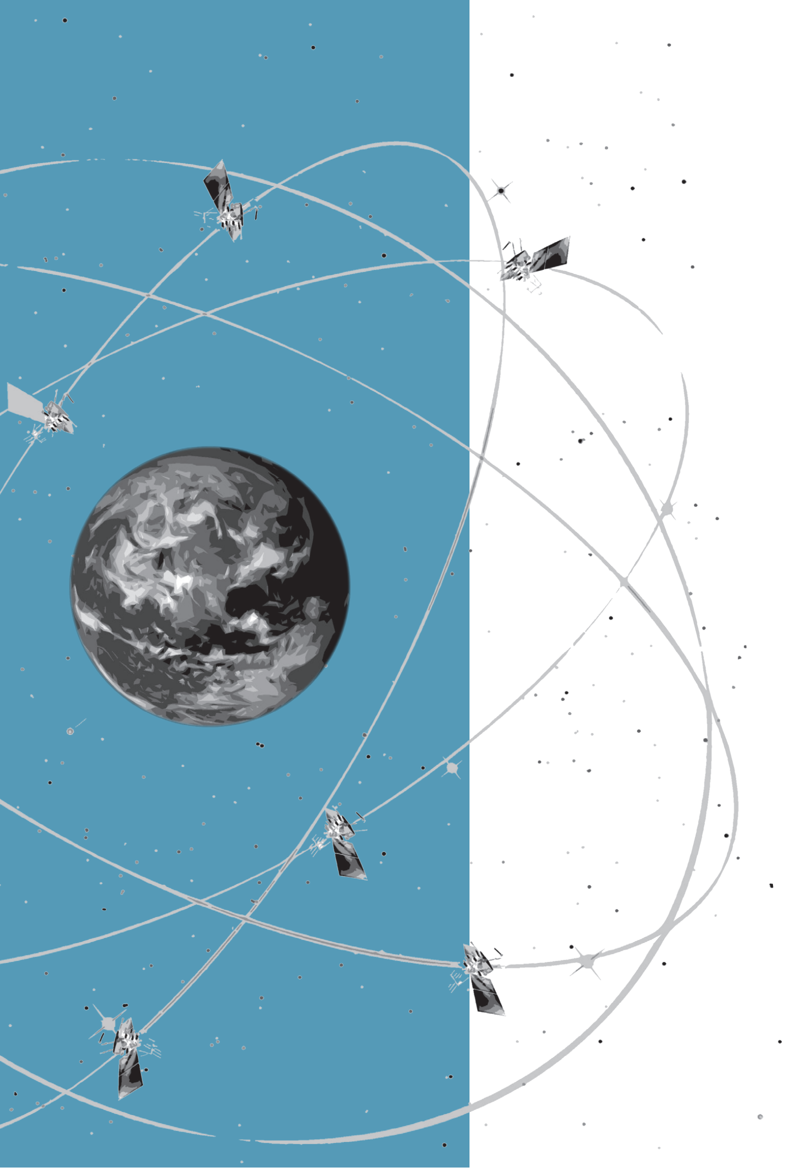
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2015



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International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

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Compiled in April and May 2015, by Yoomin Jean, Rolf Dach (Eds.)

Technical Report 2015

IGS Central Bureau

http://www.igs.org

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Published in June 2016

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IGS Technical Report 2015
ISSN: 2297-8526
ISBN: 978-3-906813-18-9 ; University of Bern, Bern Open Publishing.
DOI: 10.7892/boris.80307

Cite as:
Jean, Y., Dach, R. (eds.) (2016). *International GNSS Service Technical Report 2015 (IGS Annual Report)*. IGS Central Bureau and University of Bern; Bern Open Publishing DOI: 10.7892/boris.80307

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 2015* includes contributions from the IGS Governing Board, the Central Bureau, Analysis Centers, Data Centers, station and network operators, working groups, pilot projects, and others highlighting status and important activities, changes and results that took place and were achieved during 2015.

This report is available in electronic version at
https://files.igs.org/pub/resource/technical_reports/2015_techreport.pdf.

The IGS wants to thank all contributing institutions operating network stations, Data Centers, or Analysis Centers for supporting the IGS. All contributions are welcome. They guarantee the success of the IGS also in future.

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Gary Johnston

Geoscience Australia, Australia

1 Introduction

In June 2014, the IGS celebrated its 20th anniversary. This momentous milestone was an opportunity to recognize the significant efforts of the IGS participants, both past and present, and to marvel at the outstanding improvements in products that the service has achieved over that time. It also signaled that it was time to look forward towards our next 20 years.

In 2015, the IGS Governing Board started the process of looking forward by reviewing its strategic plan. Issues under consideration include the scope of products and services, appropriate acknowledgement of participants and contributors, interface with IAG and GGOS, data and product licensing, continued GPS to GNSS transition, and new activities around GNSS system monitoring and assessment. The new strategic plan is due for completion in late 2016.

2 IGS Operational Activities

Daily routine operations are the heart of the IGS. Various components of the service ensure that tracking data and products are made publicly available every day. Approximately 500 tracking stations are maintained and operated globally, making tracking data available at time latencies spanning from daily RINEX files to real–time streams.

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

Twelve Analysis Centers and a number of Associate Analysis Centers utilize tracking data from between 70 to more than 350 stations to generate precision products up to four times per day. Product Coordinators combine these products on a continuous basis and assure the quality of the products made available to the users.

The collective effort of the IGS produces 700 IGS final, rapid, ultra–rapid and GLONASS–only product files, as well as 126 ionosphere files weekly. Furthermore, troposphere files for more than 300 stations are produced on a daily basis. A total of 640 million tracking data files (60 TB) and 110 million product files (15 TB) were downloaded in 2015 from the NASA Crustal Dynamics Data Information System (CDDIS), one of four IGS global Data Centers, by more than 10,000 unique hosts – demonstrating the intense interest of users in IGS data and products.

The Central Bureau is operationally responsible for day–to–day management, interaction with station operators, and answering typically some 150–200 questions and requests from users per month. All these activities are performed year round, on a daily basis, with high redundancy and reliability – an impressive effort that is only made possible by the strong engagement of many individuals and the support of more than 240 institutions worldwide, in over 100 countries.

3 IGS Highlights in 2015

The following is a brief summary of key highlights in 2015:

- AC coordinator:

  The Governing Board has endeavored for some time to identify a new Analyses Centre Coordinator (ACC). This role has until recently been undertaken by Kevin Choi from the US National Geodetic Survey (NGS). NGS flagged some time ago that their support for the function needed to finish by the end of 2015. In the absence of any other nominations Geoscience Australia, jointly with MIT, put forward a proposal for a joint ACC. This proposal identified Dr Tom Herring (MIT) as the lead ACC, with operational support from Dr Michael Moore (GA). This proposal utilizes Amazon Web Services (AWS) for the computing platform, and a collaborative operational model where the monitoring of combination systems is undertaken by MIT during their working day and GA at other times. This reduces the need for 24hour /day monitoring by one individual. This proposal was subsequently accepted and endorsed by the GB.

The ACC software suite was subsequently installed on AWS jointly by Kevin Choi and Michael Moore. Operational transfer of the ACC functions occurred progressively through December 2015 culminating in February 2016. The Governing Board thanks NGS for their support over an extended period in fulfilling the requirements of the ACC role.

- MGEX experiment:

  The success of the MGEX experiment has demonstrated the inevitability of a transition of the IGS to a full multi–GNSS Service. Accordingly, the Governing Board decided to acknowledge this by terminating the "experiment" status and move MGEX to a pilot project. Continued efforts are required to negotiate access to satellite specific information for new satellites from system providers, allowing for more realistic models of satellite behavior to be developed and utilized by the IGS AC's.

- Wuhan Data Center:

  In 2015 the Governing Board endorsed the proposal by Wuhan University to become an IGS Global Data Center. The Wuhan data center offers access to the full collection of IGS data and products to any user globally, especially those within the Asia Pacific Region. Importantly the data center gives direct access to the IGS data holdings to the very large research sector within China.

- ICG Monitoring and Assessment Joint Pilot Project:

  In 2015 discussions occurred between the IGS GB and representatives from the International Committee on GNSS (ICG) concerning the establishment of joint pilot to undertake monitoring and assessment of the GNSS constellations. This requirement has emerged from the ICG in which the IGS is an active participant. Planning continues on how this pilot project can be constructed and managed. A call for participation will occur in 2016.

- Planning for the Sydney workshop:

  Following the success of the Pasadena workshop, and the many that had occurred before that, 2015 saw the planning for the Sydney workshop take shape. A full summary of the Sydney workshop will be included in the 2016 report.

4 IGS Governing Board Meetings in 2015

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.

Table 1: IGS events in 2015

Date	Event
April 12	GB Business Meeting in Vienna (Sunday prior to EGU)
June 23	GB Business Meeting, during 26^{th} IUGG/IAG General Assembly, Prague
December 13	45th GB Meeting in San Francisco (prior to AGU)

5 Communications, Advocacy, and Outreach

The IGS is represented in a variety of roles throughout the geodetic community. IGS Governing Board and Associate Members served on the Coordinating Board, Executive Committee, Consortium, and Science Panel of the IAG Global Geodetic Observing System (GGOS).

Members of the IGS Governing Board actively participated in the United Nations Committee of Experts on Global Geospatial Information Management (UN–GGIM), participating in the fifth session of the UN–GGIM at UN Headquarters in New York. IGS Governing Board members involved in the UN GGIM Global Geodetic Reference Frame (GGRF) Working Group played an active role in drafting a resolution for "A Global Geodetic Reference Frame for Sustainable Development" – the first resolution recognizing the importance of a globally–coordinated approach to geodesy. This resolution was adopted in February 2015 by the UN General Assembly.

IGS Governing Board members also served in leadership roles in the United Nations International Committee on GNSS (ICG), including the Working Group D on Reference Frames, Timing, and Applications, as well as Working Group A subgroup on International GNSS Monitoring and Assessment (IGMA). In this capacity, the IGS participated in the ICG–10 meeting in November 2015 in Boulder, Colorado, USA. The IGS is also well–represented in the International Earth Rotation and Reference Systems Service (IERS), in IAG Sub–Commission 1.2 on reference frames, in the RTCM SC104, and others.

Governing Board members continue to be actively involved in communications, advocacy, and outreach through presentations at international meetings and articles in geospatial magazines.

6 Outlook 2016

The year 2016 will continue to be challenging for the IGS as the reliance on IGS products grows, and our products are being integrated into a wide variety of scientific and societal applications, often with very little understanding or acknowledgement of where the products come from. The collaborative nature of participation in the IGS poses resourcing issues for many of the participants, and raises serious questions around the scope of IGS activities. To help the GB better understand these issues and develop an appropriate strategic plan to help manage the issues, a stakeholder questionnaire will be undertaken, seeking input from existing members, and a broader user community on how they perceive the IGS currently, and how that differs from the ideal. This process should be completed by the December 2016 GB meeting.

Implementation of RINEX 3.n continues in 2016. Network operators, Data Centers and Analysis Centers are working actively to transition data products and workflows to accommodate the new RINEX standard, a key milestone in the transition to Multi–GNSS.

Under the leadership of the Infrastructure Committee, and with significant input from the Network coordination team, the IGS network is being upgraded to unify the existing GPS network with the multi–GNSS requirements. Specific efforts are also underway to encourage participation by site operators in locations where the existing IGS network is not optimum. In these cases, sites meeting the requirements of the IGS Site guidelines are incorporated into the network.

Table 2: Governing Board Membership 2015

Member	Affiliation	Country	Function
Gary Johnston*	Geoscience Australia	Australia	Board Chair
Loukis Agrotis	ESA/ESOC	Germany	Real–Time Analysis Coordinator
Zuheir Altamimi	Institut National de l'Information Géographique et Forestière	France	IAG Representative
Felicitas Arias	BIPM	France	BIPM/CCTF Representative
Fran Boler	UNAVCO	USA	Data Center Representative
Claude Boucher	Institut National de l'Information	France	IERS Representative
Carine Bruyninx	Royal Observatory of Belgium	Belgium	IGS Network Representative
Mark Caissy	Natural Resources Canada	Canada	Real–Time WG, Chair
Kevin Choi	National Geodetic Survey (NOAA)	USA	Analysis Center Coordinator
Michael Coleman	Naval Research Laboratory	USA	IGS Clock Product Coordinator
Rolf Dach	Astronomical Institute, University of Bern	Switzerland	Analysis Center Representative
Yamin Dang	Chinese Acedamey of Surveying and Mapping	China	Appointed
Shailen Desai	Jet Propulsion Laboratory	USA	Analysis Center Representative
Steve Fisher	IGS Central Bureau, JPL	USA	IGS Central Bureau, Secretariat
Bruno Garayt	Institut National de l'Information Géographique et Forestière	France	IGS Reference Frame Coordinator
Christine Hackman	United States Naval Observatory	USA	Troposphere WG, Chair
Urs Hugentobler*	Technische Universität München	Germany	Immediate past chair of the GB B
Satoshi Kogure	JAXA	Japan	Appointed (IGS)
Andrzej Krankowski	University of Warmia and Mazury in Olsztyn	Poland	Ionosphere WG Chair
Ken MacLeod	Natural Resources Canada	Canada	IGS/RTCM RINEX WG Chair
Chuck Meertens*	UNAVCO	USA	Appointed (IGS)
Oliver Montenbruck	DLR/German Space Operations Center	Germany	Multi–GNSS WG Chair
Ruth Neilan	IGS Central Bureau, JPL	USA	Director of IGS Central Bureau Secretary
Carey Noll	NASA/GSFC	USA	Data Center WG Chair
Chris Rizos*	Univ. of New South Wales	Australia	Appointed (IAG) former IAG President
Ignacio Romero	ESA/ESOC	Germany	Infrastructure Committee Chair
Laura Sanchez	TU Munich, DGFI	Germany	IGS Network Representative
Stefan Schaer	Federal Office of Topography, Swisstopo	Switzerland	Bias and Calibration WG Chair
Ralf Schmid	DGFI	Germany	Antenna WG Chair
Tilo Schöne	Deutsches GeoForschungs-Zentrum	Germany	TIGA WG Chair
Tim Springer*	ESA/ESOC	Germany	Analysis Center Representative
Marek Ziebart	University College London	UK	Space Vehicle Orbit Dynamics WG Chair

* Member of IGS GB Executive Committee

IGS Central Bureau Technical Report 2015

R. Neilan[1], S. Fisher[1], G. Walia[1], D. Maggert[2], A. Craddock[1]*

1 Caltech/JPL
2 UNAVCO

1 Introduction

The Central Bureau's (CB) mission is to provide a continuity of management and technology to sustain the IGS in perpetuity. It functions as the executive office of the service and is responsive to the IGS Governing Board in carrying out its directives and decisions. The CB coordinates the IGS tracking network and operates CB information system (CBIS), the principal information portal where the IGS web, ftp and mail services are hosted. The CB also represents the outward face of IGS to its diverse global user community. The CB office is hosted at the California Institute of Technology/Jet Propulsion Laboratory, Pasadena, California, USA. It is funded principally by the US National Aeronautics and Space Administration (NASA), which generously contributes significant staff, resources and coordination to advance the IGS. The following report highlights progress made by the Central Bureau in 2015.

2 Executive Management and Governing Board Participation

Governing Board meetings were held in April (Vienna), June (Prague) and December (San Francisco) 2015. The Executive Committee met additionally by teleconference approximately every other month. CB staff followed–up throughout the year by implementing actions defined by the GB to carry out the business of the service.

*Director

A biennial review of the IGS Associates (defined as those individuals who contribute a significant effort to the IGS) was conducted by the Associate Member Committee with CB support in 2015. The number of IGS Associates grew by 63 members to 337 since the last review in 2013. Those members represent 118 countries vs. 90 in 2013. The IGS Associates form the body of voters who elect the Governing Board.

The CB supported the Elections Committee in conducting the December Governing Board election where two Analysis Representatives were elected to replace members whose terms expired at the end of the year. Of 4 candidates who stood for the election, M. Fritsche and S. Desai received most of the Associate Member votes. Their 4–year terms started on January 1 2016. The Associate Member and Governing Board Member lists are maintained on the IGS website (http://igs.org/about/organization).

3 Strategic Plan/Progress

Formal benchmarking of progress made in advancing the IGS mission has continued for three years in a row. Metrics indicating performance on defined objectives are tracked annually by the CB and published on the IGS website (http://kb.igs.org/hc/en-us/sections/200623533). The IGS has continued through this period to exceed the targeted product availability, which is our most important measure of success. In addition, metrics related to the growth of IGS participants, users, competencies and external influence all trended favorably, though devoting more effort to sustain the IGS funding has consistently been identified as an area for future improvement.

The 2017–2021 strategic plan development cycle was kicked–off just before the December Governing Board Meeting where a meeting was held to establish a work plan and timeline for writing the new strategic plan. A review of the current plan found it still to be relevant and that the new plan would rely on it as a basis for incremental improvement. The planning group suggested after considerable discussion and analysis that broader user input would be desirable in identifying future opportunities for IGS. This input is to be solicited through a survey questionnaire form to be broadly circulated in the first part of 2016.

4 Network Coordination

The 49 MGEX stations that that fully meet IGS requirements were elevated to full status in 2015. An additional 30 other proposed stations were also reviewed and accepted following a strict vetting process involving the CB/Network Coordinator and Infrastructure Committee Chairman. 38 stations that were either replaced with new stations, failed to provide data to IGS standards, or ceased operation were decommissioned during the year. In net, the number of IGS stations has increased by 53 to 491 total stations through 2015.

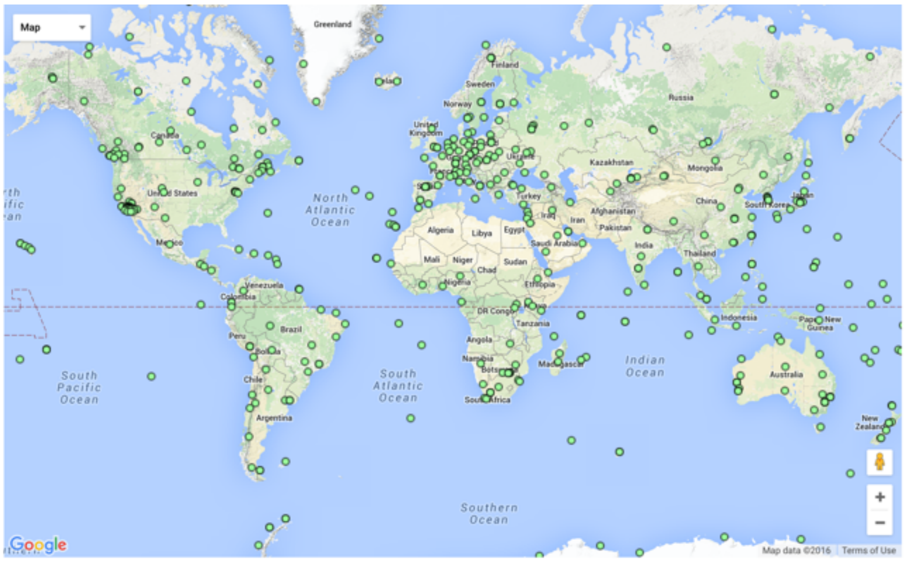

Figure 1: Network map from www.igs.org/network.

Of these, 127 are capable of multi-GNSS tracking and 118 stream observation data to support real–time applications.

