to two CAST and two SECM MEO satellites. In February 2023, the International Laser Ranging Service (ILRS) added the remaining 20 BeiDou-3 MEO satellites to the general pool of satellites where station operators are free to decide to track these targets. Orbit predictions for these satellites in CPF format are generated by SHAO on a routine basis.

Figure 3 shows the number of SLR normal points per BeiDou-3 MEO satellite. Most satellites have between 1000 and 1500 normal points. The four satellites previously recommended for SLR tracking (CAST MEO-3/4 and SECM MEO-9/10) have still a signif-

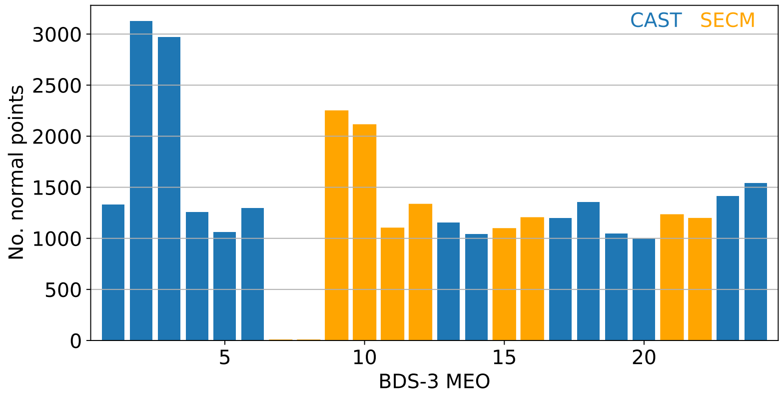


Figure 3: Number of SLR normal points obtained in 2023 for the BeiDou-3 MEO satellites.

icantly higher number of up 3000 observations. For the MEOs 7 and 8, no normal points are available due to missing orbit predictions.

6 Satellite Metadata

The new GNSS satellites discussed in Sec. 2 as well as other changes in the constellations are continuously incorporated into the IGS satellite metadata file (Steigenberger and Montenbruck, 2022) available at `https://files.igs.org/pub/station/general/igs_satellite_metadata.snx`. On request of the combination task force (Sec. 7) a new `SATELLITE/PLANE` block is currently under discussion to provide information about the orbital plane and slot of individual GNSS satellites.

Additional satellite metadata were published in 2023 by the system providers: Boeing provided antenna gain and phase patterns of the GPS Block IIF satellites (Igwe, 2023). A characterization of these phase patterns and a comparison with estimated patterns is given in Montenbruck et al. (2023). Band-specific transmit antenna gain patterns for all active QZSS satellites as well as the future QZS-5/6/7 satellites are described in Cabinet Office (2023) and available at `https://qzss.go.jp/en/technical/antenna-patterns.html`

7 Combination Task Force

The IGS Combination Task Force (CTF) has been established as an independent entity next to the MGWG in order to coordinate and advance the combination of multi-GNSS orbit clock and bias users. The CTF currently comprises the following 17 members from nine institutions:

- 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, Dhruv Upadhyay
- Université Paris-Cite: Paul Rebischung, Pierre Sakic
- Wuhan University: Guo Chen, Jianghui Geng
- UPWR: Radoslaw Zajdel

and held a total of six virtual meetings throughout the year 2023. Following an initial decision to focus on the orbit/clock/bias combination process in support of multi-GNSS Precise Point Positioning (PPP) users, the CTF has targeted the multi-GNSS orbit combination process. Use of python and the pandas data analysis library was adopted for the development and integration of a new orbit combination software. To facilitate cross exchange of software and study results, a github repository was created and populated with software modules and demo utilities (e.g., file reading, Helmert transformation, basic combination steps). As a starting step, a consolidated SP3 reader for loading orbit files from different analysis centers and processing chains as well as associated metadata into a pandas object was developed.

Following a literature and software review, a consolidated formulation for Helmert transformations was agreed within the group and applied in subsequent studies. Independent analyses by various CTF members suggest that Helmert transformations have become of limited relevance for the quality of the combination process. A good frame consistency was found among the MEO constellations in the various AC solutions. Even though constellation-specific transformations appear to be of benefit (in terms of more consistent combined orbits) at first sight when including IGSOs and GEOs, the specific GNSS-specific Helmert transformations are likely to mask systematic orbit errors in this case. As such, Helmert transformations in the combination process should be determined on a per-AC basis considering all available constellations but excluding IGSO and GEO satellite. Even though the resulting Helmert transformations of individual ACs with respect to a mean or combined orbit are typically small for the current operational and MGEX products, the Helmert transformation may still be kept as a quality check and indicator of possible occasional misalignments.

Concerning the combination technique itself, Variance Component Estimation (VCE) was identified as a promising alternative to the L1-norm based (non-iterated) weighting in the legacy combination software. GFZ is already using least-squares VCE (LS-VCE) successfully in their existing multi-GNSS combination software (Mansur et al. 2022). As an alternative with lower computational complexity, the VCE scheme of Förstner (1979) was discussed and tested with promising results. Compared to the LS-VCE, the latter approach will protect against negative weights that may occasionally arise in LS-VCE in case of unfavorable data. Further tests are ongoing at GFZ and UPWR to assess use of

Förstner's scheme for orbit computation on a larger set of test cases.

As an additional activity, the CTF provided inputs to the IGS Governing Board for the upcoming transition of the Analysis Center Coordinator. A phased transition was recommended, in which the prospective new ACC would start exercising full multi-GNSS orbit, clock, and, optionally, bias combinations parallel to a continued generation of GPS products by the current/old ACC. While the CTF is not expected to come up with a fully consolidated combination software in the near future, various software tools have already been developed outside the immediate CTF work. These include the multi-GNSS orbit and clock combination of GFZ (Mansur et al., 2022), the multi-GNSS orbit combination software of GA used for the Repro3 combination and, more recently, for operational GPS/GLO/GAL orbit products (Zajdel et al., 2023), as well as clock and bias combination software of Wuhan University (Chen et al., 2022; Lin et al., 2023). While the CTF does not provide a specific recommendation for the ACC, it proposes the above software tools as candidates for the next ACC prior to the completion of a dedicated IGS-internal combination software development.

Concerning the introduction of new constellations into combined GNSS orbit and clock products, initial studies performed within and outside the CTF suggest that the combined GPS products are not contaminated by the incorporation of other GNSSs. As part of the Repro3 campaign and IGS20 refence frame development, it was furthermore demonstrated that the latest igs20.atx antenna model enables a fully consistent processing of GPS, GLONASS, and Galileo. On the other hand multi-GNSS PPP results may still be contaminated when adding BeiDou and possibly QZSS due to a lacking compatibility of the manufacturer transmit antenna calibrations with the IGS20 reference frame. A dedicated campaign for BDS/QZSS antenna calibration was therefore initiated by the reference frame coordinator and will be conducted in 2024. This campaign was joined by multiple MGEX ACs and will closely be followed by the CTF.

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
ESA European Space Agency
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 Universtität München
UPWR Wroclaw University of Environmental and Life Sciences
WU Wuhan University

References

Cabinet Office (2023). QZSS antenna patterns. National space policy secretariat. URL https://qzss.go.jp/en/technical/oid281000000021d-att/qzss_antenna_patterns.pdf.

Chen, G., J. Guo, N. Wei, M. Li, Q. Zhao, J. Tao (2022). Multi-gnss clock combination with consideration of inconsistent nonlinear variation and satellite-specific bias. *Earth, Planets and Space*, 74(142). ISSN 1880-5981. doi: 10.1186/s40623-022-01702-6.

European Union (2023a). Galileo Open Service signal-in-space interface control document. OS SIS ICD Issue 2.1. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OS_SIS_ICD_v2.1.pdf.

European Union (2023b. Galileo Open Service: Service definition document. OS SDD Issue 1.3. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-SDD_v1.3.pdf.

European Union (2023c). Galileo PRN spreading code assignment process. Technical Report Issue 1.0. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_PRN_Spreading_Code_Assignment_Process_v1.0.pdf.

European Union (2023d). Galileo High Accuracy Service: Service definition document. HAS SDD Issue 1.0. URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-HAS-SDD_v1.0.pdf.

Förstner, W. (1979). Ein Verfahren zur Schätzung von Varianz- und Kovarianzkomponenten. *Allgemeine Vermessungsnachrichten*, 86(11-12):pp. 446–453.