5 Web Development and IT Support

In addition to administering and generally supporting the CBIS operation, we have carried forward the move of all of the CB processes external cloud hosted servers to allow global access. Disaster recovery procedures were reviewed and we're now in process of implementing new backup and restore procedures in conjunction with UNAVCO. The Website has been more actively updated with events, news and current information than in previous years. Our web access metrics show that the newer content is attracting users to the IGS website, as is our presence on social media platforms. Development of the Site Log Manager (SLM) database application was substantially completed by April, though incremental improvements have continued to be made based on user feedback. The SLM was introduced to IGS station operators in May with 77 new users adopting it for IGS site metadata management during the year. Some assistance has been provided to the ACC transition with requirements definition and minor IT tasks to aid in the transition of the IGS combination software to cloud based servers. A summary of progress on a number of IT tasks can be seen in Tab. 1.

Table 1: Progress on web and IT activities

Task or component	Progress
`IGS.org/mgex`	added - content reference 1.5
	added - Product Comparisons Section
	added - SLM powered network page
	resolved - support numerous requests
`IGS.org/network`	Network 1.5 update
	added - link access to all networks
	resolved - support numerous requests
`connect.igs.org`	added - Workflow - Impact on Strategic Objectives
	added - Workflow - IGS Component Summary Report
	added - Workflow - Requests - `http://connect.igs.org/request`
	added - https over entire Site
	resolved - JPL disallow access to the site server
	support and administration
`upload.igs.org`	added - no effort upload and generation of website for meetings
`IGSCB.jpl.nasa.gov`	dreamhost host migration of dependent services igscb administration
	resolve downtime (4–10 times)
	server move / re–move
	security ticket resolution
	mailman administration Support
	server documentation
	support and administration
`slm.igs.org`	development management with UNAVCO
	metadata workshop contribution
	user support – introduce SLM to 77 new users
	server support and administration
`kb.igs.org`	support ticket resolution 400 tickets
	renewal of `http://kb.igs.org` service
	server support and administration
`igs.org/analysis`	ACC server requirements discovery
	website coordination
	mailing list and support for DNS
`rts.igs.org`	web content updates
	caster operation and administration
	user registration and support
	server support and administration
CMS	added - version .5 of Content Management System
CBIS cloud migration	Migrating operational cron jobs from JPL to cloud server
	(Migrating remaining web content from old server)
	eliminating old server dependencies
	Planning mail list transition to cloud
Disaster recovery	specified backup and restore requirements across all servers
	working cooperatively with UNAVCO

6 Project Support, Committee and Working Group Participation

The CB's participation within the IGS Working Groups and Projects was limited in 2015. Principally, high priority and essential maintenance activities were addressed, such as:

- preparing site metadata systems for RINEX 3 adoption,
- integrating MGEX stations within the IGS network,
- maintaining a Real–time caster and minimally supporting the Real–time Service IOC operation,
- helping the Antenna Working Group with maintaining the IGS equipment files,
- handling specific needs during the ACC transfer to Geoscience Australia,
- participating in the site metadata Workshop and subsequent discussions,
- and supporting related working group web content.

In addition, the CB and IC Chairman met by teleconference roughly once per month on a range of station and infrastructure management issues.

7 IGS User Support

The CB expend considerable effort on IGS community and user technical support. As measure of this, the CB tracks email traffic through the CB mail list. This traffic has increased by 10% in 2015 to about 3300 messages, though much of the increase is from notification emails from various CBIS processes that do not require response. Increasingly over the last year we have steered many of the user support inquiries received through the web into a support trouble ticketing system. With 2015 being its first full year of operation, the system tracked over 400 support issues that were resolved through the year. This coupled with the IGS knowledge base is relieving some of the email–based support that the CB has historically provided.

8 External Participation

The CB has continued to extensively interact with many IGS stakeholders. In 2015, these efforts were highlighted by UN–GGIM working group activities, particularly adoption of the resolution for the GGRF, which is anticipated to open additional avenues for international cooperation for IGS and geodesy in general (http://ggim.un.org/UN_GGIM_wg1.html). Significant progress was also made in developing a cooperative plan with the ICG to monitor performance and interoperability metrics between the different GNSSs, which is expected to take the form of a joint working group between ICG and IGS beginning in 2016. The CB Director and staff members have continued representing the IGS within the IAG services committees and boards, including R. Neilan on the GGOS Coordinating Board and Executive Committee, and S. Fisher as the IGS Network Representative to the IERS Directing Board. R. Neilan has also maintained her appointment as NASA representative to the US PNT Coordination office (pnt.gov). Tab. 2 provides a listing of the principal external meetings attended by CB staff during 2015.

Table 2: Principal meetings attended by CB staff and role/outcomes

Meeting	Month	Venue	Role/Outcomes
NASA HQ Programmatic Interactions	Jan.	Washington DC	Programmatic meetings at NASA HQ with ESIP Partners and WDS representatives
ICG strategic directions meeting	Mar.	Munich	Represent IGS on WG–D and IGMA activities
ICSU World Data System	Mar.	San Diego	Represent IGS on WDS scientific committee meetings
Governing Board Business Meeting	Apr.	Vienna	Discussion on “IGS 2.0” a new paradigm to support IGS’s ever–increasing growth
NASA HQ Programmatic Interactions	May	Washington DC	NASA/SGP strategy meeting
United Nations Global Geographic Information WG	Sep.	New York	Adoption of Resolution for Global Geodetic Reference System for economic development
Programmatic Interactions with INPE, Brazil	Sep.	Sao Paulo	Meetings on NASA/INPE cooperation in developing space geodetic capabilities
GGOS Meta Data Workshop	Oct.	Boulder	Initiated development of geodetic metadata standard
GGOS Days	Oct.	Frankfurt	Board and committee representation
International Committee on GNSS 10th Meeting	Nov.	Boulder	Supported local meeting planning IGMA proposal to IGS was developed
PNT Advisory Board	Nov.	Boulder	Ongoing Board participation
IERS DB Meeting	Dec.	San Francisco	In lieu of participating, coordinated with AC and RF coordinators to participate in meeting for IGS
Governing Board Meeting	Dec.	San Francisco	Two AC representatives elected to GB New ACC transition plan accepted 2017–2021 Strategic planning cycle initiated
Monthly GB Exec. Committee	Monthly	Video–conference	Ongoing IGS business

9 Publications

- *2015 IGS Performance Dashboard*, IGS website
- *IGS 2014 Technical Report section*, IGS website
- *NASA SGP/ICPO annual progress report*, NASA internal publication

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2015

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1 Introduction

In 2015, IGS core products were combined and distributed in a timely manner over 99% of the time. To ensure continued production of high–quality IGS products, the Analysis Center Coordinator (ACC) performed high–level oversight and quality control of Analysis Center (AC) products, combination performance, and maintenance of the ACC website with updated plots. Also coordinated among ACs to assimilate changes made by them and to ensure that the best analysis models and procedures are used, along with coordination among the other relevant IGS components, preparation of component reports, and coordination of the IGS 2nd reprocessing campaign. IGS has contributed to the ITRF2014 by providing station coordinates and EOP values.

2 Product Quality and Reliability

With the exception of a few unusual delays, delivery of all IGS products was generally uninterrupted. IGV (IGS Ultra–rapid GNSS products) still remains as experiment status due to lack of contributing ACs as a stable production. Currently, only four ACs are submitting the orbit solutions regularly but only three of them provide the GNSS clocks. More GNSS clock centers are desirable.

Sporadic errors in the GLONASS broadcast files have caused delays in the Final GLONASS products. IGS data centers rely on the quality of the broadcast files from each station.

Table 1: IGS core product series with latency, issue times and data spans

Series	ID	Latency	Issue times(UTC)	Data spans(UTC)	Remarks
Ultra–Rapid (observed half)	IGA	3–9 hr	@ 03:00, 09:00, 15:00, 21:00	–24 hr @ 00:00, 06:00, 12:00, 18:00	• for near real–time apps • GPS & GLONASS • issued with following IGU
Ultra–Rapid (predicted half)	IGU	real–time	@ 03:00, 09:00, 15:00, 21:00	+24 hr @ 00:00, 06:00, 12:00, 18:00	• for real–time apps • GPS & GLONASS • issued with prior IGA
Rapid	IGR	17 – 41 hr	@ 17:00 daily	±12 hr @ 12:00	• for near–definitive, rapid apps • GPS only
Final	IGS	12 – 19 d	weekly each Thursday/Friday	±12 hr @ 12:00 for 7 d	• for definitive apps • GPS & GLONASS

2.1 Combined orbit quality

Inter–AC agreement of the Final orbit products is ∼5 mm with precision ranges 3–4 mm (1D error). Due to Repro2 ACs switched their operation to match with the Repro2 strategies around the week 1820, inter–AC agreement has been improved to ∼5 mm with precision ranges 3–4 mm (1D error).

WRMS differences between the full–weight ACs and the zero–weight ACs became more distinctive in the Rapid solutions.

2.2 Events Impacting Product Quality and Reliability

- In Jan–Feb, GFZ had fixed the issues with the SV DCBs
- In early March, MIT Final clocks are set to be comparison only.
- Network outage at the NRL facility:
  - [IGSMAIL–7060] Ultra–rapid product was delayed 5.5 h
  - [IGSMAIL–7064] IGU1835_6–12 and 18, IGR wk1834_5 delayed until 21:35 [UTC]
- GOU temporarily stopped Ultra–rapid contribution since wk1854–4 06h. – after break down trying to update the software but having lack of resources.
- Minor issues:

2015–03–10	Beginning 1835_1, NGS and GFZ Rapid Polar motion and LOD is back in the combination.
2015–07–21	IGV reference clock is switched from GFZ to EMR due to missing GFZ submission since igv18541_18.
2015–08–03	wk1856–0 COD starts GPS/GLO clock for Rapid

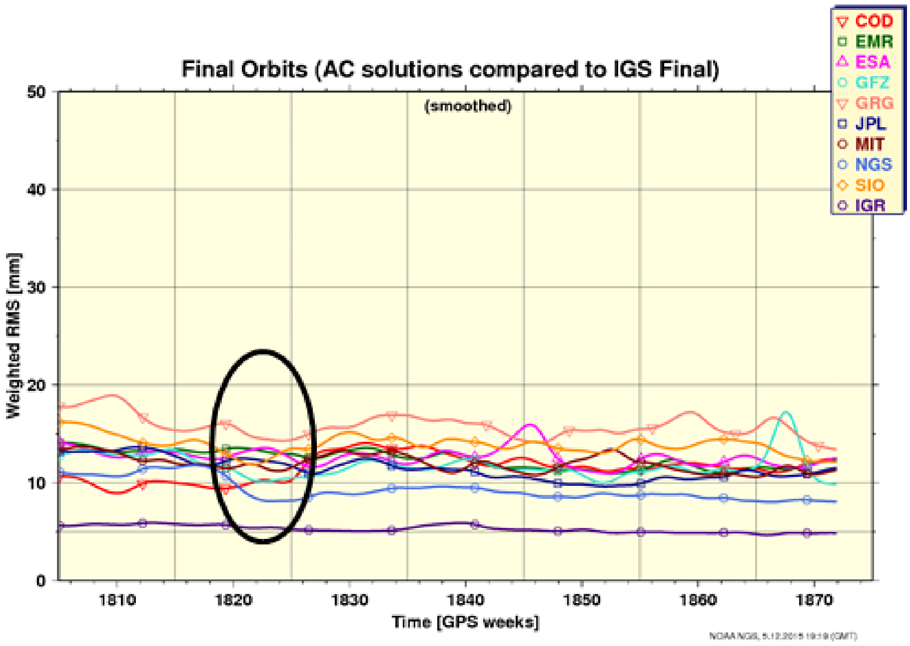

Figure 1: Weighted RMS for the Final orbit combinations for recent weeks.

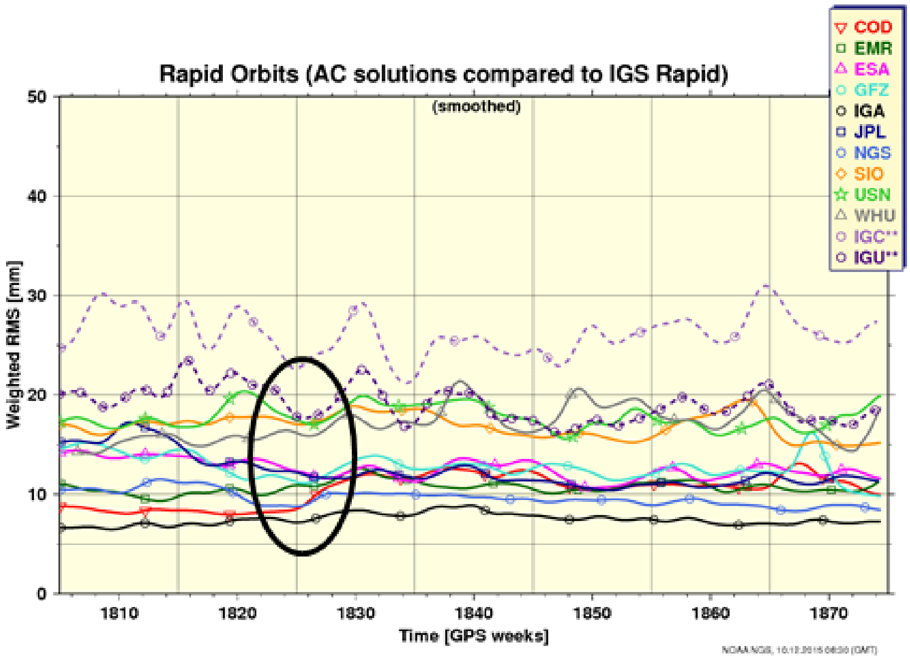

Figure 2: Weighted RMS for the Rapid orbit combinations for recent weeks.

2.3 New Analysis Center Coordinator

Since July 2015, NOAA/NGS has been working with Geoscience Australia (GA) and Massachusetts Institute of Technology (MIT) for the Analysis Center Coordinator (ACC) duty transition at the end of 2015. We plan to implement two new changes: Placing combination server on the Cloud (Amazon EC2 service), and splitting duties into two time zones (US Eastern time and Australian standard time). We've remotely worked to set up the server environment and preliminary testing for 3 months and had intensive on–the–job training in Geoscience Australia for 3 weeks in November 2015. In order to reduce the internet connection latency, we've decided to use the Cloud service based on Frankfurt, Germany as a primary server and use Sydney–based service as an emergency back–up. Parallel combination has been started in week 1868 and generating results that are fully consistent with the current operational combination server.

Actual transition of duty will happen in January 2016 although the current NGS combination server will still be running in the background for another month to ensure the continuity of operation.

For users and analysis centers, there should be no apparent changes after the transition. The ACC Email is switched to acc@igs.org and igs.acc@noaa.gov will be decommissioned in the near future. All the products are available from and deposited to the same locations as currently. While it is expected that the transition should happen transparently, there could be some delays as the new team works through any problems that do arise.

2.4 Recommendations

For the stable UTCk clock processing, Mike Coleman (NRL) recommended for the ACs to include important sites for their clock processing. Below lists are available in http://acc.igs.org.

- UTCk Reference Clock Stations: Preferred to have at all times both in IGS and IGR (in the order of importance) – http://acc.igs.org/utck_ref_clk.list
  - PTBB, USN7, OPMT, IENG, BJNM, SPT0, SFER, WAB2, NIST, TWTF, NRC1, NRL1
- Non UTCk stations but very stable clocks: – http://acc.igs.org/non_utck_clk.list
  - YELL, PIE1, WSRT, HERS, PRDS, HRAO, WTZR, KOUR, GODE, STJO, KOKB, KOKV, MKEA

3 Publications and Meeting Presentations

This section highlights a selection of papers and presentations in 2015 that are relevant to the quality of the IGS products. Download is available at http://acc.igs.org.

- **Preliminary Analysis of IGS 2nd Reprocessed Orbits (2015)**

  K. Choi, a poster presentation at the 2015 European Geosciences Union

- **Combination of the IGS repro2 Terrestrial Frames (2015)**

  P. Rebischung et al., a poster presentation at the 2015 European Geosciences Union

- **Impacts of GNSS Position Offsets on Global Frame Stability (2015)**

  J. Griffiths and J. Ray, a presentation at the 2015 European Geosciences Union Meeting

- **The IGS Contribution to ITRF2014 (2015)**

  P. Rebischung, B. Garayt, Z. Altamimi, X. Collilieux, a presentation at the 26th IUGG General Assembly, Prague, 28 June 2015

4 ACC Activities Planned for 2016

- Maintain existing products, as usual.
- ACC server/duty transfer will be completed in January.
- Smooth ACC duty transition
- Completing Repro2 Orbit and Clock combination
- Implementation of ITRF2014 (IGS14)

CODE Analysis Center Technical Report 2015

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E. Brockmann[2], D. Ineichen[2], S. Lutz[2], A. Wiget[2],
A. Rülke[3], D. Thaller[3], H. Habrich[3], W. Söhne[3], J. Ihde[3],
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Technische Universität München, 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 for Cartography and Geodesy (BKG), Frankfurt a. M., Germany
- Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG, TUM), Munich, Germany

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

[a] Institute of Geodesy, Czech Technical University in Prague, Czech Republic

2 CODE products available to the public

A wide range of GNSS solutions based on a rigorously combined GPS/GLONASS data processing scheme is computed at CODE. The products are made available through anonymous ftp at:
`ftp://ftp.unibe.ch/aiub/CODE/` or `http://www.aiub.unibe.ch/download/CODE/`
An overview of the files is given in Tab. 1.

Within the table the following abbreviations are used:

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

With GPS week 1706, CODE started to generate a pure one–day solution (label "COF") in addition to the traditional three–day long–arc solution (label "COD"). The result files from both series are submitted to the IGS data centers hosting the products. The related files are listed in Tab. 2.

The network used by CODE for the final processing is shown in Fig. 1. Almost 80% of the stations support GLONASS (red stars).

Referencing of the products

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

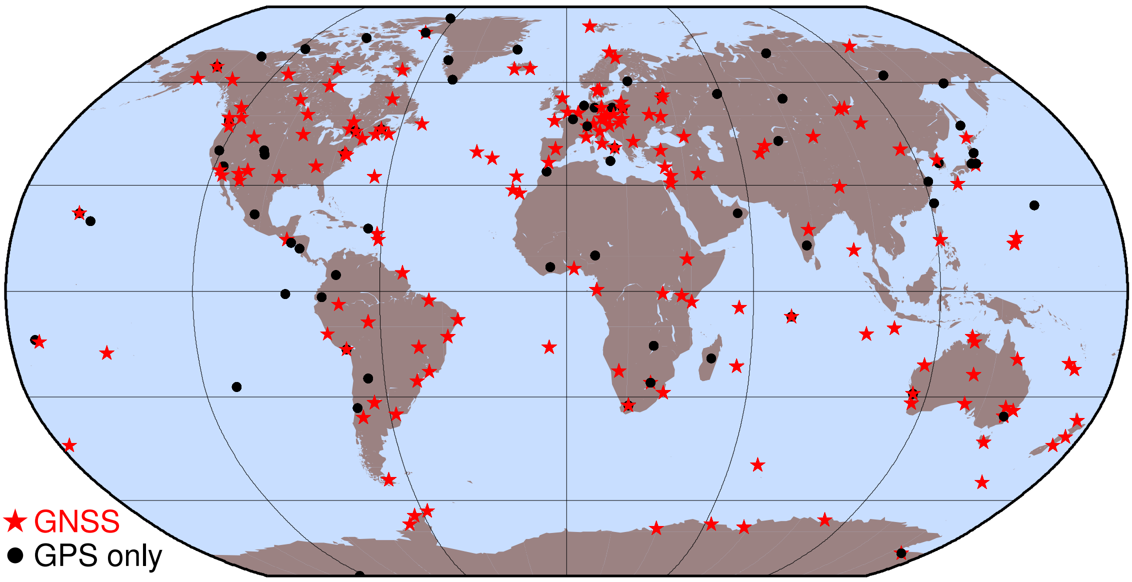


Figure 1: Network used for the GNSS final processing at CODE by the end of 2015.

- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Orliac, Etienne; Prange, Lars; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE final product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75876 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Orliac, Etienne; Prange, Lars; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE rapid product series for the IGS*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75854 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Orliac, Etienne; Prange, Lars; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE ultra-rapid product series*

Table 1: CODE products available through anonymous ftp

CODE *final* products available at ftp://ftp.unibe.ch/aiub/CODE/yyyy/	
`yyyy/CODwwwwd.EPH.Z`	CODE final GNSS orbits
`yyyy/CODwwwwd.ERP.Z`	CODE final ERPs belonging to the final orbits
`yyyy/CODwwwwd.CLK.Z`	CODE final clock product, clock RINEX format, with a sampling of 30 sec for the satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/CODwwwwd.CLK_05S.Z`	CODE final clock product, clock RINEX format, with a sampling of 5 sec for the satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/CODwwwwd.SNX.Z`	CODE daily final solution, SINEX format
`yyyy/CODwwwwd.TRO.Z`	CODE final troposphere product, troposphere SINEX format
`yyyy/CODGddd0.yyI.Z`	CODE final ionosphere product, IONEX format
`yyyy/CODwwwwd.ION.Z`	CODE final ionosphere product, Bernese format
`yyyy/CODwwww7.SNX.Z`	CODE weekly final solution, SINEX format
`yyyy/CODwwww7.SUM.Z`	CODE weekly summary file
`yyyy/CODwwww7.ERP.Z`	Collection of the 7 daily CODE-ERP solutions of the week
`yyyy/COXwwwwd.EPH.Z`	CODE final GLONASS orbits (for GPS weeks 0990 to 1066; 27-Dec-1998 to 17-Jun-2000)
`yyyy/COXwwww7.SUM.Z`	CODE weekly summary files of GLONASS analysis
`yyyy/CGIMddd0.yyN.Z`	Improved Klobuchar–style ionosphere coefficients, navigation RINEX format
`yyyy/P1C1yymm.DCB.Z`	CODE monthly P1−C1 DCB solution, Bernese format, containing only the GPS satellites
`yyyy/P1P2yymm.DCB.Z`	CODE monthly P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites
`yyyy/P1P2yymm_ALL.DCB.Z`	CODE monthly P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites and all stations used
`yyyy/P1C1yymm_RINEX.DCB`	CODE monthly P1−C1 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
`yyyy/P2C2yymm_RINEX.DCB`	CODE monthly P2−C2 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used

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

CODE *rapid* products available at ftp://ftp.unibe.ch/aiub/CODE	
`CODwwwwd.EPH_M`	CODE final rapid GNSS orbits
`CODwwwwd.EPH_R`	CODE early rapid GNSS orbits
`CODwwwwd.EPH_P`	CODE 24–hour GNSS orbit predictions
`CODwwwwd.EPH_P2`	CODE 48–hour GNSS orbit predictions
`CODwwwwd.EPH_5D`	CODE 5–day GNSS orbit predictions
`CODwwwwd.ERP_M`	CODE final rapid ERPs belonging to the final rapid orbits
`CODwwwwd.ERP_R`	CODE early rapid ERPs belonging to the early rapid orbits
`CODwwwwd.ERP_P`	CODE predicted ERPs belonging to the predicted 24–hour orbits
`CODwwwwd.ERP_P2`	CODE predicted ERPs belonging to the predicted 48–hour orbits
`CODwwwwd.ERP_5D`	CODE predicted ERPs belonging to the predicted 5–day orbits
`CODwwwwd.CLK_M`	CODE GNSS clock product related to the final rapid orbit, clock RINEX format
`CODwwwwd.CLK_R`	CODE GNSS clock product related to the early rapid orbit, clock RINEX format
`CODwwwwd.TRO_R`	CODE rapid troposphere product, troposphere SINEX format
`CODwwwwd.SNX_R.Z`	CODE rapid solution, SINEX format
`CORGddd0.yyI`	CODE rapid ionosphere product, IONEX format
`COPGddd0.yyI`	CODE 1–day or 2–day ionosphere predictions, IONEX format
`CODwwwwd.ION_R`	CODE rapid ionosphere product, Bernese format
`CODwwwwd.ION_P`	CODE 1–day ionosphere predictions, Bernese format
`CODwwwwd.ION_P2`	CODE 2–day ionosphere predictions, Bernese format
`CODwwwwd.ION_P5`	CODE 5–day ionosphere predictions, Bernese format
`CGIMddd0.yyN_R`	Improved Klobuchar–style coefficients based on CODE rapid ionosphere product, RINEX format
`CGIMddd0.yyN_P`	1–day predictions of improved Klobuchar–style coefficients
`CGIMddd0.yyN_P2`	2–day predictions of improved Klobuchar–style coefficients
`CGIMddd0.yyN_P5`	5–day predictions of improved Klobuchar–style coefficients
`P1C1.DCB`	CODE sliding 30–day P1−C1 DCB solution, Bernese format, containing only the GPS satellites
`P1P2.DCB`	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites
`P1P2_ALL.DCB`	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites and all stations used
`P1P2_GPS.DCB`	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing only the GPS satellites
`P1C1_RINEX.DCB`	CODE sliding 30–day P1−C1 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
`P2C2_RINEX.DCB`	CODE sliding 30–day P2−C2 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
`CODE.DCB`	Combination of `P1P2.DCB` and `P1C1.DCB`
`CODE_FULL.DCB`	Combination of `P1P2.DCB`, `P1C1.DCB` (GPS satellites), `P1C1_RINEX.DCB` (GLONASS satellites), and `P2C2_RINEX.DCB`

Note that as soon as a final product is available the corresponding rapid, ultra–rapid, or predicted products are removed from the anonymous FTP server.

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

CODE *ultra–rapid* products available at ftp://ftp.unibe.ch/aiub/CODE	
COD.EPH_U	CODE ultra–rapid GNSS orbits
COD.ERP_U	CODE ultra–rapid ERPs belonging to the ultra–rapid orbit product
COD.TRO_U	CODE ultra–rapid troposphere product, troposphere SINEX format
COD.SNX_U.Z	SINEX file from the CODE ultra-rapid solution
COD.SUM_U	Summary of stations used for the latest ultra–rapid orbit
COD.ION_U	Last update of CODE rapid ionosphere product (1 day) complemented with ionosphere predictions (2 days)
COD.EPH_5D	Last update of CODE 5–day orbit predictions, from rapid analysis, including all active GPS and GLONASS satellites
CODwwwwd.EPH_U	CODE ultra-rapid GNSS orbits from the 24UT solution available until the corresponding early rapid orbit is available (to ensure a complete coverage of orbits even if the early rapid solution is delayed after the first ultra-rapid solutions of the day)
CODwwwwd.ERP_U	CODE ultra-rapid ERPs belonging to the ultra-rapid orbits

Table 2: CODE final products available in the product areas of the IGS data centers

Files generated from three–day long–arc solutions:	
CODwwwwd.EPH.Z	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a long–arc analysis
CODwwwwd.SNX.Z	GNSS daily coordinates/ERP/GCC from the long–arc solution in SINEX format
CODwwwwd.CLK.Z	GPS satellite and receiver clock corrections at 30–sec intervals referring to the COD–orbits from the long–arc analysis in clock RINEX format
CODwwwwd.CLK_05S.Z	GPS satellite and receiver clock corrections at 5–sec intervals referring to the COD–orbits from the long–arc analysis in clock RINEX format
CODwwwwd.TRO.Z	GNSS 2–hour troposphere delay estimates obtained from the long–arc solution in troposphere SINEX format
CODwwww7.ERP.Z	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COD–ERP solutions of the week in IGS IERS ERP format
CODwwww7.SUM	Analysis summary for 1 week
Files generated from pure one–day solutions:	
COFwwwwd.EPH.Z	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a pure one–day solution
COFwwwwd.SNX.Z	GNSS daily coordinates/ERP/GCC from the pure one–day solution in SINEX format
COFwwwwd.CLK.Z	GPS satellite and receiver clock corrections at 30–sec intervals referring to the COF–orbits from the pure one–day analysis in clock RINEX format
COFwwwwd.CLK_05S.Z	GPS satellite and receiver clock corrections at 5–sec intervals referring to the COF–orbits from the pure one–day analysis in clock RINEX format
COFwwwwd.TRO.Z	GNSS 2–hour troposphere delay estimates obtained from the pure one–day solution in troposphere SINEX format
COFwwww7.ERP.Z	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COF–ERP solutions of the week in IGS IERS ERP format
COFwwww7.SUM	Analysis summary for 1 week

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

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

Other product files (not available at all data centers):	
CODGddd0.yyI.Z	GNSS 2-hour global ionosphere maps in IONEX format, including satellite and receiver P1−P2 code bias values
CKMGddd0.yyI.Z	GNSS daily Klobuchar-style ionospheric (alpha and beta) coefficients in IONEX format
GPSGddd0.yyI.Z	Klobuchar-style ionospheric (alpha and beta) coefficients from GPS navigation messages represented in IONEX format

for the IGS. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75676 .

- Prange, Lars; Orliac, Etienne; Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Jäggi, Adrian (2016). *CODE product series for the IGS MGEX project*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE_MGEX; DOI: 10.7892/boris.75882 .
- Steigenberger, Peter; Lutz, Simon; Dach, Rolf; Schaer, Stefan; Jäggi, Adrian (2014). CODE repro2 product series for the IGS. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2013; DOI: 10.7892/boris.75680 .

3 Changes in the daily processing for the IGS

The CODE processing scheme for daily IGS analyses is constantly subject to updates and improvements. The last technical report was published in Dach et al. 2015b.

In Sect. 3.1 we give an overview of important development steps in the year 2015. Section 3.2 describes the introduction of the extended Empirical CODE orbit model (ECOM) and Section 3.3 provides details on the extension of the clock rapid product at CODE .

3.1 Overview of changes in the processing scheme in 2015

Table 3 gives an overview of the major changes implemented during the year 2015. Details on the analysis strategy can be found in the IGS analysis questionnaire at the IGS Central Bureau (ftp://igscb.jpl.nasa.gov/igscb/center/analysis/code.acn).

Several other improvements not listed in Tab. 3 were implemented, too. Those mainly concern data download and management, sophistication of CODE's analysis strategy, software changes (improvements), and many more. As these changes are virtually not relevant for users of CODE products, they will not be detailed on any further.

Table 3: Selected modifications of the CODE processing over 2015

Date	DoY/Year	Description
04-Jan-2015	004/2015	Extended ECOM as described in Arnold et al. 2015 has been activated in the final, rapid and ultra-rapid processing scheme by adding the twice- and four times-per revolution terms in D-component
09-Feb-2015	040/2015	Include a completeness check for RINEX observation files that are used for the rapid or ultra-rapid processing
15-Feb-2015	046/2015	Switch from IGRF11 to IGRF12 Tébault et al. 2015 for computing the higher-order ionosphere (HOI) corrections
15-Feb-2015	046/2015	Correct a software bug that may extract VMF1 coefficients and atmosphere pressure loading corrections from an extrapolation to outside a cell in the grid file instead of interpolating within grid cells. Whether the problem occurred or not depends on the baseline and network configuration. An effect is more likely if dense regional networks instead of global networks are processed; but a limited number of examples have also been found in the operational and repro2 series for the IGS.
19-Feb-2015	050/2015	Update the Bernese GNSS Software to allow for filenames longer than 32 characters
27-Febr-2015	058/2015	Relax some screening criteria in the data preprocessing
24-Apr-2015	115/2015	Earth rotation parameters are set up per orbital plane and geocenter parameters per satellite for internal purposes when generating the normal equations in the final processing chain. These parameters are stacked to one global set of parameters over all satellites when computing the solutions submitted to the IGS
28-Jun-2015	179/2015	Disable the four times per revolution terms in the new ECOM because they degrade some of the GLONASS orbits
01-Jul-2015	182/2015	Add the leap second
20-Jul-2015	201/2015	Request at least 8 hours between a stochastic pulse for GNSS satellite orbit modelling and a repositioning event, otherwise the pulse is removed
21-Jul-2015	202/2015	A new version of download script was activated in order to support RINEX3 files with long filenames. This includes a priority selection for several RINEX files from the same station: 1. RINEX3 file created by the receiver 2. RINEX3 file created from streamed data 3. RINEX3 file with unknown source or short filenames 4. RINEX2 files
03-Aug-2015	214/2015	A new multi-GNSS procedure to generate the clock corrections in the rapid chain was activated considering GPS and GLONASS at the moment.
27-Aug-2015	112–239/2015	The RMS for the linear fit of the estimated clock corrections for station BRAZ was significantly higher for the 5 s clock solution (based on streamed data) than in the 30 s solution (based on legacy RINEX data). The effect on the ultra-high-rate satellite clock corrections is unclear.
14-Sep-2015	214–255/2015	In the new clock generation procedure for the rapid, observations that have not passed the residual screening procedure may have been used for the final parameter estimation. The Problem was fixed.

3.2 Introducing the extended ECOM

The Empirical CODE Orbit Model (ECOM, Beutler et al. 1994) was developed in the early 1990s, motivated by the lack of reliable satellite information. It is widely used in the IGS and allows for a successful modeling of non-gravitational accelerations — especially induced by solar radiation pressure — acting on GPS satellites.

The ECOM decomposes the perturbing accelerations into three orthogonal directions of a Sun-oriented coordinate system in the center of mass of the satellite, namely a D component oriented from the satellite to the Sun, a Y component pointing along the satellite's solar panel axes, and a B component to complete the orthogonal system. In the original ECOM the functions $D(u)$, $Y(u)$ and $B(u)$ are represented as Fourier series truncated after the once-per-revolution (1pr) terms, whereas Springer et al. 1999 proposed the so-called reduced ECOM,

$$\begin{aligned} D(u) &= D_0 \\ Y(u) &= Y_0 \\ B(u) &= B_0 + B_\mathrm{c}\cos u + B_\mathrm{s}\sin u\,, \end{aligned} \tag{1}$$

where u is the argument of latitude for the satellite. It was used for the IGS contributions of CODE for a long time. Arnold et al. 2015 proposed an extension of the ECOM according to:

$$\begin{aligned} D(u) &= D_0 + \sum_{i=1}^{n_D} \{D_{2i,\mathrm{c}}\cos 2i\Delta u + D_{2i,\mathrm{s}}\sin 2i\Delta u\} \\ Y(u) &= Y_0 \\ B(u) &= B_0 + \sum_{i=1}^{n_B} \{B_{2i-1,\mathrm{c}}\cos(2i-1)\Delta u + B_{2i-1,\mathrm{s}}\sin(2i-1)\Delta u\}\ , \end{aligned} \tag{2}$$

where $\Delta u \doteq u - u_\mathrm{s}$ and u_s is the argument of latitude of the Sun. The extended ECOM thus contains even-order periodic terms in $\vec{e}_\mathrm{D}$-direction and odd-order periodic terms in $\vec{e}_\mathrm{B}$-direction.

Starting with GPS week 1826 (January 04, 2015), CODE started to use the extended model with $n_B = 1$ and $n_D = 2$ (resulting in 2pr and 4pr terms according to Equation 2) . Although Arnold et al. 2015 have demonstrated the advantages of the new with respect to the old ECOM, the introduction of the new model has led to a reduction of consistency with the other IGS ACs (see Fig. 2).

Unfortunately, some of the (older) GLONASS satellites did show a degradation due to the additional terms. The relations between the cosine and sine terms and between the twice and four-times per revolution terms did not agree with the expected magnitudes in Arnold et al. 2015. Obviously, the higher-order terms do amplify other not modelled effects on the satellites. For that reason the 4pr D-terms of the extended ECOM were

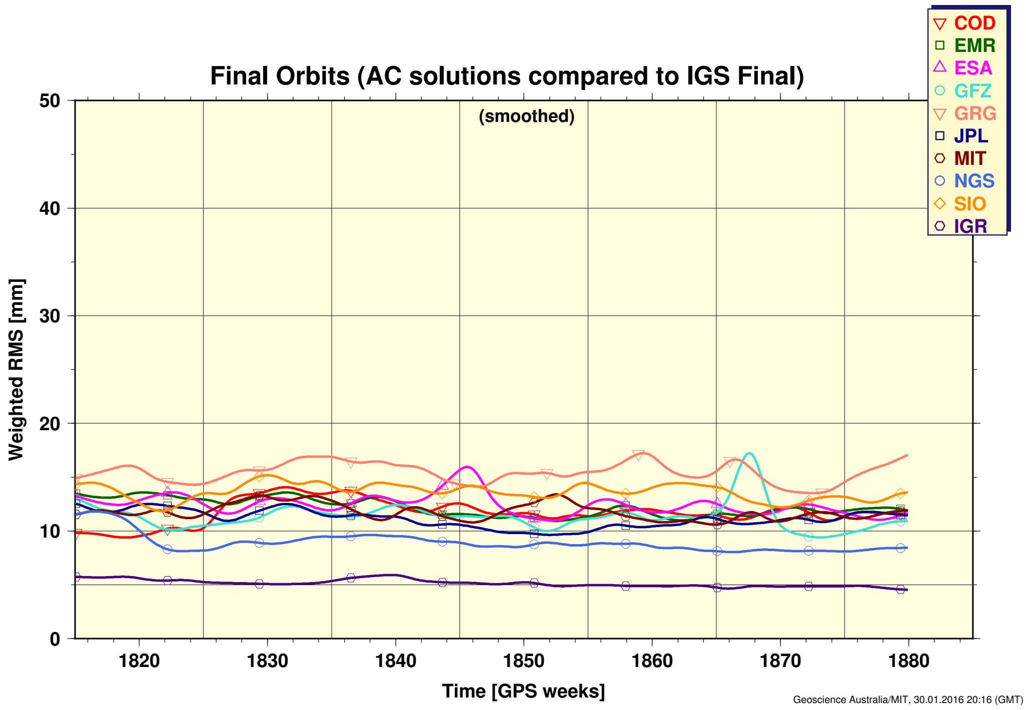


Figure 2: Consistency of the GPS final orbits among the IGS analysis centers during the recent weeks (from http://acc.igs.org/media/Gmt_sum_final_all_orb_smooth.ps.

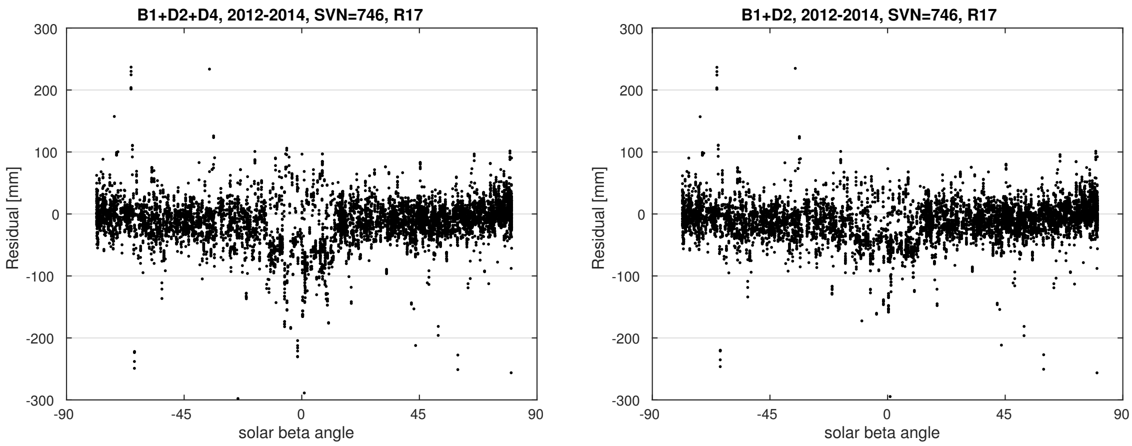


Figure 3: SLR residuals to GLONASS satellite R17 (SVN 746).

deactivated starting from GPS week 1851 (June 28th, 2015). The benefit can be seen in the SLR residuals displayed in Fig. 3 for one of the affected GLONASS satellites.

3.3 Extending the CODE rapid clock product

For the CODE clock product, GNSS satellite orbits, Earth rotation parameters (ERPs) and station coordinates are introduced as known from the double-difference solution. Figure 4 illustrates the processing flow to generate the GPS/GLONASS rapid clock corrections. The procedure is executed two times per day: once for the early and a second time for the final rapid solution (see Dach et al. 2015b).

After some general preparatory steps described in the violet boxes in Fig. 4 (steps 1.1 and 1.2), the independent preprocessing of the code and phase measurements is initiated. In the green chain (steps 2.1 to 2.4), the pseudorange data are preprocessed. This includes apart from a residual screening also the computation of station-specific weights because of the different noise level of the individual stations due to the different environmental conditions and receiver/firmware behavior. Furthermore, the inter-system and inter-frequency biases are computed for all stations.

In parallel the preprocessing of the phase measurements takes place following the steps described in the brown boxes (steps 3.1 and 3.2) including the cycle slip and outlier detection as well as the update of the list of ambiguities. For this step satellite clock corrections are needed that are computed from a limited subset of the stations that offer a global coverage.

After cleaning the pseudorange and phase measurements in the two separate chains, they need to be processed first together in a further preprocessing step to make sure that the full consistency is given (an overview on potential receiver events is given, e.g., in Dach et al. 2006).

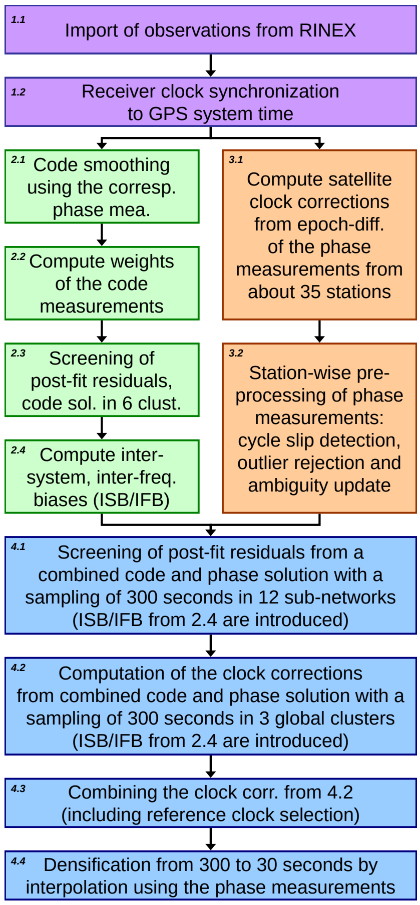


Figure 4: Flow chart of the GPS/GLONASS rapid clock product generation.

Now the observations are prepared to compute the clock corrections. The stations are divided into three clusters that are analysed in parallel with a sampling of 5 minutes where also the biases from processing step 2.4 are introduced as known. In a subsequent step the clock corrections of the three clusters are combined and the reference clock for the solution submitted to the IGS is selected. The densification from 300 to 30 seconds is done according to the phase-based interpolation procedure as described in Bock et al. 2009.

4 CODE contribution to the IGS–MGEX campaign

Since 2012 CODE contributes to the IGS Multi-GNSS EXperiment (MGEX) aiming on the integration of new GNSS into existing processing chains (Prange et al. 2016a). The product is generated using the latest development version of the Bernese GNSS Software package and is derived from a rigorously combined five system solution considering GPS, GLONASS, Galileo, BeiDou (MEO and IGSO), and QZSS satellites. Even if the focus is on the satellite orbits and satellite clock corrections, also other parameters need to be estimated like diverse biases for the receivers, ERPs, station coordinates, and troposphere parameters. A more detailed description is given in Prange et al. 2016b.

During the year 2015 the following updates have been introduced in the processing scheme:

- Since January 2015 the MGEX solution is regularly computed and posted to the product file area at CDDIS:

  `ftp://cddis.gsfc.nasa.gov/gnss/products/mgex`

  as well as since beginning of 2016 also to the anonymous ftp server of AIUB:

  `ftp://ftp.unibe.ch/aiub/CODE_MGEX/CODE`

  The list of products is given in Table 4.

Table 4: CODE MGEX products available through anonymous ftp

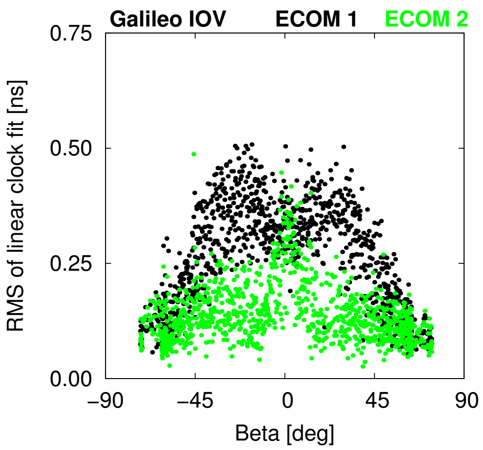
CODE *final* products available at ftp://ftp.unibe.ch/aiub/CODE_MGEX/CODE/yyyy/	
yyyy/COMwwwwd.EPH.Z	CODE GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format
yyyy/COMwwwwd.ERP.Z	Earth rotation parameters related to the MGEX orbits, IERS format
yyyy/COMwwwwd.CLK.Z	Satellite and Receiver clock corrections consistent to the MGEX orbits with a sampling of 5 minutes, clock RINEX format
yyyy/COMwwwwd.BIA.Z	GNSS code biases related to the MGEX clock correction product, bias SINEX format v0.01
yyyy/COMwwwwd.DCB.Z	GNSS code biases related to the MGEX clock correction product, Bernese format

- Since January 2015 the extended ECOM (Arnold et al. 2015) is used for Solar radiation pressure modelling in the MGEX product generation including the 2pr and 4pr terms in the D direction ($n_D = 2$ in Equation 2).
  As in the operational processing, the 4pr terms in the D direction are skipped since day 251 of year 2015 (08-Sep-2015).

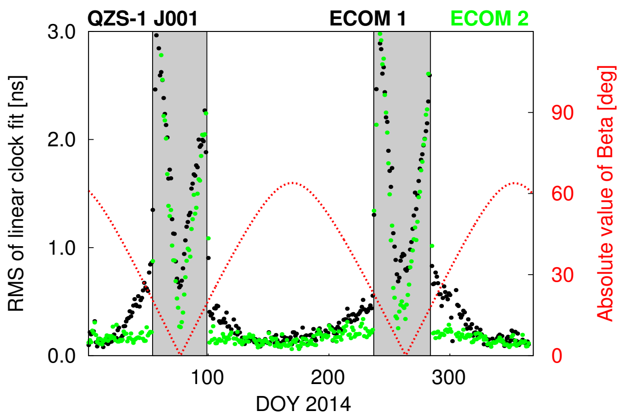
  Figure 5 confirms the positive impact of the new orbit model (green dots, label ECOM 2) over the traditional one (black dots with label ECOM 1). For the Galileo and the QZSS satellites the RMS of a linear fit of the epoch-wise independently estimated satellite clock corrections are shown. As long as the satellites are flying in the yaw-steering mode there is a clear reduction of the dependency of the orbit quality parameter from the elevation of the Sun above the orbital plane (beta angle). In the gray shaded areas, the QZSS satellite is switched to the so-called orbit normal mode where the ECOM decomposition as introduced by Beutler et al. 1994 is not designed for. An adaptation is currently under development.

- Since August 2015 the observations from QZSS and BeiDou satellites, that come close to the beta angle where the attitude mode of the satellite is changed, are introduced with a very low weight. In this way, the mis-modelling of the Solar radiation pressure cannot degrade the solution and the orbits of other satellites.

Based on the MGEX solution, CODE has also contributed to a comparison and validation of estimated satellite antenna phase center offsets for Galileo satellites (Steigenberger et al. 2015).



(a) Galileo IOV satellites, except of E20 (SVN 104)



(b) QZSS satellite J001 (QZS–1)

Figure 5: RMS of daily linear fit through estimated epoch-wise satellite clocks as a function of the beta angle.

5 Influence of the length of the orbit arc on GNSS results

Based on the reprocessing series computed in the year 2013 (see Dach et al. 2014) – the contribution of CODE to the IGS repro2 effort – detailed investigations on the influence of the orbit arc length on several products have been carried out. In this context the clean one day and three day long arc solutions (that are also regularly computed by the CODE AC in the operational final processing chain) were evaluated. Because the IGS is requesting daily coordinate solutions (for correcting the loading effect on solution level) and daily independent polar motion parameters, an additional *special long arc solution* has been generated where only continuity conditions were applied to the orbit parameters.

The detailed analysis can be found in Lutz et al. 2016. The improvement of the estimated polar motion rates when increasing the arc length from one day (red) to three days (blue) is a highlight of the article (see Fig. 6). On the one hand, the reduced number of independent sets of polar motion parameters in the three day long arc solution due to the continuity conditions results in the best agreement to the C04 series. On the other hand, the clean one day solutions show a significant deviation with periods of one and half a year. With the increasing influence of GLONASS (from top to bottom) also a third of a year period becomes relevant for the clean one day solutions.

The special long arc solution with only applying continuity conditions on the orbit parameters reduces the amplitudes of the annual and biannual periods in the differences to the C04 series by a factor of two with respect to the clean one day solutions. It is remarkable that particularly the periods at a third of a year that are introduced by the increasing number of GLONASS satellites in the clean one day solution are nearly completely removed. Lutz et al. 2016 also studied the properties of non-overlapping 3-day solutions. The polar motion rates of such solutions are close in quality to those of the classic overlapping 3-day solutions. This corresponds to the observation that longer arcs improve the robustness of the orbit estimates more for GLONASS than for GPS satellites (e.g., in terms of discontinuities at the day boundaries in the celestial frame by a factor of 2 for GPS but 3.5 for GLONASS).

6 CODE contribution to the EGSIEM reprocessing

In the framework of the European Gravity Service for Improved Emergency Management (EGSIEM) project, monthly gravity field solutions derived from the Gravity Recovery and Climate Experiment (GRACE) mission will be combined. Since a consistent reference frame is a prerequisite for precise orbit and related gravity field determination, a reprocessing campaign was initiated at AIUB (subsequently labelled as repro15). To get a consistent series of GNSS satellite clock corrections, GNSS orbits, Earth rotation parameters, and station coordinates, more than 250 globally distributed tracking stations of the IGS network are homogeneously reprocessed for the interval between 2003 to the end of 2014 following the processing standards from the CODE analysis center by March 2015.

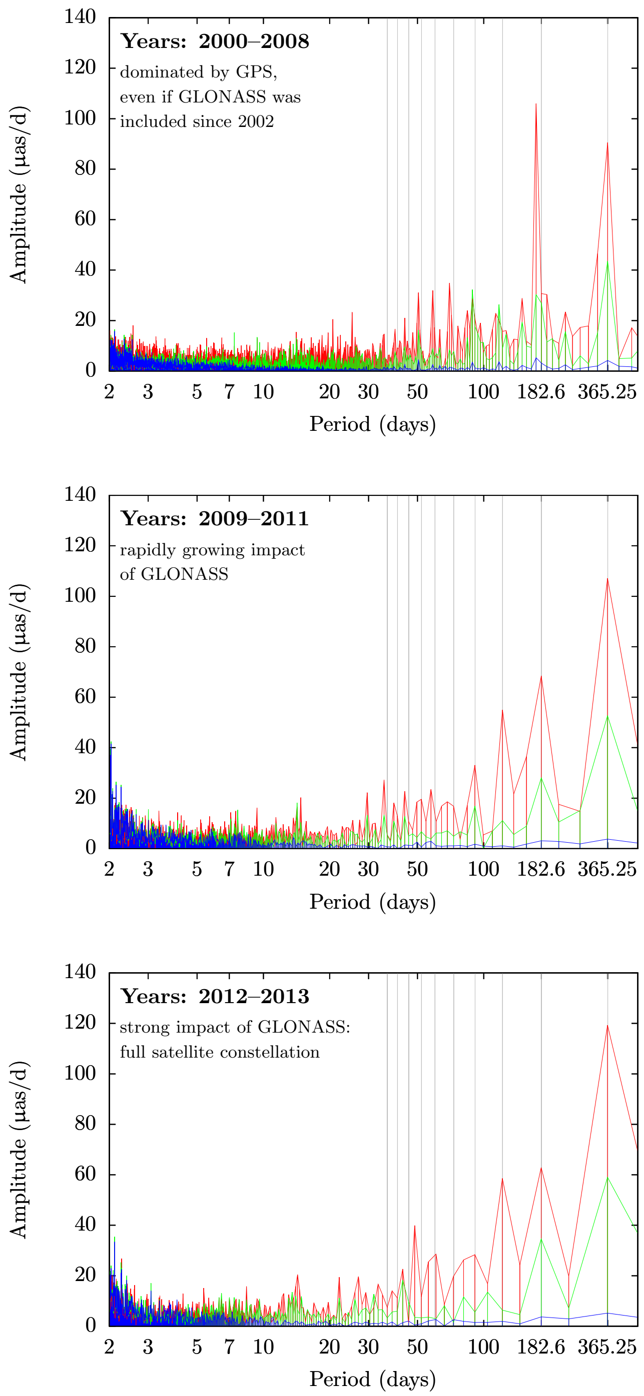


Figure 6: Amplitude spectra of polar motion rate $\dot{x}$ differences between the C04 series and the combined GPS/GLONASS solutions: clean one day solution (red), three day long arc solution (blue), and special long arc solution (green).

Even if the POD for GRACE will only base on GPS satellites, the reprocessing activity considered GPS and GLONASS measurements.

In order to provide within the EGSIEM project reference frame products using latest GNSS orbit modelling effort, reprocessing of the GNSS data was performed using the extended Empirical CODE orbit model (Arnold et al. 2015), which significantly improves the accuracy of the GNSS orbits (in particular for the GLONASS satellites) and reduces the deficiencies in the geodynamical parameters. Since the reference frame for the most recent reprocessing is still IGb08 the same station selection as in IGS-repro2 from CODE was reused for the repro15 effort. The processing starts from the original GNSS observations in the RINEX files. As a priori orbit information the results from the repro2 campaign for the IGS was used and completed by alternative sources (e.g., broadcast orbits) in order to include as many satellites into the processing as possible. This effort resulted in a bigger number of satellites for the repro15 series when comparing with the number of satellites in the result files of the 1-day solutions of repro2 (see Fig. 7).

Since all GLONASS and two GPS satellites are equipped with retro-reflector arrays, SLR provides an independent tool to validate microwave-based GNSS orbits. Because the maximum angle of incidence of a laser pulse to a GNSS satellite does not exceed 14°, SLR residuals indicate mainly the radial accuracy of microwave-based GNSS orbits (Sośnica et al. 2014; Fritsche et al. 2014; Maier et al. 2015). Figure 8 shows SLR residuals w.r.t. the 1-day GLONASS-M orbits – once using the old ECOM (repro2, left side) and once using the extended ECOM (repro15, right side). When the old ECOM model is used (left plot of Fig. 8), there is a clear dependency of the SLR residuals on the elongation angle: whereas the residuals to the satellite positions near solar beta angle 90° are scattered around zero, those to satellite positions of smaller absolute solar beta angle show a significant offset to zero. The dependency of the SLR residuals on the elongation angle is significantly reduced

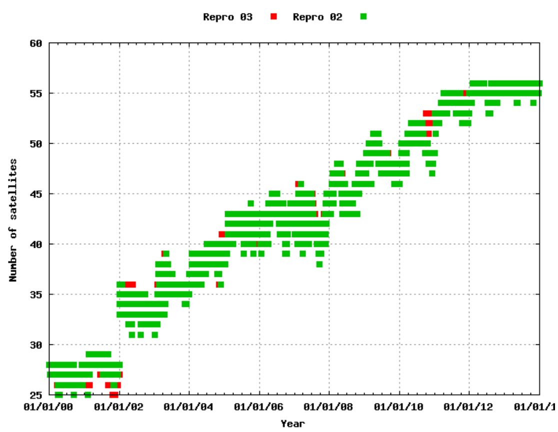


Figure 7: Number of GNSS satellites available in 1-day orbits for the period between 2000 and 2013. Red color represents repro15 and green repro2.

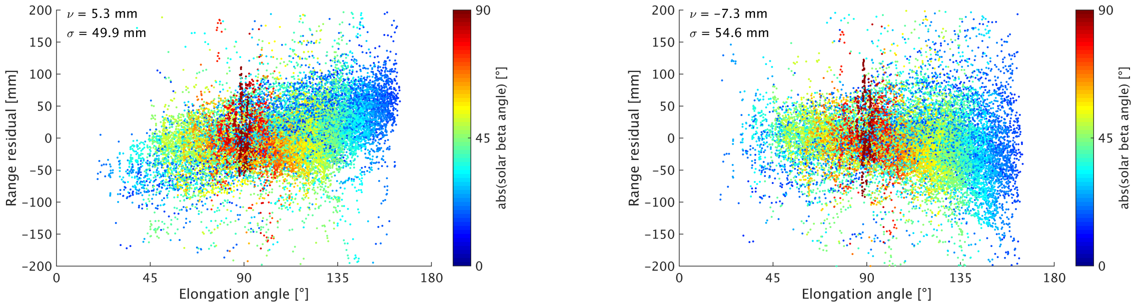


Figure 8: SLR residuals w.r.t. GLONASS-M orbits using the original ECOM (left) and the extended ECOM (right). Mean value (ν) and standard deviation (σ) are based on all residuals whose absolute value is smaller than 150 mm. Observations to four GLONASS satellites (SVN 723, 725, 736, 737) have been excluded due to anomalous patterns. Furthermore, all residuals having an absolute beta angle smaller than 15° have been not taken into account due to unmodeled attitude during eclipses.

in the case of the new ECOM (right plot of Fig. 8).