Gini, F. (2023). RINEX, The Receiver Independent Exchange Format, Version 4.01. Technical report. URL https://files.igs.org/pub/data/format/rinex_4.00.pdf.

Igwe, C. (2023). GPS-IIF satellites: Antenna patterns for L1, L2 and L5 (SVN 62–73). URL https://www.navcen.uscg.gov/gps-technical-references.

Lin, J., J. Geng, Z. Yan, S. Masoumi, and Q. Zhang (2023). Correcting antenna phase center effects to reconcile the code/phase bias products from the third IGS reprocessing campaign. *GPS Solutions*, 27(2). doi: 10.1007/s10291-023-01405-9.

Loyer, S. (2023). [IGS-ACS-1610] GRG/MGX Beidou final products.

Mansur, G., P. Sakic, A. Brack, B. Männel, H. Schuh (2022). Combination of GNSS orbits using least-squares variance component estimation. *Journal of Geodesy*, 96(11). doi: 10.1007/s00190-022-01685-y.

Montenbruck, O., P. Steigenberger, and T. Mayer-Gürr (2023). Manufacturer calibrations of GPS transmit antenna phase patterns: a critical review. 98(2). ISSN 1432-1394. doi: 10.1007/s00190-023-01809-y.

Sosnica, K., D. Thaller, R. Dach, P. Steigenberger, G. Beutler, D. Arnold, A. Jäggi (2015). Satellite Laser Ranging to GPS and GLONASS. *Journal of Geodesy*, 89(7):pp. 725–743. ISSN 0949-7714. doi: 10.1007/s00190-015-0810-8.

Steigenberger, P., O. Montenbruck (2022). IGS Satellite Metadata File Description, Version 1.00, December 13, 2022. Technical report. URL https://files.igs.org/pub/resource/working_groups/multi_gnss/Metadata_SINEX_1.00.pdf.

Steigenberger, P., J.-M. Sleewaegen, O. Montenbruck (2023). New NavIC clock outperformsprevious generation. *GPS World*, 34(9):12–14.

Zajdel, R., S. Masoumi, K. Sośnica, F. Gałdyn, D. Strugarek, G. Bury (2023). Combination and SLR validation of IGS repro3 orbits for ITRF2020. 97(10). doi: 10.1007/s00190-023-01777-3.

Precise Point Positioning with Ambiguity Resolution Pilot Project Technical Report 2023

J. Geng[1], Q. Zhang[1], J. Lin[1], Z. Yan[1], S. Loyer[2], E. Saquet[2]

[1] GNSS Research Center, Wuhan University, Wuhan, China
[2] Collecte Localisation Satellites, Ramonville Saint Agne, France

1 Introduction

The precise point positioning with ambiguity resolution (PPP-AR) Working Group (WG) was established in 2018, and after the 65$^{\text{th}}$ Governing Board Meeting in 2023, the PPP-AR working group was renamed to the PPP-AR Pilot Project. In 2023, the PPP-AR Pilot Project accomplished the Phase 1 goals set in 2018. The goals in the first phase include:

- Survey the technical practices, requirements, and goals of the participating analysis centers (ACs) currently producing PPP-AR products.
- Encourage maximum participation with a target of a minimum of three analysis centers generating reliable PPP-AR products.
- Propose the adoption of a satellite attitude exchange format as a necessary step to ensure compatibility of clock solutions.
- Assess whether current data formats are adequate to convey all information related to PPP-AR clocks/biases, and explore extension and additions, if necessary.
- Examine the interoperability of PPP-AR products generated by various analysis centers.
- Develop a modernized satellite clock/bias combination software.
- Generate combined clocks and biases for internal tests.
- Communicate the performance of combined PPP-AR products to the GNSS community in comparison to the corresponding products of the contributing ACs.

By the end of 2023, three analysis centers (COD, GRG, WUM) have routinely released qualified final and rapid phase biases. COD and WUM products phase clocks and OSBs, while GRG releases integer clocks with auxiliary biases. Products from three ACs all contain GPS and Galileo phase biases, while only WUM and GRG provide BDS phase biases. Based on the efforts of these three ACs, a combination task of phase clocks/biases is achievable. Members of the PPP-AR pilot project have been dedicated to this issue for nearly one year, and the combination software has been well exanimated with the combination tasks of IGS Repro3 clocks. Finally, in October of 2023, the GPS and Galileo clock/bias weekly assessment and combination were operational, with illustrations weekly shown on the IGS PPP-AR WG website.

In this year, promotions are witnessed from each AC. WUM final products started to provide G/E/C/J phase biases, and WUM rapid products started to release all-frequency phase biases. GRG started to provide BDS PPP-AR products, and they changed their clock/code DCB/wide-lane UPD products to the clock/OSB products. To relieve the file transmission pressure, GRG and WUM have changed the number of decimal digits of attitude quaternions from 16 to 7. To further align the day boundary discontinuity, COD and WUM provide the 24:00 epoch record in clock products.

In November, an online meeting was hosted drawing new goals for the Pilot Project, with new Phase 1 and Phase 2 updated on the website. In the future, work will be carried out around these new goals, but the beginning could be the release of combined PPP-AR products.

2 Online Meeting

The PPP-AR pilot project hosted an online meeting in November 2023 to review its achievements, challenges, and plans in the field of PPP-AR, based on its current charter. The meeting gathered representatives from several ACs and other WGs to foster collaboration and outreach within the IGS community.

The meeting began with an overview of the past working progress after the PPP-AR WG was established five years ago. The influence of phase bias products increased significantly thanks to the ACs' efforts. The products include both the routine MGEX/OPS products since 2018 and the Repro3 products that go back to 2000, enabling users to implement PPP-AR in various periods. The PPP-AR WG ensured the format and interoperability (Banville et al., 2020) of code/phase bias products from each AC, such as promoting SINEX-BIAS files (Schaer, 2016) and assessing the effect of antenna phase centers (Lin et al., 2023). The clock/bias product combination software examined by the Repro3 campaign has been applied to the daily service of rapid/final products, and the outcomes of the daily combination were shown and discussed at the meeting, with examples in the following section.

The PPP-AR Pilot Project reached a consensus on its short-term and long-term goals and updated its charter. The short-term (Phase 1) goals are proven technically feasible and focus more on the dissemination and improvement of existing methods:

- Survey the technical practices and problems from current phase bias estimates.
- Encourage more ACs to produce GPS/Galileo/BDS phase clock/bias products.

- Start a cross-validation task to assess the phase clock/bias qualities and improve the consistency among the contributing products.
- Work with the Bias WG to ensure continuity of clocks/biases at day boundaries by using the integer properties of the combined products.
- Initiate a project to expose the combined clock/bias solution to open testing for the public.
- Develop a phase clock/bias combination software open-sourced across the IGS community.

the long-term (Phase 2) goals are about collaboration with other WGs and establishing a theoretical framework to accommodate multi-frequency phase biases:

- Work in partnership with the Clock WG on time scale issues associated with continuous "phase" clocks.
- Encourage the RT WG to compute and broadcast real-time phase biases by sharing knowledge on phase bias generation.
- Survey proper models, algorithms, and requirements for multi-frequency phase bias products, and start a pilot project to generate such products.
- Assess the versatility and scalability of multi-frequency phase biases for all conceivable observable combinations and frequency choices, and start a pilot combination task.

The other topics discussed were about the minor quality and formatting issues of some ACs' products. The participants agreed to recommend ACs to provide ORBEX products to enhance the performance of kinematic positioning (Loyer et al., 2021) and the consistency of clock/bias combinations. ACs are also advised to limit the number of decimal digits in the attitude quaternions to 7 to ease the file transmission pressure while preserving the necessary accuracy.

3 Routine combination and webpage illustration

In order to encourage the participation of research institutions in the study of phase bias, and to fulfill the role of product combination in quality assessment and product enhancement, a webpage has been successfully developed and organized to show the weekly results of clock and bias product combination. Below are the links to access the combined results of the rapid and final product:

- rapid product combination: https://igs.org/wg/ppp-ar/#rapid
- final product combination: https://igs.org/wg/ppp-ar/#final

This webpage will be updated on a weekly basis, with content and illustrations provided by the server at Wuhan University. Within this webpage, a comprehensive table with explanatory text meticulously details all products used in the combination process, along with information on sampling rates and satellite constellations. The webpage further offers a graphical representation of the comprehensive evaluation results, specifically as follows (take the combined results of final products as an example):

1. The figure of the combined weight.
   The clock combination employs an iterative weighting method in which the weight assigned to a specific product depends on its residuals in relation to the combined clock, as Figure 1 illustrates.

2. The figure of the weekly clock/bias RMSE.
   The clock/bias RMSE refers to the daily RMSE of clock/bias for each AC with respect to the combined integer clock, which reflects the accuracy of the clock and bias combination and the consistency between individual ACs. Figure 2 shows the RMSE figures for GPS and Galileo systems.

3. The figures of the accumulated clock/bias RMSE.
   The accumulated clock/bias RMSE refers to the daily RMSE of the clock/bias series for all the ACs with respect to the combined integer clock, as Figure3 shows, which reflects the change of the combined accuracy over time.

4. The figure of PPP-AR validation.
   The GPS/Galileo data with a sampling interval of 300 s from 10 globally distributed stations are processed for PPP-AR in a static mode with the PRIDE PPP-AR software. The fixing rate and position precision of each single constellation solution are presented in Figure 4.

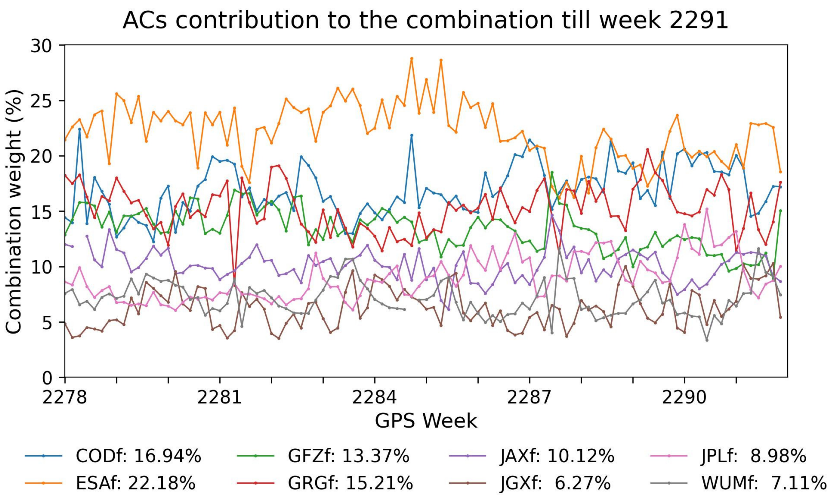
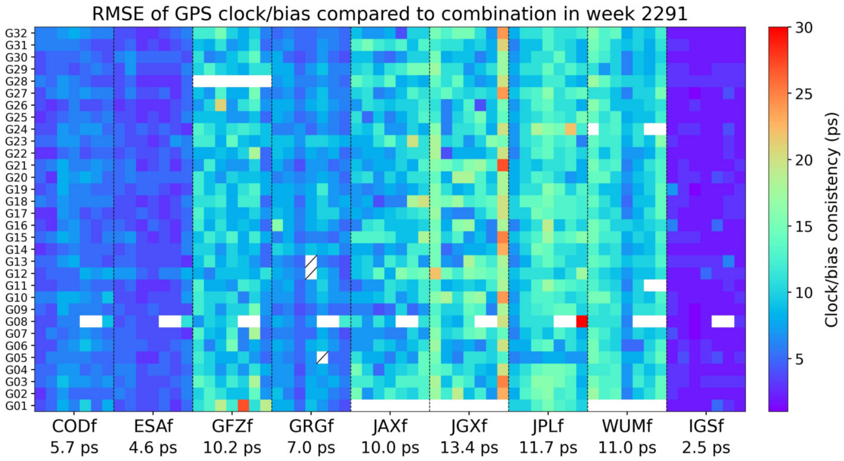
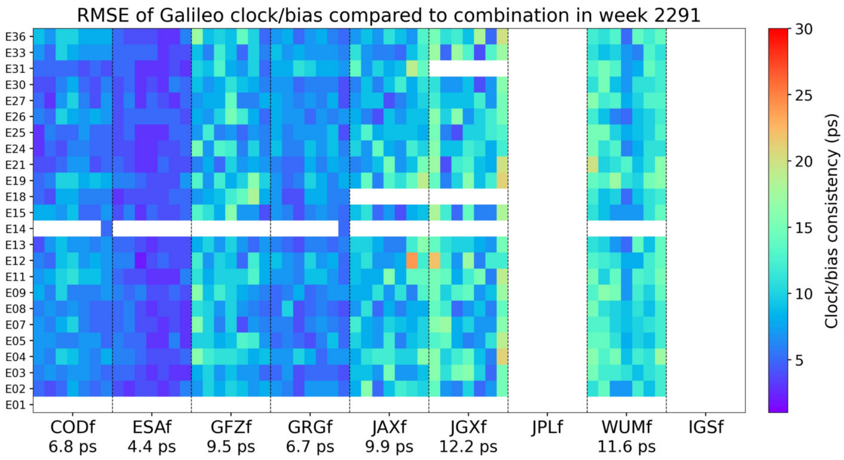


Figure 1: The combination weight of each participating AC.

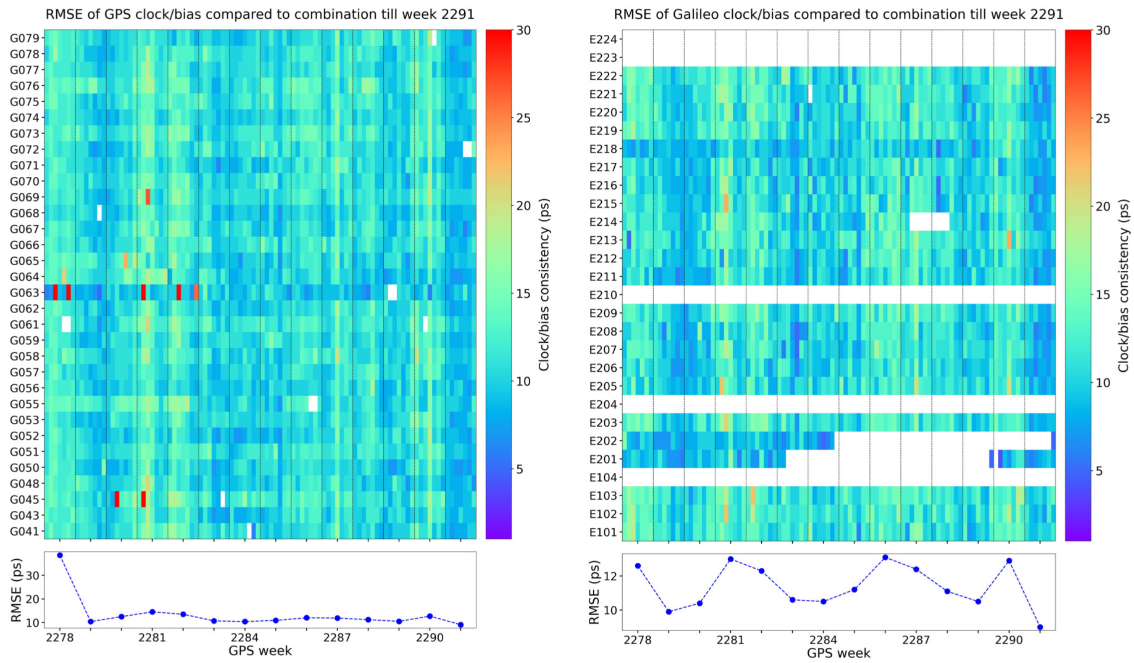


(a) GPS weekly clock/bias RMSE.



(b) Galileo weekly clock/bias RMSE.

Figure 2: Weekly clock/bias RMSE. Each grid represents a satellite on a particular day. Blank grids mean unavailable products and a slash inside means an outlier excluded from the combination.



(a) GPS (b) Galileo

Figure 3: The figure of the accumulated clock/bias RMSE.