For the POD of the GRACE satellites the Precise Point Positioning (PPP, Jäggi 2007) is well established. It requires the knowledge of precise and consistent GNSS orbits and satellite clock corrections. Assuming 1 Hz sampling of GNSS data of LEOs, the GNSS satellite clock corrections are required with a sampling of at least 5 seconds (Bock et al. 2009). For the generation of 5 second clock products, GNSS observation files with a higher sampling than the common 30 seconds are needed. They are available from the IGS real-time service with a sampling of 1 Hz (Caissy et al. 2012). At least in the early years, the IGS real-time network was to a large extent independent from the legacy network. In this context, in particular for generation of GLONASS satellite clock products, we have been confronted with the limitation of available GLONASS tracking data in early years of the IGS real-time network. The number of available stations providing 5 s data is shown on the left side of Fig. 9, where grey color represents GPS only, green GPS/GLONASS and white no data available. As can be seen from Fig. 9 before the end of 2010 no 5 s RINEX2 files with GLONASS data are available. On the right side of the Fig. 9 the percentage of completeness of the GLONASS satellite clock products is shown for the 30 s sampling rate.

Figure 10 shows the percentage of completeness of the satellite clock products with 30 s (left side) and 5 s sampling (right side) over the period 2006–2007. It can be noticed that for the period shown, the overall completeness is 100% for both sampling rates, however there are some GPS satellites (namely G12, G15, G29, G31 and G32) for which both, 30 s and 5 s clock corrections are not complete. These data gaps are mainly due to reduced tracking of (unhealthy) satellites.

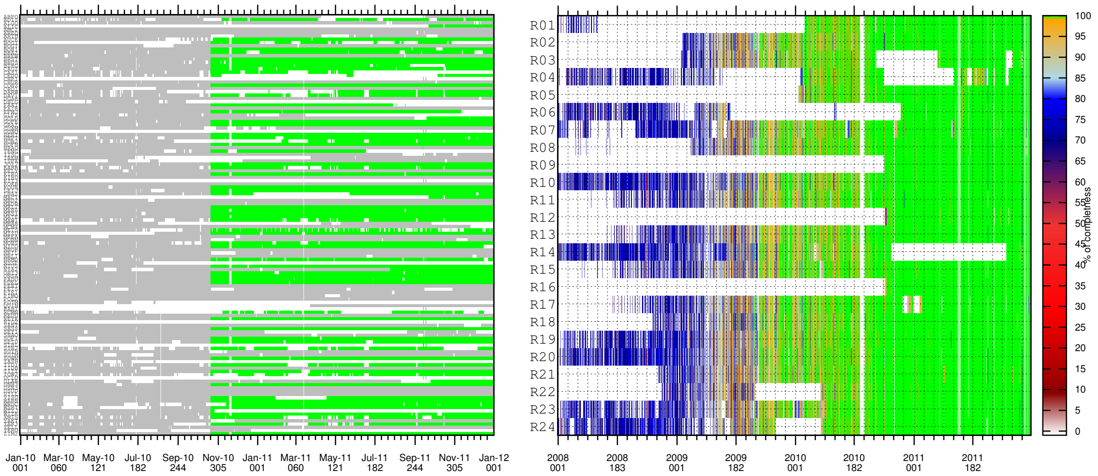


Figure 9: (Left): number of stations delivering 5 s RINEX2 files, where grey color presents GPS only, green GPS/GLONASS and white no data available. (Right): completeness of 30 s GLONASS clock corrections for the 2008-2011 period.

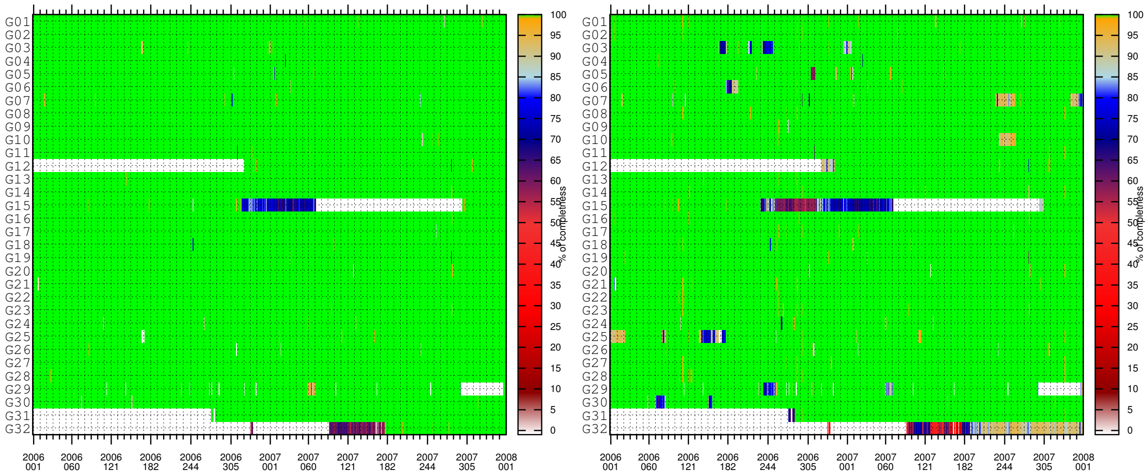


Figure 10: Completeness of 30 s (left) and 5 s (right) GPS clock corrections for the time period between 2006 and 2007.

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

NRCan Analysis Center Technical Report 2015

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1 Introduction

This report covers the major activities conducted at the NRCan Analysis Center (NRCan–AC) and product changes during the year 2015 (products labelled "em*"). Additionally, changes to the stations operated by NRCan are briefly described. Readers are referred to the Analysis Coordinator web site (http://acc.igs.org) for historical combination statistics of the NRCan–AC products.

2 NRCan Core Products

There was one major change for NRCan–AC Ultra–Rapid, Rapid and Final (GLONASS) core products in 2015. The Bernese production software supporting these was updated from version 5.0 to version 5.2 (Dach et al. 2015). The exact dates were: Ultra–Rapid [2015–02–13], Rapid [2015–02–12] and Final [2015–02–01]. The analysis summary (ACN) for both the Ultra–Rapid and Rapid strategies is available from the following anonymous ftp site: ftp://ftp.igs.org/pub/center/analysis/emr_Ultra_And_Rapid_V52.acn

No changes were made to the Final GPS products based on GIPSY–OASIS. Table 1 summarizes the products available from the NRCan–AC. The Final and Rapid products are available from the following anonymous ftp site: ftp://rtopsdata1.geod.nrcan.gc.ca/gps/products

Table 1: NRCan–AC Products 11.1

Product	**Description**
Repro2	
em2wwwwd.sp3	GPS only
em2wwwwd.clk	• Time Span 1994–11–02 to 2014–03–29
em2wwwwd.snx	• Use of JPL's GIPSY-OASIS II v6.3
em2wwww7.erp	• Daily orbits, ERP and SINEX
	• 5-min clocks
	• Submission for IGS repro2 combination
Final(weekly)	
emrwwwwd.sp3	GPS only
emrwwwwd.clk	• Since 1994 and ongoing
emrwwwwd.snx	• Use of JPL's GIPSY–OASIS II v6.3
emrwwww7.erp	• Daily orbits, ERP and SINEX
emrwwww7.sum	• 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 from 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	GPS only
emrwwwwd.clk	• From July 1996 to 2011–05–21
emrwwww7.erp	• 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
Ultra-Rapid(hourly)	
emuwwwwd_hh.sp3	GPS only
emuwwwwd_hh.clk	• From early 2000 to 2013–09–13, hour 06
emuwwwwd_hh.erp	• 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 [from 2015–Feb–13] • Orbits and ERP (hourly) • 30–sec GNSS clocks (every 3 hours) • 30–sec GPS-only clocks (every other hours) • Submission for IGU/IGV combination (4 times daily)
Real–Time	
	GPS only • Since 2011–11–10 • In-house software (HPGPS.C) • RTCM messages: – orbits & clocks: 1060 (at Antenna Reference Point) – pseudorange biases: 1059 • Interval : 5 sec

3 Ionosphere and DCB monitoring

Daily and near–real–time ionosphere products and DCB estimates continue to be generated internally. NRCan's global daily total electron content maps (`emrg[ddd]0.[yy]i`), generated from about 350 stations in hourly intervals, have resumed their submission to IGS data center (CDDIS) since April 2015.

Ionospheric irregularities as sensed by GPS phase rate derived indices from real–time IGS network continue to be monitored in near–real–time. These have been used in a number of research studies to complement other sensors to study space weather storms and characterization of ionospheric irregularities over high latitudes (see e.g. Ghoddousi-Fard et al. 2015a, 2015b; Ghoddousi-Fard and Lahaye 2015; Prikryl et al. 2015a, 2015b, 2015c).

4 Operational NRCan stations

In addition to routinely generating all core IGS products, NRCan is also providing public access to GPS/GNSS data for more than 80 Canadian stations. This includes 40 stations currently contributing to the IGS network through the Canadian Geodetic Survey's Canadian Active Control System (CGS–CACS), the CGS Regional Active Control System (CGS–RACS), and the Geological Survey of Canada's Western Canada Deformation Array (GSC–WCDA). The NRCan contribution to the IGS network includes 25 GNSS + 15 GPS only stations. Several upgrades/changes to the CGS–CACS were completed in 2015 and these are listed in Tab. 2. Fig. 1 shows a map of the NRCan GPS/GNSS network as of January 2016. Further details about the NRCan stations and access to the

NRCan public GPS/GNSS data and site logs can be found at http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/10781 or from the following anonymous ftp site: ftp://rtopsdata1.geod.nrcan.gc.ca/gps

Table 2: NRCan Station Upgrades in 2015

Station	Date	Remarks
albh	2015–09–15	Station upgraded from GPS–only to GNSS
albh	2015–09–15	Antenna AOAD/M_T SCIS switched to TRM59800.00 SCIS
alg2	2015–12–10	Station repaired and brought back on–line with JAVAD TRE_G3TH DELTA receiver after extended outage
dra3	2015–07–11	Antenna NOV750.R4 NONE switched to TPSCR.G3 NONE
dubo	2015–10–23	New antenna cable
flin	2015–07–06	NOVS dome installed
hlfx	2015–07–23	New antenna cable
sch2	2015–08–06	New antenna cable

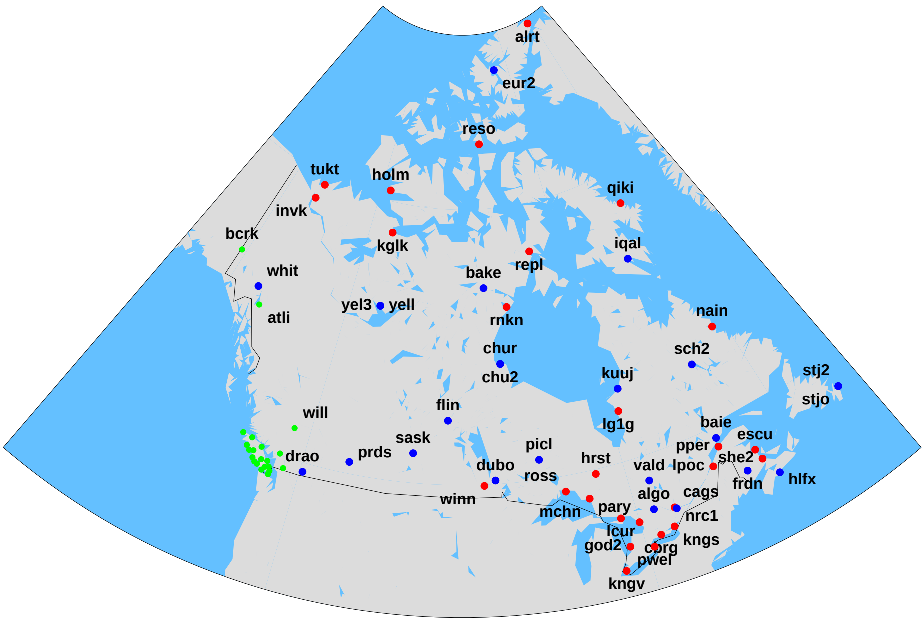

Figure 1: NRCan Public GPS/GNSS Stations (CGS–CACS in blue, CGS–RACS in red and GSC–WCDA in green).

5 Acknowledgment

ESS Contribution number / Numéro de contribution du SST: 20150427

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ESA/ESOC Analysis Center Technical Report 2015

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1 Introduction

The IGS Analysis Centre of the European Space Agency (ESA) is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The ESA/ESOC Analysis Centre has been involved in the IGS since its very beginning in 1992. In this report we give a summary of the IGS related activities at ESOC in 2015.

2 Overview 2015

2.1 Routine Products

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

- Reprocessed Final GPS products (repro2)
  - Provided from 1995 to 2015 day 180, from there on our normal Final products.
  - Based on 24hour solutions using 150 stations GPS-only, until 2008
  - Based on 24hour solutions using 110 stations GPS+GLONASS, from 2009
  - Consisting of Orbits, Clocks (300s), daily SINEX coordinates, and EOPs
  - Clocks with 30s sampling are also generated but not made publicly available
- Final GNSS (GPS+GLONASS) products

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

- Rapid GNSS (GPS+GLONASS) products
  - Provided daily for the previous day
  - Available within 3 hours after the end of the observation day
  - Based on 24hour solutions using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, Ionosphere, and EOPs
  - Rapid SINEX coordinates and EOPs available as well
- Ultra-Rapid GNSS (GPS+GLONASS) products
  - Provided 4 times per day covering a 48 hour interval; 24 hours of estimated plus 24 hours of predicted products
  - Available within 3 hours after the end of the observation interval which start at 0, 6, 12, and 18 hours UTC
  - Based on 24 hours of observations using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting out of Orbits, Clocks, and EOPs
  - Separate Ionosphere estimates and predictions
- 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

- GNSS Sensor Stations
  - A set of 10 globally distributed GNSS sensor stations
  - Station data available in real-time with 1 second data sampling

Besides these core products ESA is very active in different working groups. Most notably are our efforts in the Real-Time Service where besides being one of the analysis centres we are also responsible for the analysis centre coordination. Also our efforts in the scope of MGEX, the antenna calibarations and satellite orbit modeling working groups are significant.

An up to date description of the ESA IGS Analysis strategy may always be found at: ftp://dgn6.esoc.esa.int/products/esa.acn

2.2 Product Changes

The main changes in our processing in 2015 were the following:

- Upgrade of the ESA/ESOC GNSS Sensor Station network
- Continue using box-wing models for the GNSS satellites to a priori model the Solar and Earth Albedo radiation pressure. Besides GPS and GLONASS also developed box-wing models for Galileo, BeiDou and QZSS

2.3 Product Highlights

The main highlight of the ESA/ESOC Analysis Centre products is that they are one of the best products available from the individual IGS analysis centres. Furthermore, the ESA products are one of the most complete GNSS products. In fact ESA/ESOC was the first IGS analysis centre to provide a consistent set of GNSS orbit *and* clock products. Our GNSS products constituted the very first products that could, and are, used for true GNSS precise point positioning. In particular for this purpose, the sampling rate of our final GPS+GLONASS clock products is 30 seconds. Another special feature of the ESA products is that they are based on completely independent 24 hour solutions. Although this does not necessarily lead to the best products, as in the real world the orbits and EOPs are continuous, it does provide a very interesting set of products for scientific investigations as there is no aliasing and no smoothing between subsequent solutions. An other unique feature is that our rapid products are, besides being one of the best, also one of the most timely available products. Normally our GNSS rapid 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 radiation pressure. The GNSS block type specific models were tested thoroughly in the scope of our IGS reprocessing and the results were presented at the IGS workshop in 2014 (Springer 2014). Significant improvements were observed for most, if not all, estimated parameters.

2.4 Reprocessing Activities

ESA/ESOC has participated in the IGS reprocessing efforts (repro1 and repro2) for the IGS contribution to the realisation of the International Terrestrial Reference Frame 2008 and 2014 (ITRF2008, and ITRF2014). For this reprocessing effort ESA has processed all historic GNSS data of the IGS from 1994 to 2015 day 180. In this reprocessing the years 1994 to 2008 are reprocessed using only GPS observations, and from 2009 onwards the reprocessing fully includes the GLONASS observations and thus provides true GNSS solutions. The products from the ESA official reprocessing efforts are available from the official IGS data centres (label "es1" and "es2"). The most recent ESA reprocessing products, based on the ITRF2008, are also available from our ftp server: ftp://dgn6.esoc.esa.int/igs/repro2 (label "es2").

An interesting difference between our es1 and es2 reprocessing is that, as mentioned before, from 2009 onwards our es2 products are GNSS products. Also for our es2 products we did generate 30 second clock estimates. We produce these high-rate clock products because we are also very active in processing GNSS data from Low Earth Orbiting (LEO) receivers. For LEO processing high-rate clocks are very much needed to get accurate orbits based when using the well-known PPP approach for precise orbit determination.

3 GNSS Sensor Station Upgrade

ESA/ESOC is committed to provide worldwide data for all GNSS constellations during this year as a result of having completed the upgrade of the equipment at all the current installations over the last year as well as focusing on the establishment of collaborations with third parties in order to install new stations at various new locations if agreements can be reached with the corresponding organizations. Following the acquisition of a large number of Septentrio PolarRx4 receivers and Septentrio Chokering MC antennas plus 4 Leica AR25 rev.4 antennas in 2011-2012, the entire ESA GNSS network, see Figure 1, now operates these Septentrio receiver/antenna combinations, with the exception of MGUE, MAL2, MAS1 and FAA1 where the Leica antennas are used. The network was expanded with the new station AWAR (New Zealand) in the 2nd half of 2014, followed by DUBA (U.A.E), BANT (Malaysia) and TSBA (Japan) in the 1st half of 2015. Finally, in November 2015 the current status of the network was completed with the new station ESOC. No data is publicly available for any of these newly installed stations. The Septentrio receivers provide all the expected measurements for the GNSS constellations as available:

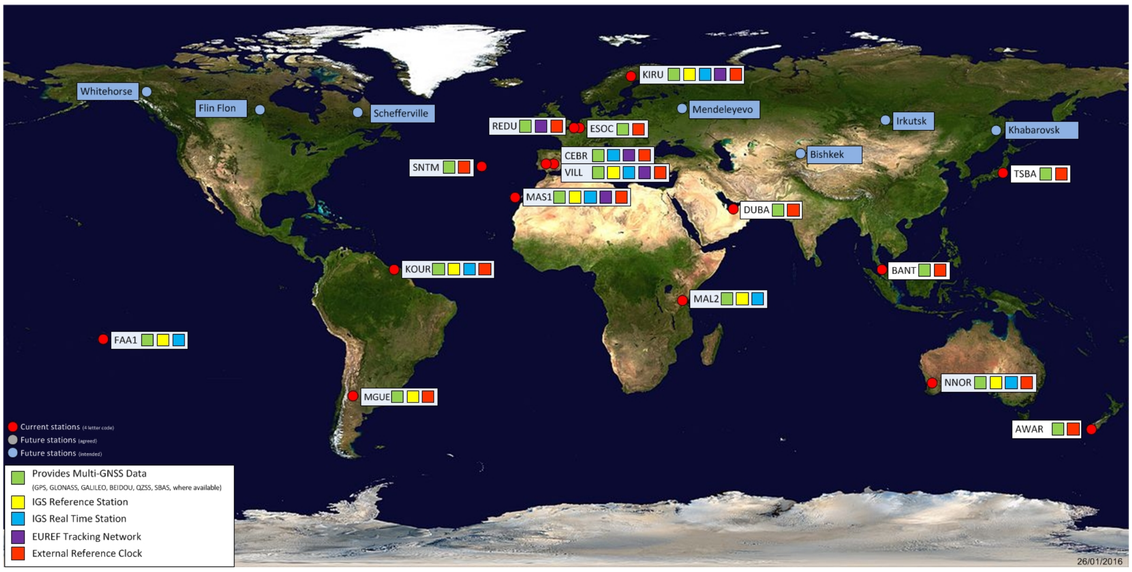

Figure 1: ESA/ESOC GNSS Station Network

GPS, GLONASS, Galileo, QZSS, Compass, SBAS, EGNOS, etc. and as of mid-2013, ESA/ESOC has been contributing with daily, hourly and high rate multi-GNSS Rinex 3 data to the MGEX campaign for 10 of its 16 stations. Also, since the beginning of 2013, ESA/ESOC has been providing NBS (NavBits) data from this same set of stations to Eumetsat to support LEO satellite occultation processing. For 2016 worldwide coverage is planned to be enhanced considerably with negotiations with third parties in Russia and Canada ongoing. The maps below show a projection of the impact on the global coverage for the inclusion of the 6 new sites that are envisaged througout both countries.