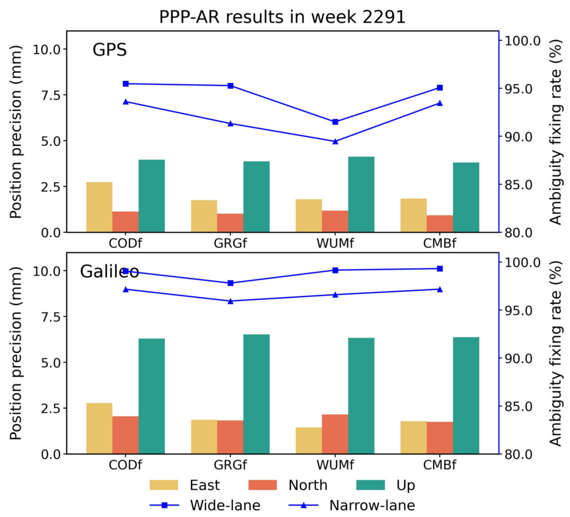


Figure 4: The figure of PPP-AR validation.

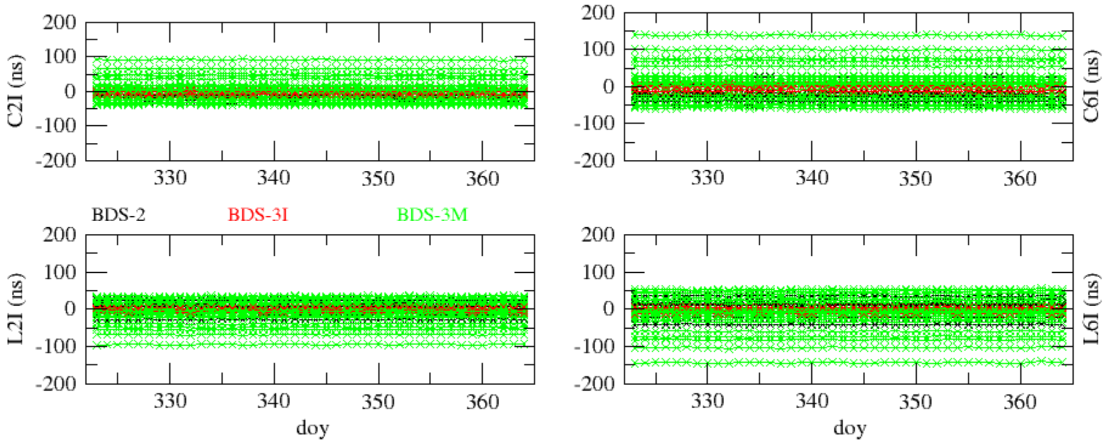


Figure 5: BDS-2 & BDS-3 OSB estimates at the end of year 2023 (1 pt per day).

4 GRG BDS phase biases

At the end of 2024, GRG-AC provided MGEX products (Multi-GNSS-Experiment) including BDS satellites. These products use C2/C6 (B1/B3) measurements and include BDS-2 and BDS-3 satellites, but only BDS-3 satellite measurements are processed with fixed integer ambiguities. The precision of orbits is at a level of several centimeters for BDS-3 satellites and ≈ 10 cm for BDS-2 satellites. These products are delivered with Observable-Specific Biases (OSB) to be used with our clocks to process code and phase observations. Since GPS week 2238 and the adoption of IGS20 standards, the geometry-free combination of these OSB requires consistent use of an antenna phase center (APC). As Galileo and GPS, the BDS-3 satellite clock estimates provided in SP3 and CLK files are the so-called integer clocks (Banville et al., 2020). The stability of these biases is between 0.5 and 1 ns as can be seen in Figure 5 displaying individual daily OSB estimates.

If corrected by OSB, the phase observations allow ambiguity Wide-Lane and Narrow-Lane fixed for PPP-AR and the code observations become compatible with our clocks.

Future work will focus on the process of the C1/C5 (B1C/B2a) couples of BDS-3 signals.

5 WUM all-frequency rapid phase biases

In 2023, WUM started to provide all-frequency rapid phase bias products, covering all available frequencies of unclassified signals, as Table 1 lists. The corresponding method is proposed by Geng et al. (2022), which makes sure that OSBs on diverse frequencies are aligned to the same dual-frequency clock datum.

Although clock products are based on baseline frequencies, for satellites such as Galileo,

Table 1: Frequencies of WUM rapid phase biases.

System	Frequencies
GPS	L1, L2, L5
Galileo	E1, E5a, E5b, E6, E5
BDS-2	B1I, B3I, B2I
BDS-3	B1I, B3I, B2b, B1C, B2a

BDS-3 and GPS Block IIIA, no significant time-variable difference is found between ionosphere-free combinations of arbitrary frequency pairs. In this condition, baseline-frequency phase clock products plus one-day multi-frequency OSBs are enough to describe phase biases. On the other hand, for BDS-2 and GPS Block IIF, inter-frequency clock biases are remarkable one the third frequency, thus 15-min OSBs are used to portray these clock-like time-variable phase biases.

In the past few years, WUM rapid products were released only within the WHU data website (ftp://igs.gnsswhu.cn/pub/whu/phasebias). Since November 26th of 2023, WUM has started to upload MGEX rapid products to the IGN website (ftp://igs.ign.fr/pub/igs/products/mgex), with the phase biases upgraded to an all-frequency version. The new products support a reasonable ambiguity resolution performance, and the fixing rates of conceive ionosphere-free combination positioning with PRIDE PPP-AR are shown in Table 2.

Table 2: Fixing rates with all-frequency phase biases.

System	Frequencies	Fixing rates (WL/NL)	
GPS	L1/L2	91.32%	95.98%
	L1/L5	81.74%	93.19%
Galileo	E1/E5a	97.88%	96.76%
	E1/E6	96.36%	94.90%
	E1/E5b	98.00%	96.32%
	E1/E5	98.77%	96.42%
BDS-2	B1I/B3I	86.17%	82.75%
	B1I/B2I	75.64%	81.98%
BDS-3	B1I/B3I	92.74%	92.43%
	B1I/B2b	85.15%	94.25%
	B1C/B2a	94.02%	94.23%

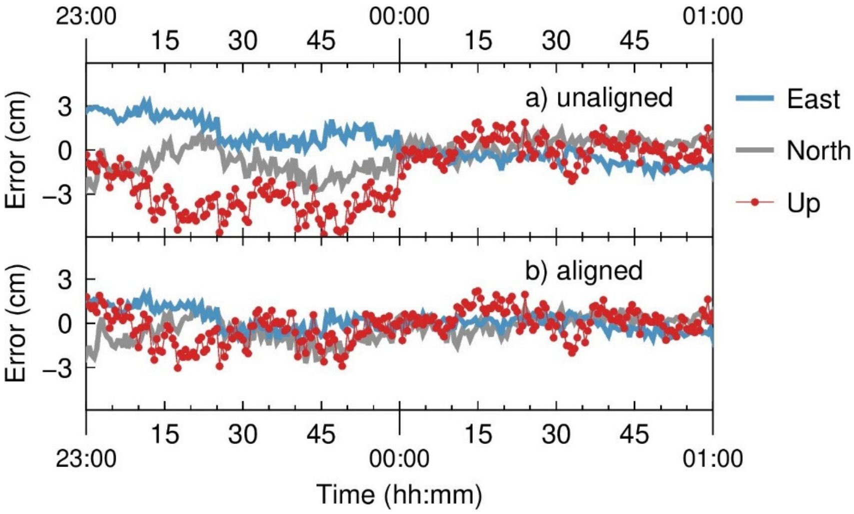


Figure 6: Positioning time series before and after alignment of day boundary discontinuity.

Specifically, WUM adopts a state-of-the-art approach to remove the positioning boundary discontinuity in the time series across adjacent days, as shown in Figure 6. Orbit or clock alone is still not continuous after alignment, but the integrated impact for continuous positioning from all products is removed. As a result, users could conduct multi-day positioning without breaking the ambiguity arc at 24:00, which is meaningful to continuous monitoring like earthquake measurement.

6 Future work

In the next year, the combined clock/bias products will be released as IGS formal products. Note that a BDS/QZSS campaign is going on within IGS. A combination for BDS will be conducted if a third AC provides BDS phase clock/bias products. If so, BDS products will also be included in the combined products.

Issues like day boundary discontinuity, multi-frequency phase biases, and time scale will be discussed gradually. In 2024, the IGS workshop will be held in July, hoping some preliminary conclusion could be drawn at the meeting.

References

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

Lin, J., J. Geng, Z. Yan, S. Masoumi, and Q. Zhang (2023). Correcting antenna phase center effects to reconcile the code/phase bias products from the third IGS reprocessing campaign. GPS Solution, 27(70) doi: 10.1007/s10291-023-01405-9.

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

Geng, J., Q. Wen, Q. Zhang, G. Li, K. Zhang (2022) GNSS observable-specific phase biases for all-frequency PPP ambiguity resolution. Journal of Geodesy, 96(11), doi: 10.1007/s00190-022-01602-3.

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

IGS Real-Time Committee Technical Report 2023

Axel Rülke[1], Ningbo Wang[2], Andrea Stürze[1]

[1] Federal Agency for Cartography and Geodesy, Germany
axel.ruelke@bkg.bund.de
[2] Aerospace Information Research Institute,
Chinese Academy of Sciences, China

1 Introduction

The Real Time Committee takes care of real time GNSS activities within the IGS compiled in the IGS Real Time Service (RTS). This includes to operate real time caster infrastructure at the IGS Real Time Data Centres. This data centres allow access to observation data streams from the global IGS network as well es access to real time product streams. The product streams are computed by the IGS Real Time Analysis Centres (RTACs). The Real Time Analysis Center Coordinator (RT-ACC) performs quality control checks tests to these individual products and computes a combined IGS real time products.

The IGS Real Time Working Group now renamed to the IGS Real Time Committee has organized two telephone conferences in March and October 2023. At the occasion of the IUGG Conference 2023 an informal meeting of Working Group members has been organized in Berlin.

After many years of service to the IGS Real Time Working Group Loukis Agrotis stepped down from his position as the RT-ACC. We thank Loukis for his effort pushing the IGS Real Time Service. Andrea Stürze from BKG took over the RT-ACC position which was confirmed by the IGS GB at their Meeting in July 2023 in Potsdam. The RT-ACC generates multi-GNSS combination solutions and provides resources for solution monitoring.

This report gives an overview on the IGS real time activities in last year. We also present developments of the combined RT products and the quality assessment performed RT-ACC.

Table 1: IGS GNSS Ntrip broadcasters

Agency	Content
BKG	Global and European observation data IGS RTS products
CDDIS	Global observation data IGS RTS products
Geoscience Australia	Observation data of stations located in Australia and the Asia-Pacific region
UCAR	Global observation data IGS RTS products

2 IGS RTS Structure

2.1 Real time observation data and products access

Real time GNSS observation data is disseminated through the IGS GNSS Ntrip broadcasters according to Table 1.

More information is given at https://igs.org/rts/user-access/.

2.2 Real Time Analysis Centres and their products

In 2023, 10 real time analysis centres contributed to the IGS Real Time Service. Table 2 summarizes the product streams of the individual RTACs. Most of the RTACs provide orbit and clock corrections for multi-GNSS constellations. Some of them are providing bias information in addition. Two RTACs products include VTEC values from global ionosphere maps as well. There are also two separate data streams providing VTEC values and one data stream providing observable specific signal biases (OSB). ESA will terminate their contributions within 2024.

There are several combined multi-GNSS broadcast ephemeris data streams available. BKG produces also data streams for each separate constellation (Table 3).

2.3 Real Time Analysis Center Coordinator (RT-ACC)

The product streams available in the RTS are combination solutions generated by processing individual real time solutions from participating RTACs. The effect of combining the different RTAC results is a more reliable and stable performance than that of any single AC's product. Operational responsibility for the official combination products lies with the IGS RT-ACC. The official RTS combination products consist of multi-GNSS satellite orbit and clock correction as well as code bias information. In addition, the combined real-time global ionospheric maps are generated and provided in two separate data streams (cf. Table 4):

- SSRA02IGS/SSRC02IGS (GPS, GLONASS, Galileo)
- SSRA03IGS/SSRC03IGS (GPS, GLONASS, Galileo, Beidou)
- IONO00IGS/IONO01IGS (ionospheric VTEC)

In the past IGS RTS correction were formatted according to the RTCM SSR standard for State Space Representation. Because the standard extension for other GNSS beyond GPS and GLONASS is still under development within RTCM, products are currently provided in the IGS-SSR format using the NTRIP protocol. RTS corrected products refer to the International Terrestrial Reference Frame 2020 (ITRF 2020).

BKG has developed a combination technique based on a Kalman filter, which is able to deal with outages and offsets in individual RTAC solutions. This approach has been used already since many years within IGS RTS and was now improved to work with multi-GNSS data. The Kalman filter combination is included in BKG's BNC software. The BKG Ntrip Client (BNC) is an open source multi-stream tool box for a variety of real time GNSS applications. It can be used to decode, convert and monitor RTCM 2.x and RTCM 3.x data streams and supports real time PPP, high rate RINEX data centres, real time GNSS engines and real time combination. In 2023 BKG has released version 2.13 which can be downloaded for a variety of operating systems at https://igs.bkg.bund.de/ntrip/bnc.

In the Kalman Filter approach the satellite clocks as estimated by individual Analyses Centers (ACs) are used as pseudo-observations within the adjustment process. Each observation is modelled as a linear function of three estimated parameters: AC specific offset, satellite specific offset common to all ACs, and the actual satellite clock correction which represents the result of the combination. These three parameter types differ in their statistical properties. The satellite clock offsets are assumed to be static parameters while AC specific and satellite specific offsets are stochastic parameters with appropriate white noise. The solution is regularized by a set of minimal constraints. A recursive algorithm is used to detect orbit outliers. The largest difference between AC specific and mean satellite positions is computed. If this exceeds a threshold, the corrections of the affiliated AC are ignored for the affected epoch. This procedure has now transitioned to the official multi-GNSS combination solution. The combination is done system-wise for the reference signals as specified in the IGS RTWG and mentioned below.

Orbit corrections are provided as along-track, cross-track and radial offsets to the Broadcast Ephemeris in the Earth-centered, Earth-fixed reference frame. After applying corrections, the satellite position is referred to the antenna reference point (APR streams) defined in the IGS-SSR standard or to the satellite Center of Mass (CoM streams). Clock corrections are given as offsets to the broadcast ephemeris satellite clock corrections. The SSR format provides also for the dissemination of signal code biases, which are the biases to apply to the pseudo ranges for the signals.

The official RTS combination is done system-wise for the following reference signals as specified in the IGS RTWG:

- GPS: 1W/2W
- GLO: 1P/2P
- GAL: 1C/5Q
- BDS: 2I/6I

Assuming that the ACs generate ionosphere-free clocks based on their individual chosen signals, the ionosphere-free code biases for the RTS reference signals are determined from the supplied code biases. These are subtracted from each individual clock before combination, resulting in combined code-bias-free and ionosphere-free clocks. This fact can be used to set the ionosphere-free linear combination of two Observable-specific Signal Biases (OSBs; those of the reference signals) to zero in order to calculate all other OSBs. For this, the satellite biases which are computed by the Aerospace Information Research Institute of the Chinese Academy of Sciences (AIR/CAS) are used and send out as SSR code biases together with the combined clocks. These SINEX Bias files are archived at CDDIS: https://cddis.nasa.gov/archive/gnss/products/bias/.

The true performance of the products as well as of the individual AC solutions can be assessed by the daily statistics derived from the comparison with IGS rapid products. As part of the Center for Orbit Determination in Europe (CODE), BKG has access to high resolution CODE rapid products. Hence, these products for GPS, Galileo and GLONASS with a time resolution of 30s are used for the monitoring and comparison purposes.