4 Ionosphere Modeling Activities

ESA/ESOC contributes with IONEX products to the IGS Ionosphere Working Group since its inception in 1998. Up to now, ionosphere products for the IGS are still based on a single-layer approach, where the vertical TEC is represented by spherical harmonics, in combination with an estimation of daily receiver and satellite DCBs. ESA IONEX files are delivered in final (2h time resolution) and in rapid (2h and 1h time resolution) mode to the IGS. In addition, predicted products are delivered. ESOC employs the Ionosphere Monitoring Facility (IONMON) for its ionosphere processing, which became in 2013 and integral part of ESOC's NAPEOS software. While operational ESOC TEC maps processing is still single-layer-based, current development activities are clearly focused on 3D modelling, which shall, once available, replace the old single-layer representations. In addition to TEC observables originating from different GNSS systems (GPS, GLONASS, Galileo, Beidou, QZSS, and in addition to GNSS: altimetry, DORIS), observed electron density data from different sources (radio occultation, ionosonde, others) shall then enter into these 3D ionosphere maps production. In the new 3D approach, all the above listed observation data types shall be assimilated into a grid of background electron densities. This background will be created with an empirical median model of the ionosphere and plasmasphere. The mathematical models for the new 3D approach were worked out so far (and documented ESOC-internally), comprising:

- Background electron density model algorithms
- Dedicated 3D grid combining spherical shells with L-shells to reflect the spatial structures of the ionosphere and plasmasphere as function of SM latitude, longitude and L-value
- Transformations between solar-magnetic (SM), geomagnetic and geographic coordinates
- Dedicated assimilation methods of TEC and electron density observables into the 3D background grid
- Dedicated electron density interpolators for product generation, e.g. for IONEX files
- Dedicated TEC integrators for product generation, e.g. for IONEX files
- Creation of planar electron density and TEC cuts into any direction through the 3D electron density grid as new product type
- The new assimilation approach shall allow for a significant enhancement of time resolution; 10–15 minutes are currently targeted
- Fast and robust algorithms

At the actual stage of development (January 2016), the mathematical algorithms for this new 3D assimilation approach and their coding as new component of NAPEOS are completed. Currently, last source code upgrades and adaptions are conducted concerning the processing of the very different types of observation data, originating from very distinct sources. Then a test case and test data need to be set up. Initially the new software will be tested with GPS and GLONASS TEC data; in a next step COSMIC electron densities will be included. After that, in further steps, additional observation data types will follow. Once the new 3D assimilation approach in NAPEOS will be operational, ESOCâĂŹs ionosphere processing will be switched over from the current single layer processing to this new 3D modelling technique. This will then also concern ESOCâĂŹs ionosphere products delivered to the IGS, including new aspects such as 3D IONEX.

Additional activities at ESOC in the area of the ionosphere in 2015 will be:

- Preparation of a follow-up study to the Iono Study of 2009-10
- Establishment of a new model for the plasmasphere in cooperation with the German

Aerospace Center (DLR) in Neustrelitz, Germany. This plasmasphere model shall then complement the new 3D assimilation approach

- Establishment of an operational ionospheric and tropospheric media calibration service for ESOC Flight Dynamics (troposphere part running already in a pre-operational mode)
- Routine contributions to ESA's Space Situational Awareness (SSA) service in space weather part
- Important future aspects concerning the ionosphere:
  - Implementation of a more sophisticated Iono prediction scheme at ESOC
  - Implementation of a physics-based 3D Iono model, inspired from the outcome of the anticipated follow-up Iono study

5 Multi-GNSS (MGEX)

We periodically analyze the data from the IGS Multi-GNSS Experiment (MGEX) as at the current stage we prefer a detailed analysis of the MGEX data over routine analysis. In the scope of these activities we have derived a consistent set of Galileo, BeiDou and QZSS PCO/PCVs based on processing the data of 2014 and 2015. We have extended our box-wing modeling activities now also to the satellites of the âĂIJnewâĂİ constellations, i.e., Galileo, BeiDou and QZSS. We believe that for BeiDou and QZSS an accurate model of the satellites will be of great benefit, if not even mandatory. This is due to the fact that for small beta angles these satellites switch their attitude mode from yaw-steering (the nominal attitude mode used by GPS, GLONASS and Galileo) to orbit normal mode. In the orbit normal mode the satellite are no longer oriented towards the Sun and thus the solar radiation pressure becomes very hard to model. In the orbit normal mode phase the widely used ECOM model, and also the enhanced ECOM2 model, fail to properly model the radiations forces. The main interesting features and challenges we have found so far in our multi-GNSS analysis activities were presented at the IGS workshop in 2014 and 2016, Garcia-Serrano 2014 and Garcia-Serrano 2016, and may be summarized as:

- Strong elevation dependent pattern in the BEIDOU pseudo range residuals for the MEO satellites
- Strong azimuthal dependent pattern in the GALILEO carrier phase residuals, clearly an azimuthal ANTEX pattern needed
- Severe inconsistency between the three GPS phase signals (L1, L2, and L5); a periodic effect with an amplitude of 50 mm clearly visible
- Severe challenges to model the QZSS satellite during the orbit normal mode phase ($|\beta| < 20^0$)

	max-min [m²]	Mass [kg]	**Impact**	Sensitivity
GPS-IIA	1.3	975	**1.0**	6
GPS-IIR/RM	1.8	1100	**1.3**	4
GPS-IIF	2.3	1450	**1.2**	5
GLONASS-M	2.8	1400	**1.6**	3
Galileo-1 (IOV)	2.0	695	**2.2**	2
BeiDou-M	1.5	2000	**0.7**	7
QZSS	12.2	2000	**4.7**	1

Figure 2: Expected solar radiation pressure variations for the different GNSS satellite types

- Severe challenges to model the BeiDou GEO satellite due to orbit normal mode attitude
- Significant challenges to model the BeiDou MEO and IGSO satellites during the orbit normal mode phase ($|\beta| < 4^0$)

Clearly the "orbit normal" attitude mode is posing a significant challenge to achieve orbit with centimeter level precission. Furthermore, thanks to our work on constructing reasonable accurate box-wing models for the different GNSS types we have realised that the variability of the solar radiation pressure acting on the satelllites differs significantly between the different satellite types. In a, very, rough approximation we may consider that this variability is determined by surface ratio's of the satellite X- and Z-sides. The maximum area as seen by the Sun, when the satellit is flying in the standard yaw-attitude mode, is basically the sum of the X- and Z-areas. The minimal area is the area of the smaller of the two sides. The variability of the solar radiation pressure acting on the satellite is then given by this mass ratio devided by the mass of the satellite. The heavier the satellite the less sensitive it will be to the variation in the surface areas that are facing the sun. We have used this "crude" approximation to generate a "sensitivy" table for the different GNSS satellites, shown in Figure 2. In this table we have normalized the values with respect to the GPS-IIA satellites. The sensitivity ranking now tells us which satellites will experience larger solar radiation pressure variations, i.e., the QZSS satellites is ranked in place 1 of our senstivity table and thus is the satellite for which we expect the largest solar radiation pressure variations. This is no surprise as this is also by far the largest satellite. Surprising is that the Galileo satellites are on place 2. This is mainly caused by the fact that the Galileo satellites are very light compared to all other GNSS satellites.

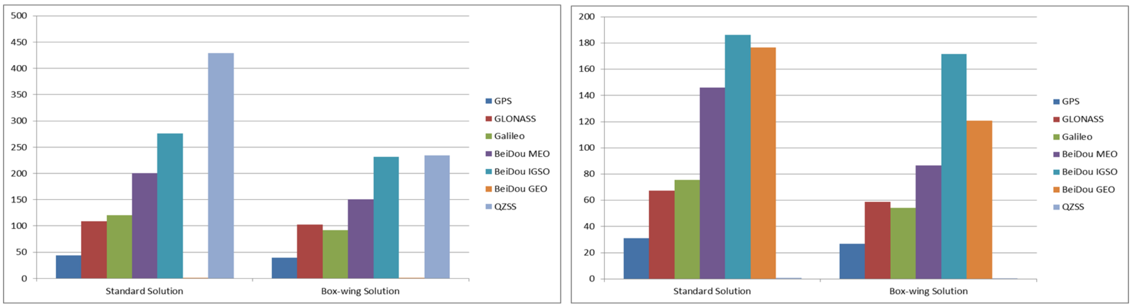

Figure 3: Along-track (left) and Cross-track (right) overlap statistics with and without applying the satellite type specific box-wing models.

Despite that it is hard to find information regarding the surface areas and properties of most GNSS satellites we have attempted to make box-wing models for all the different satellites types. Significant time was spend on validating and tuning the different box-wing parameters and this is a process that is still ongoing. However, Figure 3 does clearly show the positive effect of our box-wing models in both the along- and cross-track directions for all GNSS constellations. Notice that the improvements are most significant for QZSS and Galileo as expected based on our sensitivity index. The BeiDou satellites also profit significantly but this is maily due to the orbit normal mode phase!

6 Summary

The European Space Operations Centre (ESOC) of the European Space Agency (ESA) Analysis Center has continued to produce "best in class" products for the IGS in 2015. All products are generated using the Navigation Package for Earth Orbiting Satellites (NAPEOS) software. NAPEOS is a state of the art software that is highly accurate, very efficient, robust and reliable. It enables ESA/ESOC to deliver the high quality products as required for the IGS but also for the other space geodetic techniques DORIS and SLR. This is important because besides being an IGS Analysis Centre, ESA/ESOC is also an Analysis Centre of the IDS and the ILRS.

For 2016 our main focus will be on improving the orbit modelling for the different GNSS constellations. We need to improve our (a priori) box-wing models for the QZSS and BeiDou satellites and handle the new Glonass-K and Beidou 3rd genaration satellites. Also integer ambiguity resolution of all constellations will be in the focus in 2016 including across constellation ambiguity resolution.

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GFZ Analysis Center Technical Report 2015

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1 Summary

During 2015, the standard IGS product generation was continued with minor changes in the processing software *EPOS-8*. The GNSS observation modeling still conforms to the GFZ *repro-2* (2nd IGS Reprocessing campaign) settings for the IGS Final product generation.

Minor changes in the processing setup became necessary once a degradation of the GFZ clock solution had become evident. In particular, a large number of GPS satellite were excluded from the final clock combination. The reason was identified to be an issue related to the introduction of P1-C1 differential code bias parameters. In addition, an update related to the selection of the reference clock became necessary at the end of 2015.

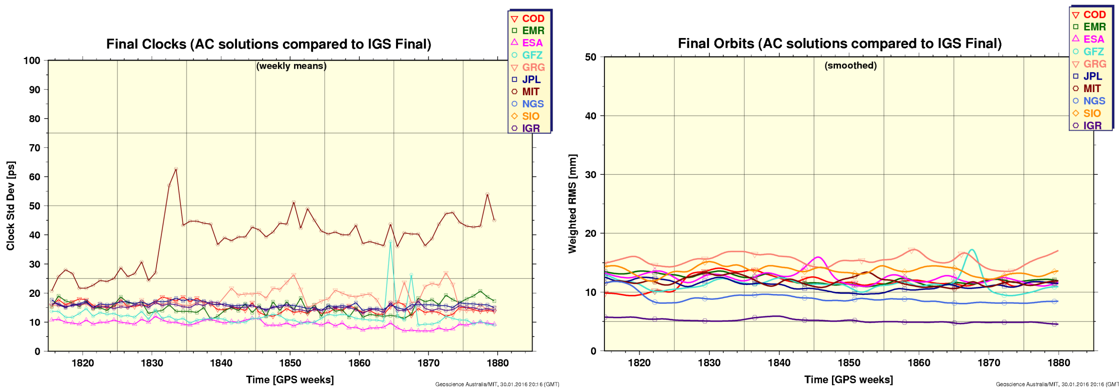
The multi-GNSS processing was continued routinely during 2015 including GPS, GLONASS, BeiDou and Galileo with only few exception from a regular submission. Since May 2015, also QZSS has been included in the processing.

2 Products

The list of products provided to the IGS by GFZ is summarized in Table 1.

Table 1: List of products provided by GFZ AC to IGS and MGEX

IGS Final	(GLONASS since week 1579)
`gfzWWWWD.sp3`	Daily orbits for GPS/GLONASS satellites
`gfzWWWWD.clk`	5-min clocks for stations and 30-sec clocks for GPS/GLONASS satellites
`gfzWWWWD.snx`	Daily SINEX files
`gfzWWWW7.erp`	Earth rotation parameters
`gfzWWWW7.sum`	Summary file including Inter-Frequency Code Biases (IFB) for GLONASS
`gfzWWWWD.tro`	1-hour tropospheric Zenith Path Delay (ZPD) estimates
IGS Rapid	(GLONASS since week 1579)
`gfzWWWWD.sp3`	Daily orbits for GPS/GLONASS satellites
`gfzWWWWD.clk`	5-min clocks for stations and GPS/GLONASS satellites
`gfzWWWWD.erp`	Daily Earth rotation parameters
IGS Ultra-Rapid	(every 3 hours; provided to IGS every 6 hours; GLONASS since week 1603)
`gfuWWWWD_HH.sp3`	Adjusted and predicted orbits for GPS/GLONASS satellites
`gfzWWWWD_HH.erp`	Earth rotation parameters
MGEX Rapid	
`gbmWWWWD.sp3`	Daily satellite orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
`gbmWWWWD.clk`	30 sec (since GPS-week 1843) receiver and satellite clocks
`gbmWWWWD.erp`	Daily Earth rotation parameters
MGEX Ultra-Rapid	since week 1869.1 (02-11-2015)
`gbuWWWWD_HH.sp3`	Adjusted and predicted orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
`gbuWWWWD_HH.erp`	Earth rotation parameters



(a) Clock standard deviation of AC individual compared to IGS Final solution.

(b) Smoothed weighted RMS of GPS orbit differences between AC individual and IGS Final solution.

Figure 1: Degradation of GFZ Final orbit and clock submissions during GPS weeks 1864 to 1871 caused by an improper epoch-wise reference clock selection.

3 Operational GPS/GLONASS data processing and latest changes

EPOS-8 processing software is following the IERS Conventions 2010 (Petit and Luzum 2010). For the IGS Final, Rapid and Ultra-rapid chains approximately 200, 110, and 95 sites are used, respectively. Recent changes in the processing strategy are listed in Table 2. Only minor changes have been applied for the observation modeling in order to keep the consistency with respect to the *repro-2* processing strategy.

A high satellite clock exclusion rate was noticed from the IGS Final clock combination. At the same time, the corresponding orbit solution was not affected. Investigations on GFZ AC side revealed that the regularly updated P1-C1 differential code biases (DCBs) did not enter into the processing. Instead, outdated monthly DCB values valid for August 2013 had been in use causing a continuous decrease in the clock solutions' consistency with the constant renewal of the GPS constellation.

GFZ product submissions for GPS weeks 1864 through 1871 are affected by an improper epoch-wise reference clock selection. Both, the satellite clock performance (Figure 1(a)) as well as the orbits (Figure 1(b)) are affected.

4 Multi-GNSS data processing

The IGR-like multi-GNSS processing was continued in 2015. Since May 2015, QZSS is included in the daily analysis. Hence, GFZ's multi-GNSS solution now covers 5 different

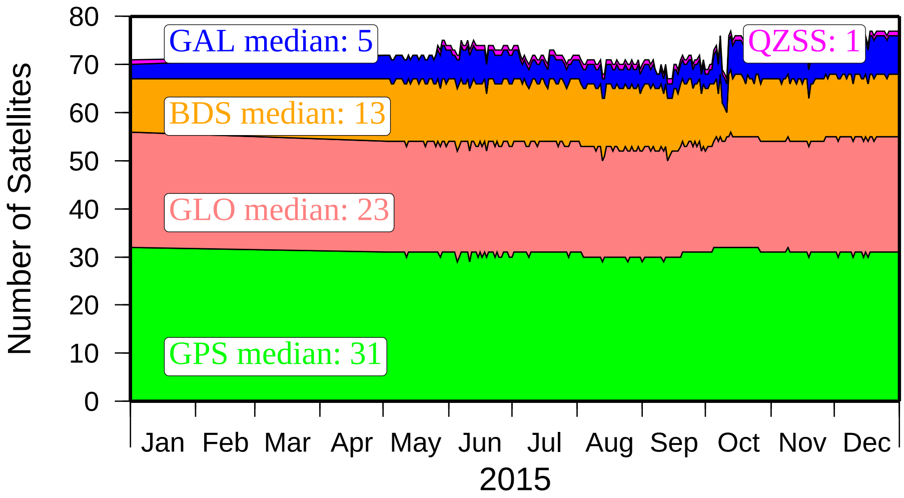


Figure 2: Total number of satellite per GNSS included in the daily MGEX processing.

systems, namely GPS, GLONASS, Galileo, BeiDou and QZSS. Figure 2 shows the total number of satellites per GNSS included in the `gbm` MGEX solution which can be accessed at `ftp://ftp.gfz-potsdam.de/pub/GNSS/products/mgex` or `ftp://cddis.gsfc.nasa.gov/gps/products/mgex`. Table 3 shows the corresponding observation type selection made for the individual GNSS.

As an orbit quality measure, the RMS of differences from overlapping orbit positions (4 hours interval) are evaluated. Figure 3 shows the daily median RMS of the orbit overlaps for each satellite. Corresponding RMS values are below 10 cm for most of the GPS satellites, while they can reach up to 30 cm for GLONASS. A similar range can be found for the Galileo satellites with the worst performance for those two FOC-type satellites in the eccentric orbit. For BeiDou, the three different types of orbits GEO, IGSO, and MEO can clearly be separated. Here, the GEO satellites reveal the largest RMS value of up to 3 meter. The IGSO and MEO satellites show RMS values of 30 cm and 10 cm, respectively. The QZSS satellite reveals an orbit overlap RMS of 90 cm. Since GPS-week 1843, the `gbm` clock product is given at a 30 sec sampling rate.

A new MGEX-processing chain was established in order to provide multi-GNSS orbit and clocks in an ultra-rapid like style. Accordingly, the analysis of 24 h observations is combined with a 24 h prediction for satellite orbits. The corresponding routine processing was started at 2nd November, 2015. Associated products identified with the `gbu` acronym (cf. Table 1) can be acquired at `ftp://ftp.gfz-potsdam.de/pub/GNSS/products/mgex`.