Table 2: : IGS RTS Analysis Centers and their products. .* The mountpoints prefix SSRC and SSRA indicate centre of mass (CoM) and antenna phase centre (APC) satellite orbits, respectively

Center	Mountpoints	Product description
BKG	SSR*00BKG1	GPS+GLO+GAL RT orbits, clocks and code biases based on CODE orbits and biases
CAS	SSR*00CAS1	GPS+GLO+GAL+BDS RT orbits and clocks based on GFZ orbits. Also includes VTEC from Global Ionospheric Map and code biases
CNES	SSR*00CNE1	GPS+GLO+GAL+BDS RT orbits and clocks based on GFZ orbits. Also includes VTEC from Global Ionospheric Map as well as code and phase biases
ESA/ESOC	SSR*00ESA1	GPS RT orbits and clocks using hourly orbits from ESOC s/w with IGS RINEX files
GFZ	SSR*00GFZ1	GPS+GLO+GAL+BDS orbits and clocks based on internal GFZ orbits every 2 hours. Also includes code biases
GMV	SSR*00GMV1	GPS+GLO+GAL+BDS RT orbits and clocks based on GMV-generated orbits
NRCan	SSR*00NRC1	GPS RT orbits and clocks based on hourly orbits from NRCan software. Also includes code and phase biases
SHAO	SSR*00SHA1	GPS+GLO+GAL+BDS RT orbits and clocks based on IGS Ultras. Also includes code biases
UPC	IONO00UPC1	VTEC from Global Ionospheric Map in stream IONO00UPC1
WUHAN	SSR*00WHU1	GPS+GLO+GAL+BDS RT orbits and clocks based on IGU (GPS) and IGS WHU AC orbits.
WUHAN	IONO00WHU0	VTEC from Global Ionospheric Map
WUHAN	OSBC00WHU1	Observable Specific signal Biases (OSB) for GPS: L1/L2/L5, Galileo: E1/E5a/E5b/E6/E5, BDS-2: B1I/B2I/B3I, BDS-3: B1I/B1C/B2a/B2b/B2/B3I. Satellite orbits and clocks are fixed and used from SSRC00WHU0. Moreover, multi-frequency raw ambiguities are all fixed during the data processing of estimating phase OSBs.

Table 3: IGS RTS broadcast ephemeris data streams.

Data Stream	GNSS	Description
BCEP00BKG0	G, R, E, C, J, SBAS	Derived from receiver data of the IGS RT network. The stream is produced by BKG's BNC software and encoded as RTCM V3 messages. The repeat interval is 5s.
BCEP01BKG0	G	Similar to BCEP00BKG0 for GPS only
BCEP02BKG0	R	Similar to BCEP00BKG0 for GLONASS only
BCEP03BKG0	E	Similar to BCEP00BKG0 for Galileo only
BCEP04BKG0	C	Similar to BCEP00BKG0 for Beidou only
BCEP05BKG0	J	Similar to BCEP00BKG0 for QZSS only
BCEP06BKG0	SBAS	Similar to BCEP00BKG0 for SBAS only
BCEP00CAS0	G, R, E, C	Derived from data of the IGS Real-Time tracking network. The data stream is provided by CAS's software BDSMART.
BCEP01CAS0	G, R, E, C	Derived from data of the IGS Real-Time tracking network. The data stream is provided by CAS's software BDSMART.
BCEP01GMV0	G, R, E, C, J	The data stream is produced by GMV's software magicGNSS.

Table 4: IGS Real Time Service combination products. .* The mountpoints prefix SSRC and SSRA indicate centre of mass (CoM) and antenna phase centre (APC) satellite orbits, respectively

Stream Name	Description	Ref Point	IGS-SSR Messages and sampling [s]	Software
SSR*01IGS1	Orbit/Clock Correction, Single-Epoch Combination	APC	4076_023(5)	ESA/ESOC
SSR*02IGS1	Orbit/Clock Correction, Kalman Filter Combination	APC	4076_021(10), 4076_022(10), 4076_041(10), 4076_042(10), 4076_061(10), 4076_062(10)	BKG
SSR*03IGS1	Orbit/Clock Correction, Kalman Filter Combination	APC	4076_021(10), 4076_022(10), 4076_041(10), 4076_042(10), 4076_061(10), 4076_062(10), 4076_101(10), 4076_102(10)	BKG
IONO00IGS1	Global Ionospheric Model		4076_201(15)	UPC
IONO01IGS1	Global Ionospheric Model		4076_201(15)	CAS

Reference Frame Committee Technical Report 2023

P. Rebischung[1,2]

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

Besides operational combinations of the daily terrestrial frame (SINEX) solutions provided by the IGS Analysis Centers as part of their final products (Section 1), the Reference Frame Committee activities in 2023 included:

- an extension of the IGS repro3 SINEX solution series for years 2021–2022 (Section 2),
- the preparation and bi-monthly updates of a new version of the IGS cumulative solution, consistent with the IGS20/igs20.atx framework and the repro3 standards (Section 3),
- the development and public release of a new website dedicated to the IGS SINEX combination products (Section 4),
- the publication of an article on the "IGS Reference Frames and their relationship to the ITRF" in the Encyclopedia of Geodesy (Rebischung, 2023a).

1 Operational SINEX combinations

The main operational task of the Reference Frame Committee consists in combining the daily terrestrial frame (SINEX) solutions provided by the IGS Analysis Centers (ACs) as part of their final products. The daily combined SINEX solutions thus obtained contain the official daily IGS station position and Earth Rotation Parameter (ERP) estimates. The residuals from the daily SINEX combinations additionally allow evaluating the consistency and quality of the SINEX solutions provided by the different ACs. Since GPS week 2238 (November 27, 2022), the daily IGS combined SINEX solutions have been, like the other IGS products, aligned to the IGS20 reference frame and consistent with the igs20.atx set of antenna phase center corrections (see Rebischung, 2023b; Villiger, 2023, for more details on the IGS20/igs20.atx framework).

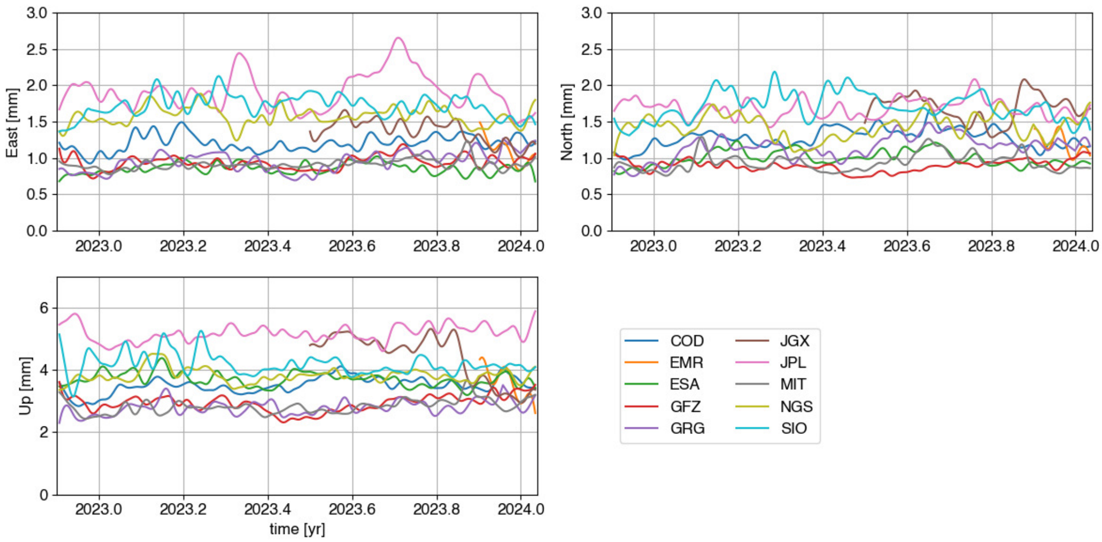


Figure 1: WRMS of AC station position residuals from the 2023 daily IGS SINEX combinations. All WRMS time series are low-pass filtered with a 20 cpy cutoff frequency.

Figure 1 shows the WRMS of the Analysis Center (AC) station position residuals from the daily IGS SINEX combinations, i.e., the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed, for the period from GPS week 2238 (November 27, 2022) to GPS week 2296 (January 13, 2024). During this period:

- The WRMS of JPL's residuals have remained at high levels, since, unlike other ACs, JPL has not transitioned to the IGS20/igs20.atx framework yet. The JPL solutions have been included for comparison only in the IGS SINEX combinations since the switch to IGS20/igs20.atx on GPS week 2238.
- EMR (NRCan) has not provided SINEX solutions for one year after the switch to IGS20/igs20.atx. They finalized the transition to the new framework and a new product line, and started providing SINEX solutions again on GPS week 2290. After an evaluation period of four weeks, those have been included with weight in the IGS SINEX combinations since week 2294.
- A new candidate AC called JGX, jointly run by the Japan Aerospace Exploration Agency and the Geospatial Information Authority of Japan, started regularly providing SINEX solutions in July 2023. After a 4.5 month evaluation period and official approval of JGX as a new AC by the IGS Governing Board, their solutions have been included with weight in the IGS SINEX combinations since week 2289. Since this inclusion, the WRMS of JGX's residuals have reached levels close to the leading ACs in the East and Up components, but remain higher than most other ACs in the North component.

- The WRMS of the station position residuals from the other ACs have remained at similar, stable levels as in the previous years.

2 repro3 SINEX combinations for 2021–2022

The IGS third reprocessing campaign (repro3) consisted in a re-analysis, by ten IGS ACs, of the history of GNSS observations acquired by a global tracking network using updated models and methodologies. The contributing ACs provided, among other products, daily SINEX solutions including station position and Earth Rotation Parameter (ERP) estimates, which were combined on a daily basis. The daily combined repro3 SINEX solutions formed the IGS contribution to the latest release of the International Terrestrial Reference Frame, ITRF2020 (Altamimi et al., 2023). A detailed analysis of this contribution can be found in Rebischung et al. (2023).

The initial repro3 campaign and IGS contribution to ITRF2020 spanned the period 1994–2020. To bridge the gap between the end of this initial campaign and the switch of the IGS operational products to IGS20/igs20.atx and the repro3 standards on November 27, 2022, six ACs extended their repro3 product series up to this date. The daily repro3 SINEX solutions provided by those ACs for the period 2021–2022 were combined, and the resulting daily combined SINEX solutions made available on April 4, 2023 (IGSMAIL #8329). Like the combined repro3 SINEX solutions for the period 1994–2020, the extended repro3 SINEX solutions for 2021–2022 are expressed in the IGSR3 reference frame and consistent with the igsR3.atx set of antenna phase center corrections (see Rebischung et al., 2023 for more details on the IGSR3/igsR3.atx framework). Note, however, that a full parallel series of repro3 SINEX solutions, expressed in the IGS20 reference frame and made consistent with the igs20.atx antenna phase center corrections has also been derived and is available upon request.

With this extension of the repro3 series up to the date of the switch of the IGS operational products to IGS20/igs20.atx and the repro3 standards, it became possible to form full, long-term IGS combined station position time series consistent with that framework. Such station position time series are available at `ftp://igs-rf.ign.fr/pub/crd` where they are updated on a weekly basis with the results from the operational SINEX combinations. Their format is described here.

3 IGS cumulative SINEX solution

Besides the daily IGS SINEX combinations, which provide daily station position and ERP estimates, another task of the Reference Frame Committee is to maintain the IGS cumulative SINEX solution. This solution is obtained from the stacking of a long-term series of daily IGS SINEX solutions, and includes long-term station coordinates in the form of piecewise linear models, i.e., successive "position+velocity" sets. Updates of the IGS cumulative solution had been temporarily suspended after the switch of the IGS operational products to IGS20/igs20.atx and the repro3 standards on November 27, 2022 (IGSMAIL #8284), but resumed with a new version on April 6, 2023 (IGSMAIL #8331), after the series of daily IGS repro3 SINEX solutions was extended to the period 2021–2022 (see Section 2).

This new version of the IGS cumulative solution is obtained from a long-term stacking of:

- the daily IGS repro3 SINEX solutions for GPS weeks 730 to 2237 (made consistent with the IGS20/igs20.atx framework);
- the daily IGS operational SINEX solutions for GPS weeks 2238 to present.

It is aligned in origin, scale and orientation to the IGS20 reference frame and consistent with the igs20.atx set of antenna phase center corrections.

Updates of the IGS cumulative solution are now bi-monthly (every 8 weeks) instead of weekly. Each update comes with the following files, which are made available at `ftp://igs-rf.ign.fr` and at the IGS data center at CDDIS:

- `IGS0OPSSNX_1994002_$yyyy$doy_00U_SOL.SNX`: full SINEX solution
- `IGS0OPSSNX_1994002_$yyyy$doy_00U_CRD.SNX`: SINEX solution without covariance matrix
- `IGS0OPSSNX_1994002_$yyyy$doy_00U_SUM.SUM`: summary of long-term stacking statistics

`$yyyy` stands here for the 4-digit year and `$doy` for the day of year (001-366) corresponding to the last day of the week of the update.

Two ancillary files to be used with the IGS cumulative solution are:

- `ftp://igs-rf.ign.fr/pub/discontinuities/soln.snx`. This file provides the validity periods of the successive "position+velocity" sets used to describe long-term station trajectories in the cumulative solution. It is based on the ITRF2020 discontinuity list, but also covers stations that are not part of ITRF2020, as well as discontinuities that occurred after the end of the ITRF2020 input data. It is updated with each new release of the IGS cumulative solution.

- `ftp://igs-rf.ign.fr/pub/psd/psd_IGS.snx`. This file provides post-seismic deformation models for stations affected by large earthquakes, in the form of exponential and/or logarithmic functions which must be added to the piecewise linear models given in the IGS cumulative solution. Details on the application of these post-seismic deformation models can be found here.

Time series of residuals from the long-term stacking made to form the IGS cumulative solution are available at `ftp://igs-rf.ign.fr/pub/stacking-res`. Their format and

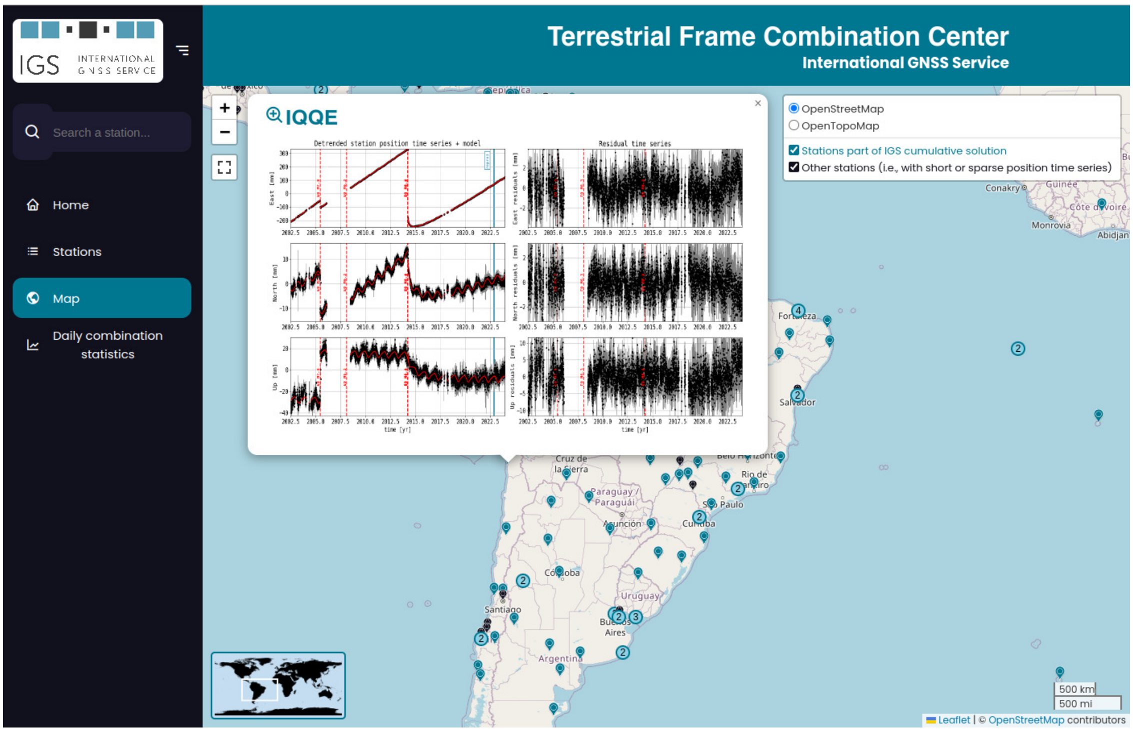


Figure 2: Screenshot of the new IGS SINEX combination website at `https://webigs-rf.ign.fr`.

content is described here. These residual time series can be considered as the IGS (repro3/operational) station position time series corrected for trends, offsets, outliers and post-seismic deformation. Note, however, that during the long-term stacking made to form the IGS cumulative solution, scale factors are estimated between each input daily solution and the long-term stacked solution. Part of the non-linear station motions are known to be absorbed by such estimated scale factors (Collilieux et al., 2012). Hence, the provided residual time series do not fully reflect the Earth's non-linear surface deformation.