An independent validation of the microwave-based `gbm` satellite orbits was performed using SLR measurements. Figure 4 shows the resulting mean bias and standard deviation for different satellite types which indicate the achieved orbit accuracies for that satellites currently observed by the International Laser Ranging Service.

Table 2: Recent Processing changes

Date	**IGS**	**IGR/IGU**	Change
2015-02-13	w1831	w1832.5	Use updated GPS P1-C1 differential code biases
2015-02-26	w1864	w1864	Switch to 12th generation of the International Geomagnetic Reference Field (IGRF)
2015-03-16	w1864	w1864	Allow inter system bias reference receiver be different from clock reference receiver
2015-10-05	w1864	-	Switch from CODE TEC maps to IGS combined TEC maps
2015-12-02	w1872	w1873.4	Fix clock reference selection procedure

Table 3: Used observation types and number of satellites in the multi-GNSS data processing.

Satellite System	**# Satellites**	**Observation Types**
GPS	31	L1/L2
GLONASS	24	L1/L2
Galileo	9	E1/E5a
BeiDou	13	B1/B2
QZSS	1	L1/L2

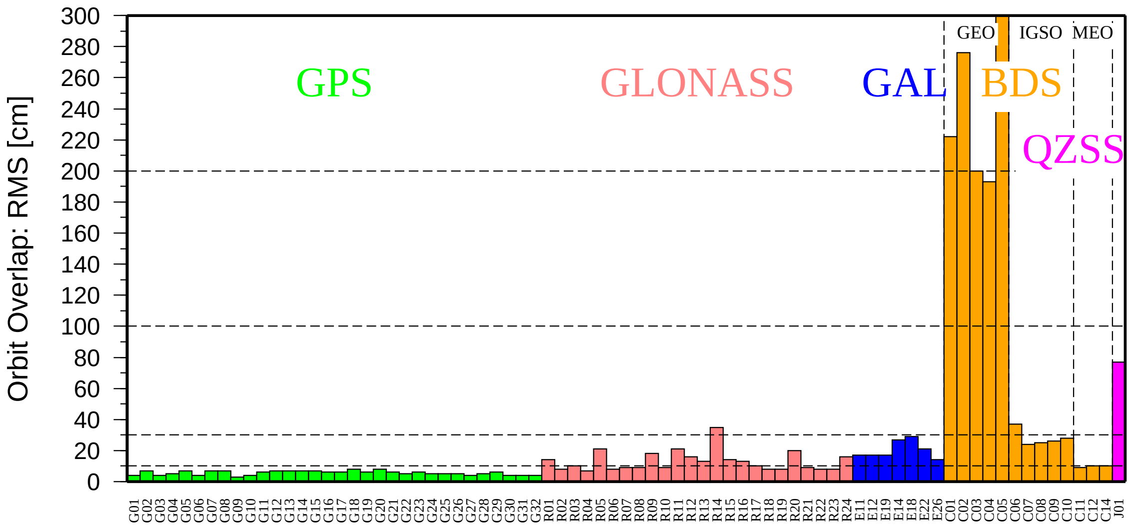


Figure 3: Daily median RMS [cm] of the differences from overlapping orbit positions (4 hours interval).

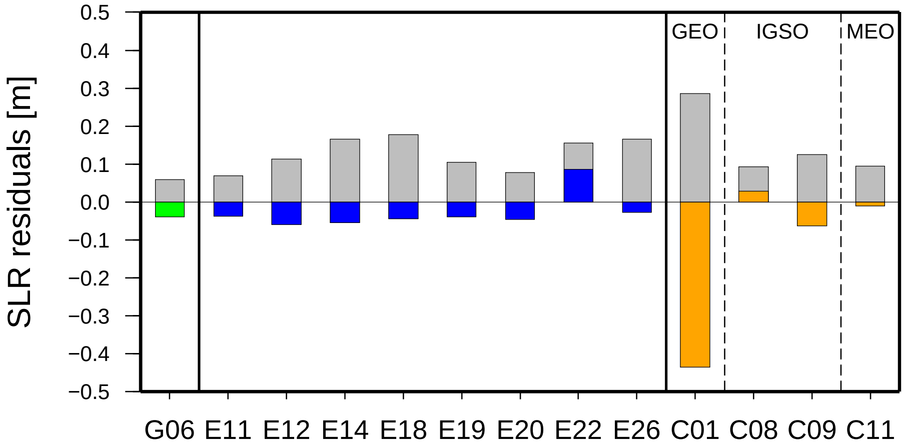


Figure 4: SLR residual statistics. The bias (colored) and STDV (grey) are given for individual GPS, Galileo and BeiDou satellites.

5 RINEX tool box `gfzrnx`

The development of a toolbox named **`gfzrnx`** was started in 2015. The primary goal of this command-line oriented toolbox is the support of RINEX file conversion and manipulation operations. The program allows to handle Observation, Navigation, and Meteorological RINEX data types. In the following, an overview of the implemented functions is given:

- Check format consistency and possibly repair
- Conversion between versions 2 and 3
- File splice/split operations
- Generation of statistics based on file content
- File header editing
- Version-dependent file naming
- File content manipulations (e. g. data sampling, observation type selection, etc.)

Currently, the following operating systems are supported: Linux, Windows, MAC OS X, and SunOS. **`gfzrnx`** can be downloaded at `http://semisys.gfz-potsdam.de/semisys/scripts/download` and can be used free of charge. Upon interest, users may also subscribe to the mailing-list `gfzrnx@gfz-potsdam.de`.

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CNES–CLS Analysis Center Technical Report 2015

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1 Introduction

In 2015, the CNES–CLS Analysis Center continued its contribution through the weekly delivery of final products (Loyer et al. 2015a, Loyer et al. 2015b) using the GINS software package (Marty et al. 2011). The models, standards and estimated parameters remained almost the same as those implemented for the REPRO2 campaign. The only but major evolution was that our hybrid GPS–GLONASS–Galileo solution dedicated to MGEX activities became our official IGS contribution starting week 1840 (April 12, 2015). More details on this change and its impact on the products are given in section 2. In 2015, we also started producing experimental 5 second sampling clock products and section 3 summarizes a comparison analysis with 30 second products. In section 4, the GPS Wide–Lane Satellites bias product dependency in the receiver manufacturer is discussed.

2 Multi–GNSS products

We started contributing to the Multi–GNSS Experiment in 2012 with a regular processing of hybrid GPS–GLONASS–Galileo products. To avoid the maintenance of two separated processing chains we decided to only operate the MGEX one starting week 1840 (12 Apr. 2015). The corresponding GPS and GLONASS orbits and clocks solutions then became our official contribution to IGS (Tab. 1 and Fig. 1).

Table 1: CNES–CLS IGS final products

Products	Files
Daily GPS, GLONASS (GRG) & Galileo (GRM) Ephemeris/clock 15–min sampling	`[grg/grm]wwwwn[0-6].sp3`
Daily GNSS clock 30–sec sampling (Compatible for GPS PPP with ambiguity resolution)	`[grg/grm]wwwwn[0-6].clk`
Daily Normal Equations for EOP and Stations coordinates	`[grg/grm]wwww[0-6].snx`
Summary report for week `wwww`	`grgwwww7.sum`
ERP weekly solution	`grgwwww7.erp`

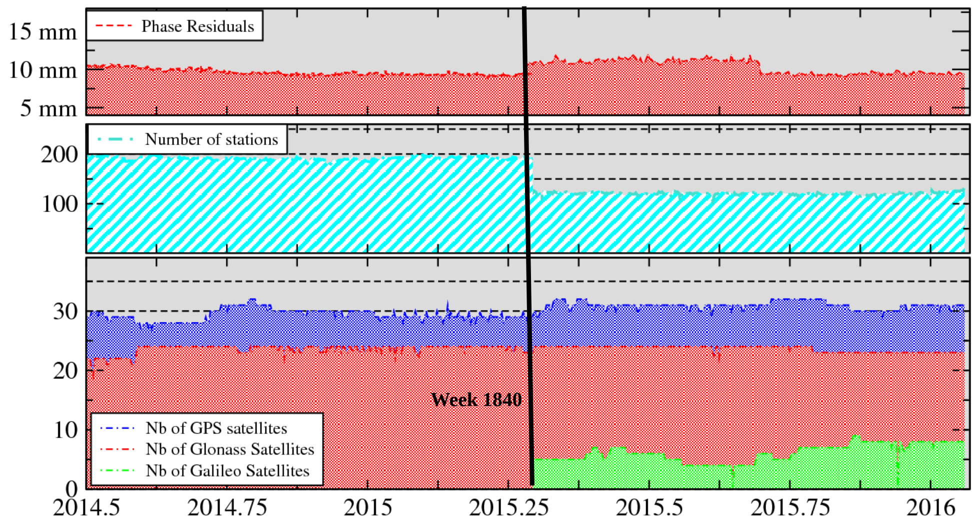

Figure 1: Main statistics of the CNES/CLS Analysis Center products during 2015. Since week 1840 Galileo satellites are included in the processing.

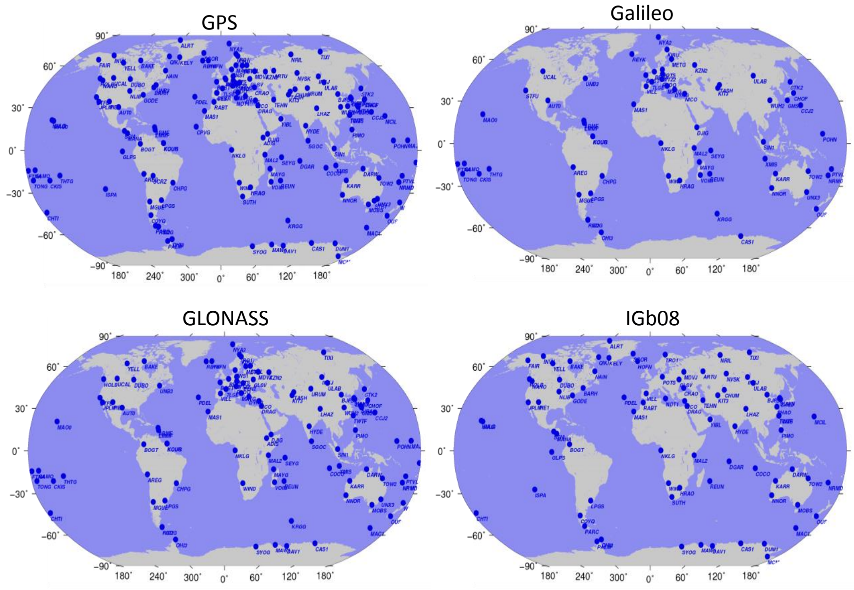

Figure 2: Network and sub–networks used in our current products. The number of data used differs for each constellation.

This change was also associated with a revision of the tracking network. The total number of stations was reduced from ∼200 to ∼120 in order to compensate the expansion of the number of measurements and estimated parameter. During the 30 seconds sampling clock densification step, the total number of observations reaches now around 8 billion for a one day arc. The station location selection was optimized in order to include the more as possible MGEX receivers as well as IGb08 core network sites (Fig. 2). Another motivation was to be prepared to the transition of IGS products to a true multi–GNSS solution in the future.

Switching to MGEX products had no significant impact on the orbit and EOP comparison to other ACs. However we made a mistake in the procedure managing the new stations (their a priori coordinates) and the alignment of the network to the Igb08 frame. This impacted during several months the global phase measurements residuals (Fig. 1) and introduced a global translation at the level of one centimeter of the orbit solution in the Z direction. This problem has been corrected week 1874. It has impacted the GRG clocks standard deviations at the level of 20 picoseconds compared to IGS combined solution as shown in Fig. 3. It was also visible on the global network PPP solution translations as estimated by the IGS ACC as showed in Fig. 4.

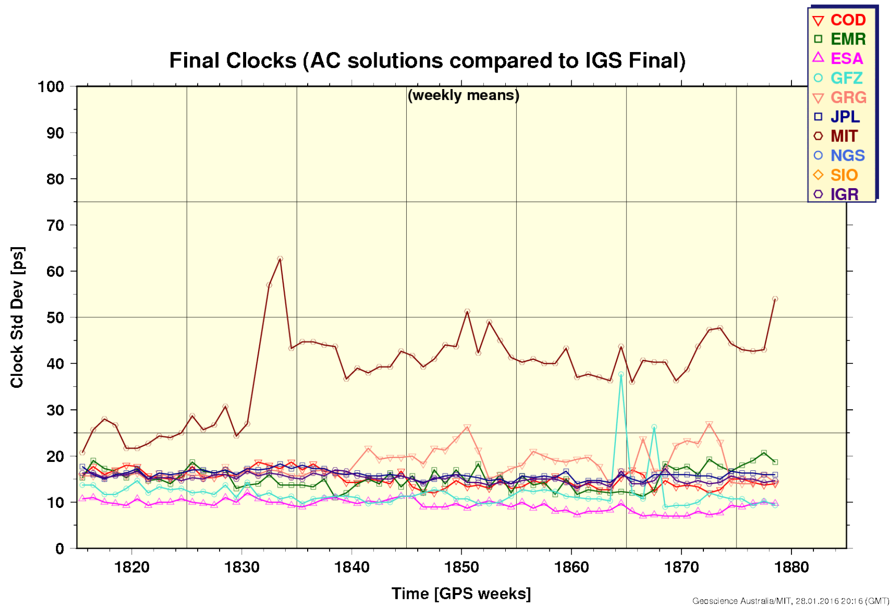

Figure 3: Final clocks (AC solutions compared to IGS final).

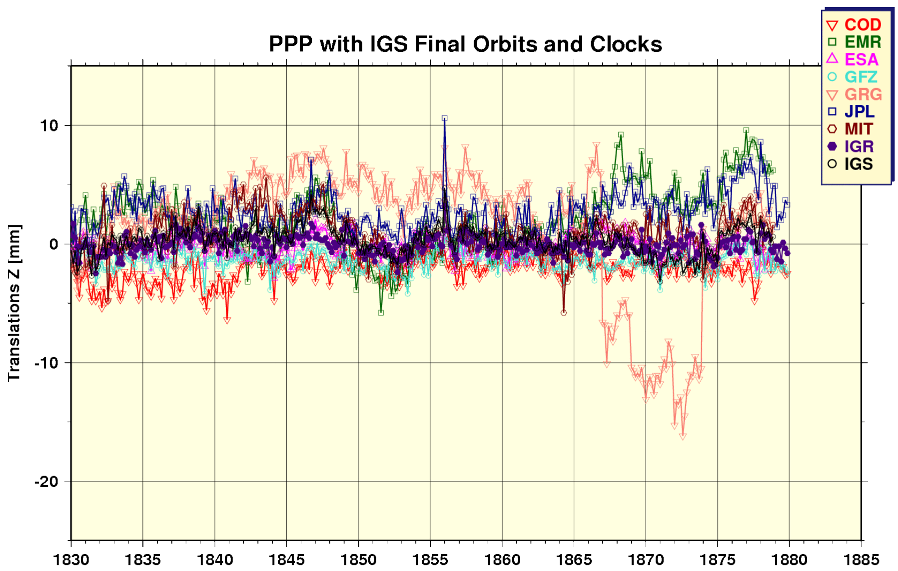

Figure 4: PPP with IGS final orbit and clocks.

3 Five–second clock products

PPP of receivers having a rapid and/or erratic displacement (buoys, boats, LEO...) may need high rate constellation clock products. At least a 5 seconds sampling is needed in such case. We included the capability to produce such clocks in our operations. But 1Hz RINEX raw data are needed. However the network of high rate stations is not as dense as the 30 seconds one. Consequently high rate clocks may not have the same quality as 30 seconds ones (Fig. 5) as they can suffer from a poor distribution, especially for GLONASS (Fig. 6). Nevertheless, it is expected that the 1Hz network will grow in the near future to overcome these difficulties.

4 Receiver type dependent satellite biases

We wanted to quantify the receiver dependent part of the GPS Wide–Lane Satellites Biases (WSB). The production of these biases is part of our routine processing as we need them to fix zero–difference GPS phase ambiguities to integers. They are also widely used for PPP with ambiguity fixing using GRG orbit and clock products. WSB are derived from the Melboune–Wübbena combination of the code and phase observables averaged over a global network of receivers. For this study we also computed individual WSB solutions from each receivers of the MGEX network and we got noticeable receiver type dependent

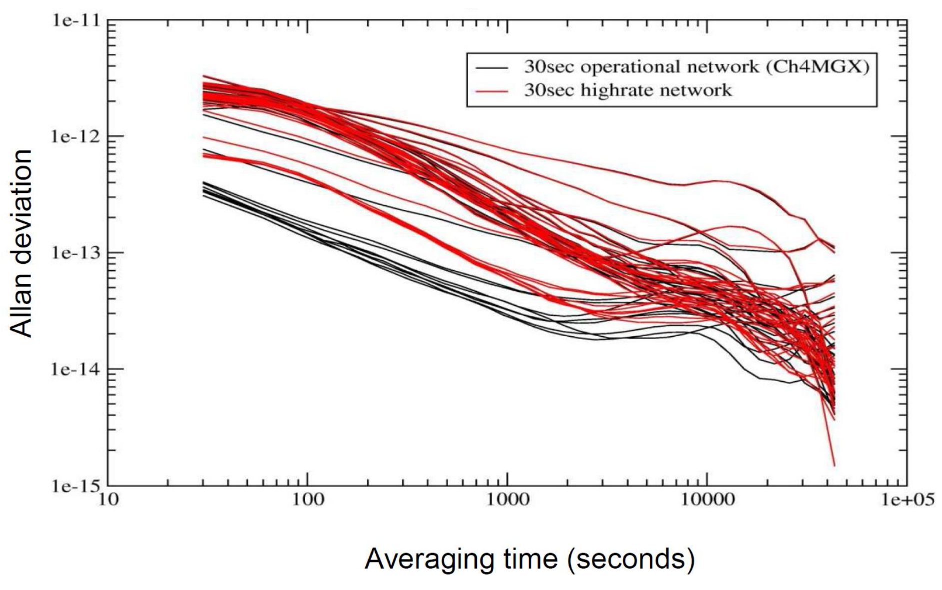

Figure 5: Allan standard deviation of the 30s sampling clock solutions: From the operational POD network (in black) and from the high rate network (in red).

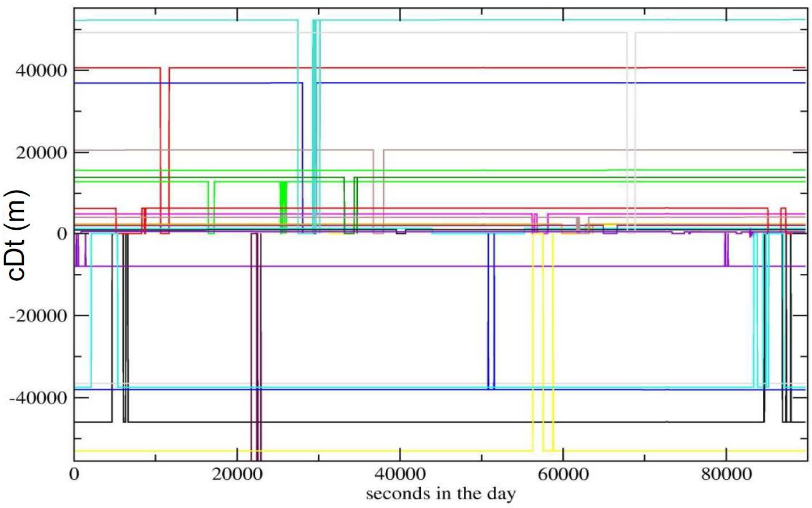

Figure 6: Example of GLONASS 30s clock solution per satellite (expressed in meters) for DOY 150, 2015. Zero values correspond to a loss of observability.