4 IGS SINEX combination website

A new website dedicated to the IGS SINEX combination products was developed and publicly released on October 3, 2023 (IGSMAIL #8377) at the address `https://webigs-rf.ign.fr`. This website allows in particular:

- to visualize station position time series extracted from the daily IGS (repro3/operational) SINEX solutions;
- to visualize the piecewise linear (+ post-seismic) models used to describe station

trajectories in the IGS cumulative solution, and their residuals;
- to visualize statistics from the daily IGS SINEX combinations (namely, the "AC ˘ IGS" station position, ERP, geocenter and scale residuals);
- to extract station coordinates from the IGS cumulative solution, as well as the latest IGS reference frames (IGS20, IGb14, IGS14).

A screenshot of the website is provided in Figure 2, showing part of the map of all stations contained in the daily IGS SINEX solutions and a miniature of the position and residual time series of the IGS station IQQE (Iquique, Chile).

References

Altamimi, Z., P. Rebischung, X. Collilieux, L. Métivier, K. Chanard (2023). ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. Journal of Geodesy, 97(47), https://doi.org/10.1007/s00190-023-01738-w

Collilieux, X., T. van Dam, J. Ray, D. Coulot, L. Métivier, Z. Altamimi (2012). Strategies to mitigate aliasing of loading signals while estimating GPS frame parameters. Journal of Geodesy, 86:1–14, https://doi.org/10.1007/s00190-011-0487-6

Rebischung, P. (2023a) IGS Reference Frames and their relationship to the ITRF. In: Sideris, M. G. (eds.) Encyclopedia of Geodesy, Encyclopedia of Earth Sciences Series, Springer, Cham, https://doi.org/10.1007/978-3-319-02370-0_94-1

Rebischung, P. (2023b) Reference Frame Working Technical Report 2022. In: Dach, R., Brockmann, E. (eds.) International GNSS Service Technical Report 2022 (IGS Annual Report). IGS Central Bureau and University of Bern, Bern Open Publishing, pp. 217–225, http://dx.doi.org/10.48350/179297

Rebischung, P., Z. Altamimi, L. Métivier, X. Collilieux. K. Gobron, K. Chanard (2023) Analysis of the IGS contribution to ITRF2020. ESS Open Archive, https://doi.org/10.22541/essoar.170365313.34695479/v1

Villiger, A. (2023) Antenna Working Technical Report 2022. In: Dach, R., Brockmann, E. (eds.) International GNSS Service Technical Report 2022 (IGS Annual Report). IGS Central Bureau and University of Bern, Bern Open Publishing, pp. 161–166, http://dx.doi.org/10.48350/179297

RINEX Committee Technical Report 2023

F. Gini

ESA/ESOC, Germany
e-mail FrancescoGini@esa.int

1 Introduction

The IGS/RTCM RINEX committee 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 Committee consists of IGS scientific and institutional members and RTCM-SC104 industry members.

2 Membership

Current membership is available here and will be adjusted in 2024 due to new addition requests and retirements. The committee has about 60 members at the current time. In addition, at the beginning of the year a new Chair was appointed.

3 Summary of Activities in 2023

Over 2023 the most important development has been the implementation and adoption by the IGS of the RINEX 4.xx format definition standard, in particular the adoption by the IGS stations of the RINEX 4.00 format, published back in December 2021. In 2023 a revised version, namely RINEX 4.01, has been redacted and published to accommodate the new (e.g., NavIC L1) and future (GPS L1/L2 RMP) signals, and is available here.

Additionally, activities within the RINEX committee were initiated to upgrade the format to include new or updated navigation messages (e.g., NavIC L1, GLONASS CDMA). It is foreseen to have the changes integrate in the next RINEX 4.02 version, to be published in the 1st half of 2024. Several requests of clarifications and editorial changes have been raised to the RINEX committee, have been proposed and discussed in the 2023 RINEX Progress Meeting and will be integrated in the next release.

Additionally, the RINEX Committee Charter was updated to reflect the latest status of the formats. The new charter, officially approved, shall be soon published here.

At the end of 2023, the new Terms of Reference were approved by the IGS Governing Board, transitioning the *RINEX Working Group* to the new nomenclature *RINEX Committee*.

4 Planned 2024 Activities

During 2024 RINEX version 4.02 will be created (targeting 1^{st} half 2024) to incorporate new navigation messages, editorial changes and other potential clarifications or format upgrades.

IGS Troposphere Committee Technical Report 2023

S. M. Byram

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

1 Introduction

The IGS Troposphere Working Group (IGS TWG) was founded in 1998. The United States Naval Observatory (USNO) assumed chairmanship of the WG as well as responsibility for producing IGS Final Troposphere Estimates (IGS FTE) in 2011. In 2023, the current working groups of the IGS were transitioned to committees, thus making the former Troposphere Working Group now the Troposphere Committee.

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) and in 2023 used the IGS20 reference frame, the IGS realization of the ITRF2020 reference frame. 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

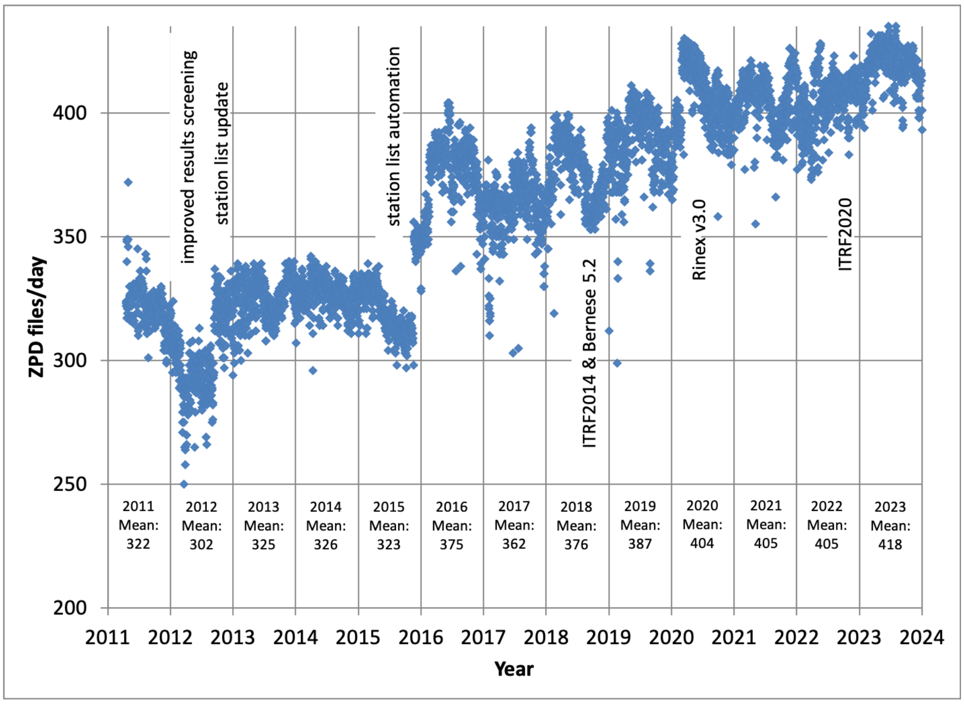


Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011–2023.

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).

Fig. 1 shows the number of receivers for which USNO computed IGS FTEs 2011-2023. The average number of quality-checked station result files subm18ted per day in 2023 was 405. Fig. 1 is annotated with major changes in the processing of the IGS FTEs, most which result in an increase of produced IGS FTEs. The result files are available for download from the CDDIS data server at: https://cddis.nasa.gov/archive/gnss/products/troposphere/zpd/.

3 IGS Troposphere Working Group Activities 2023

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 Troposphere Committee meeting was held virtually during the 2022 IGS Workshop producing the following recommendations which were the basis of activities in 2023. Communications on news and activities were distributed via the TWG mailing list.

Recommendations from the 2022 Committee 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 Committee Charter began in 2022 and extended into 2023 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

References

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

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

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

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

IGS INTERNATIONAL GNSS SERVICE

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

igs.org | cb@igs.org

AIUB

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

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

IGS is a Network Member of International Council for Science - World Data System

ICSU WORLD DATA SYSTEM
IUGG
IAG GGOS Global Geodetic Observing System