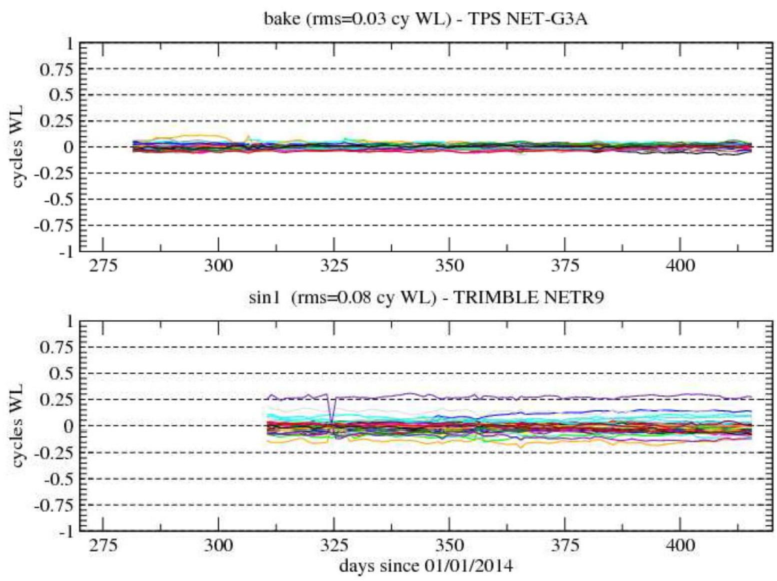

Figure 7: Two examples of single–receiver WSB sets. The TPS NET–G3A receiver agrees very well with the average solution. The Trimble NET–R9 exhibits much more discrepancies.

biases. Constant offsets are visible between individual series in Fig. 7.

Receiver "families" can be easily identified in Fig. 8 which compares each individual WSB solution to the averaged official one. Moreover two families can be identified for Trimble receivers and this is still not understood today.

The maximum discrepancy reaches 0.13 RMS in WL cycles. However we couldn't notice a significant impact on the Wide–Lane ambiguity fixing success rate when using receiver type WSB instead of averaged values. Nevertheless, this step is highly sensitive to the robustness of the algorithms and to the process parameterization. In addition, receiver manufacturer options to process new GNSS signals could lead to a more critical situation when future WL combinations (e.g. using L1L5) will be used.

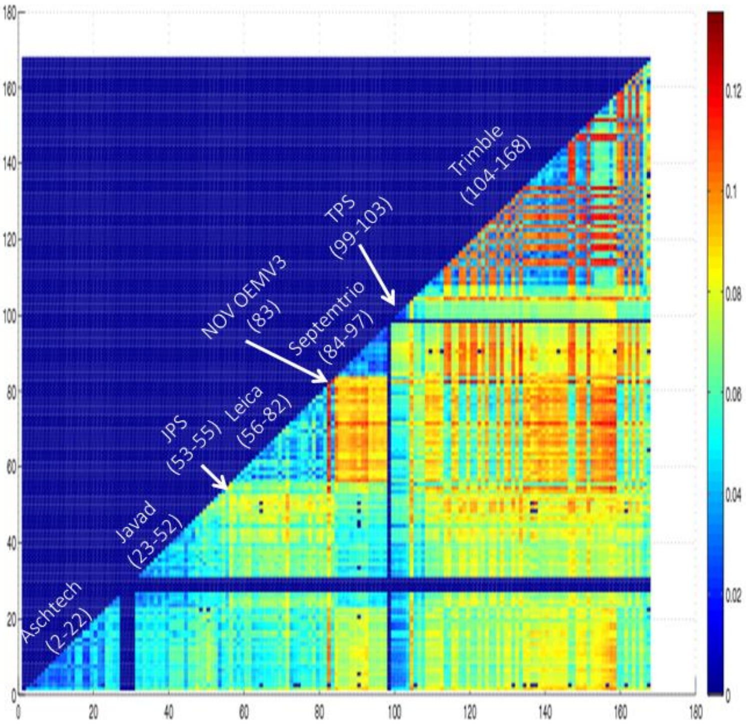

Figure 8: GPS WSB RMS differences between individual receivers of the MGEX network (sorted by receiver types).

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1 Introduction

In 2015, 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 2015.

Table 1 summarizes our contributions to the IGS Rapid and Final products. All of our

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

Product	Description	Rapid/Final
jplWWWWd.sp3	GPS orbits and clocks	Rapid & Final
jplWWWWd.clk	GPS and station clocks	Rapid & Final
jplWWWWd.clk_30s	30-second GPS clocks	Final
jplWWWWd.tro	Tropospheric estimates	Rapid & Final
jplWWWWd.erp	Earth rotation parameters	Rapid(d=0-6), Final(d=7)
jplWWWWd.yaw	GPS yaw rate estimates	Rapid & Final
jplWWWWd.snx	Daily SINEX file	Final
jplWWWW7.sum	Weekly solution summary	Final

contributions are based upon daily solutions centered at noon and spanning 30 hours. Each of our daily solutions is determined independently from neighboring solutions, namely without applying any constraint between solutions. We started delivering High-rate (30-second) Final GPS clock products starting October 26, 2014 and in our repro2 contribution we generated these products from May 07, 2000, onwards.

The JPL IGS AC also generates Ultra-Rapid orbit and clock products for the GPS constellation. These products are generated with a latency of less than 2.5 hours and are updated hourly (Weiss et al. 2010). Although not submitted to the IGS, our Ultra-Rapid products are available in native GIPSY formats at: ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Ultra-Rapid

2 Processing Software and Standards

The JPL AC continues to utilize the GIPSY/OASIS software package to generate our contributions to the IGS which we will refer to in the rest of this report simply as GIPSY. Starting on November 29, 2015, the products we deliver to the IGS have been generated with GIPSY version 6.4 which supersedes GIPSY version 6.3 that was used to produce our IGS repro2 contribution. In our operations, we have adopted our repro2 data processing approach, which has the following improvements compared to our previous data processing strategy:

- Application of second order ionospheric corrections (Garcia-Fernandez et al. 2013).
- Revised empirical solar radiation pressure model named GSPM13 (Sibois et al. 2014).
- Antenna thrust models per IGS recommendations.
- Modern ocean tide loading, using GOT4.8 (Ray 2013) (appendix) instead of FES2004 (Lyard et al. 2006).
- GPT2 troposphere models and mapping functions (Lagler et al. 2013).
- Elevation-dependent data weighting.

A complete description of our current operational processing approach, also used for repro2, can be found at: https://igscb.jpl.nasa.gov/igscb/center/analysis/jpl.acn

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).

GIPSY 6.4 is a relatively minor upgrade over GIPSY 6.3 and provides the following enhancements:

- Improved reference frame handling with support for large ITRF2014 covariance files
- Improved attitude modeling of GPS block IIF at noon and midnight turns
- Software upgrades to data editor and PPP tool, several new utilities, bug fixes
- Improved geophysical models:
  - Second-order ionosphere correction: small improvements in the use of IGRF, IRI, IONEX models
  - GPT2 model: finer 1° resolution and GPT2w a-priori wet delay calculation
  - Time-varying gravity (including ICGEM format to GIPSY format converter)

3 Overlap Statistics

Figures 1 and 2 show orbit and clock overlap boxplot statistics for 1996-2015 and 2015 respectively. In our processing we use 30-hour arcs centered on noon and determine daily orbit and clock overlaps using the central 5-hour portion of the 6-hour arc-to-arc overlap region as one indicator of our precision. The daily orbit overlap is defined to be the median of the RMS of the 1D orbit differences per transmitter in the central 5-hour region while the daily clock overlap is the RMS of the RMS clock differences per transmitter in the same 5-hour central overlap region. Figure 1 shows a slight degradation in orbit overlaps during the last few years the cause of which is currently being investigated. Figure 2 shows that the major difference between our Final and Rapid products is fewer days with large orbit and clock overlaps in the Final products.

4 Transition of Operations to Using GIPSYx

For several years, a C++/python replacement for both GIPSY and Real-Time GIPSY called GIPSYx/RTGx has been under development which has the following features:

- Supports both post-processing and real-time processing of multiple GNSS constellations
- Processes data from GPS, GLONASS, and Beidou. Galileo is under development. However, more work is needed to to be able to create orbit and clock products from constellations other than GPS.
- Readily extends to support DORIS and SLR data processing
- Multi-processor and multi-threaded capability
- Multi-GNSS PPP tool is under development

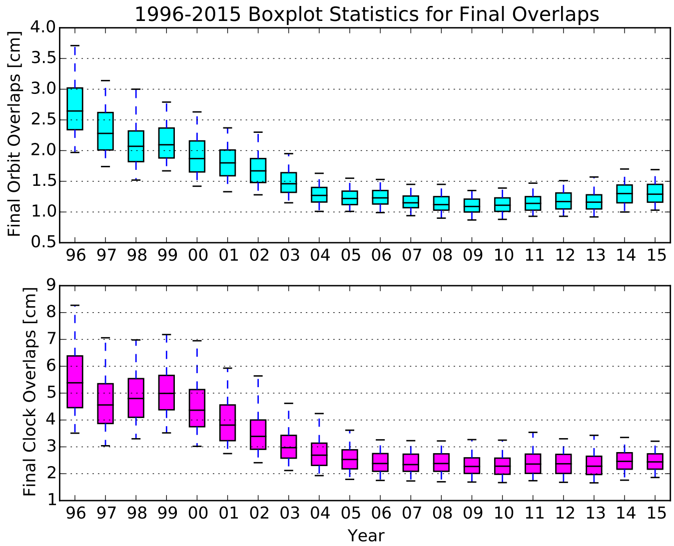

Figure 1: 1996-2015 boxplot statistics for Final orbit and clock overlaps with whiskers at the 5th and 95th percentiles. Note: overlap definitions can be found in section 3.

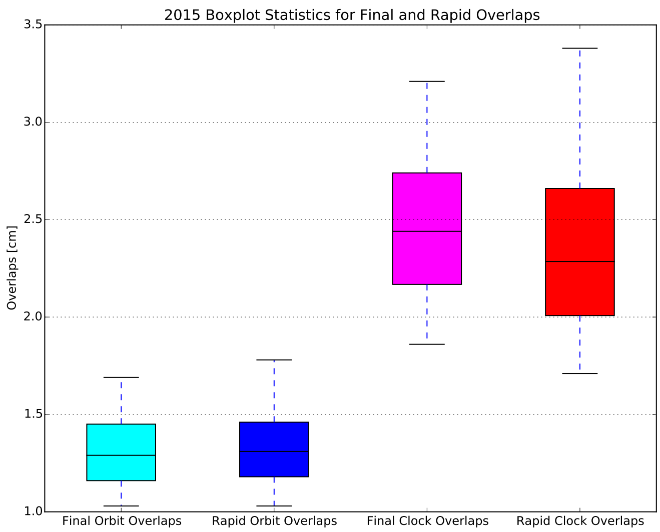

Figure 2: 2015 boxplot statistics for Final/Rapid orbit and clock overlaps with whiskers at the 5th and 95th percentiles. Note: overlap definitions can be found in section 3.

- Uses similar but not identical file formats to GIPSY

In parallel with the GIPSYx development we have also been developing new operational software in python to generate both the rapid and final products that we deliver to the IGS orbit using GIPSYx instead of GIPSY. We are currently testing this new operational software by comparing rapid and final products generated by both GIPSYx and GIPSY and expect to start generating our IGS GPS orbit and clock products using this new operational software in the second half of 2016.

5 Future Work

In 2016, JPL will continue to submit operational Rapid and Final GPS products to the IGS using our repro2 processing configuration and our current operational software, which uses GIPSY 6.4, until we make the transition to using our new operational software which uses GIPSYx. Our longer term goal is to generate other GNSS constellation orbit and clock products using this new software.

6 Acknowledgments

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

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1 Introduction

In 2015, NGS continued to serve as an IGS analysis center, a regional data center and one of our team member, Kevin Choi, continued as the analysis center coordinator. This report summarizes the routine analysis and data center activities conducted at the National Geodetic Survey (NGS), and all significant changes that occurred during the year 2015.

2 Core Analysis Center Products

There were no changes in the NGS analysis center products (see Tab. 1) for 2015. Please refer to the Analysis Coordinator website (http://acc.igs.org) for combination statistics of the NGS analysis center products.

3 Analysis Center Processing Software and Strategies

There were no changes to the processing models or strategies for 2015. For details about the models and strategies used, please refer to the NOAA/NGS Analysis Strategy Summary (ftp://igs.org/pub/center/analysis/noaa.acn).

Changes to the processing software and strategies include:

Table 1: NGS Analysis Center Products

Product	Description
Final (weekly)	
ngswwwwd.sp3 ngswwwwd.snx ngswwww7.erp	GPS only PAGES software suite (5.97 – 5.101) Orbits, ERP and SINEX
Rapid (daily)	
ngrwwwwd.sp3 ngrwwwwd.erp	GPS only PAGES software suite (5.97 – 5.101) Orbits, ERP and SINEX Daily submission for IGR combination
Ultra–Rapid (hourly)	
nguwwwwd.sp3 nguwwwwd.erp	GPS only PAGES software suite (5.97 – 5.101) Orbits and ERP 4 times a day submission for IGU combination

- *Week 1836 (2015–03–15)*

  Format change to (internal use only) processing summary file. No effect upon products.

- *Week 1848 (2015–06–07)*

  An SV indexing error reading continuation lines from the RINEX 2.XX format was corrected. Negligible effect upon products.

- *Week 1856 (2015–08–02)*

  The scripts used to produce the NGS final and rapid products were consolidated simplifying maintenance. No effect upon products.

- *Week 1861 (2015–09–06)*

  Format change to (internal use only) processing summary file. Corrected phase continuity detection. Small effect upon products.

- *Week 1870 (2015–11–08)*

  MGEX ANTEX file supersedes GPS and GLONASS only variant. No effect upon products.

Changes in staff include:

- Sungpil Yoon came on–board in February.
- Gerald Mader retired in July after 35 years of U.S. Federal service.

4 Regional Data Center Core Products

During 2015, NGS contributed data from the following sites to the IGS Network in Tab. 2

Table 2: The sites from which NGS contributed data to the IGS Network

Site	Location	Lat.	Long.	Receiver Type	System
ASPA	Pago Pago, American Samoa	–14.33	–170.72	TRIMBLE NETR5	GPS+GLO
BARH	Bar Harbor, ME, USA	44.39	–68.22	LEICA GRX1200GGPRO	GPS+GLO
BRFT	Eusebio, Brazil	–3.88	–38.43	LEICA GRX1200PRO	GPS
BRMU	Bermuda, United Kingdom	32.37	–64.70	LEICA GRX1200GGPRO	GPS+GLO
CNMR	Saipan, CNMI, USA	15.23	145.74	TRIMBLE NETR5	GPS+GLO
GUUG	Mangilao, Guam, USA	13.43	144.80	TRIMBLE NETR5	GPS+GLO
HNPT	Cambridge, MD, USA	38.59	–76.13	LEICA GRX1200GGPRO	GPS+GLO
USNO	Washington, DC, USA	38.92	–77.07	ASHTECH Z–XII3T	GPS
WES2	Westford, MA,USA	42.61	–71.49	SEPT POLARX4TR	GPS+GLO

As a Regional Data Center, NGS also facilitated data flow for the following sites in Tab. 3

Table 3: The sites where NGS facilitated data flow

Site	Location	Lat.	Long.	Receiver Type	System
BJCO	Cotonou, Benin	6.38	2.45	TRIMBLE NETR5	GPS+GLO
GUAT	Guatemala City, Guatemala	14.59	–90.52	LEICA GRX1200GGPRO	GPS+GLO
ISBA	Baghdad, Iraq	33.34	44.44	TRIMBLE NETR5	GPS+GLO
MANA	Managua, Nicaragua	12.15	–86.25	TRIMBLE NETR9	GPS
WUHN	Wuhan, China	30.53	114.36	TRIMBLE NETR9	GPS+GLO

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 Acknowledgments

The analysis and data center teams wish to express our gratitude to NGS management: Director Juliana Blackwell, Acting Deputy Director Brett Howe, Acting Division Chief Steve Hilla, Division Chief Srinivas Reddy and Division Chief Dr. Dan Roman, for their support of this work as fundamental activities of NGS. For information about how these activities fit into NGS plans, see the National Geodetic Survey Ten–Year Strategic Plan 2013–2023 (http://geodesy.noaa.gov/web/news/Ten_Year_Plan_2013-2023.pdf).

USNO Analysis Center Technical Report 2015

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1 Introduction

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

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

The USNO AC is hosted in the GPS Analysis Division (GPSAD) of the USNO Earth Orientation Department (EOD). USNO AC activities, chairing the IGS TWG, and serving on the IGS Governing Board duties were transitioned from Dr. Christine Hackman to Dr. Sharyl Byram in 2015. Dr. Byram oversees production of the IGS Final Troposphere Estimates. All GPSAD members, including Dr. Victor Slabinski, Mr. Jeffrey Tracey and contractor Mr. James Rohde, participate in AC efforts.

USNO AC products are computed using Bernese GPS Software (Dach et al. 2007)[1]. Rapid products are generated using a combination of network solutions and precise point posi-

[1]Prior to 2009, the rapid products were computed using the Jet Propulsion Laboratory (JPL) GPS Inferred Positioning System (GIPSY) (Webb and Zumberge 1997).

tioning (PPP; Zumberge et al. 1997). Ultra–rapid products are generated using network solutions. IGS Final Troposphere Estimates are generated using PPP.

GPSAD also generates a UT1–UTC–like value, UTGPS, five times per day. UTGPS is a GPS–based extrapolator of VLBI–based UT1–UTC measurements. The IERS (International Earth Rotation and Reference Systems Service) Rapid Combination/Prediction Service uses UTGPS to improve post–processed and predicted estimates of UT1–UTC. Mr. Tracey oversees UTGPS.

USNO rapid, ultra–rapid and UTGPS products can be downloaded immediately after computation from http://www.usno.navy.mil/USNO/earth-orientation/gps-products. IGS Final Troposphere Estimates can be downloaded at ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd.

2 Product Performance, 2015

Figures 1–4 show the 2015 performance of USNO rapid and ultra–rapid GPS products, with summary statistics given in Tab. 1. USNO rapid orbits had a median weighted RMS (WRMS) of 17 mm with respect to (wrt) the IGS rapid combined orbits. The USNO ultra–rapid orbits had median WRMSs of 20 mm (24–h post–processed segment) and 38 mm (6–h predict) wrt the IGS rapid combined orbits. These values are nearly identical to the 2014 values (17, 19 and 38 mm).

USNO rapid (post–processed) and ultra–rapid 6–h predicted clocks had median 172 ps and 1201 ps RMSs wrt IGS combined rapid clocks, compared to 162 ps and 1603 ps in 2014. Note the significant improvement in the ultra–rapid clock predictions.

Table 1: Precision of USNO Rapid and Ultra–Rapid Products in 2014 (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 24h	6h predict		past 24h	24h predict	past 24h	6h predict
1/1/2015 – 12/31/2015	17	20	38	x: 178 y: 131	x: 176 y: 159	x: 390 y: 316	172	1201

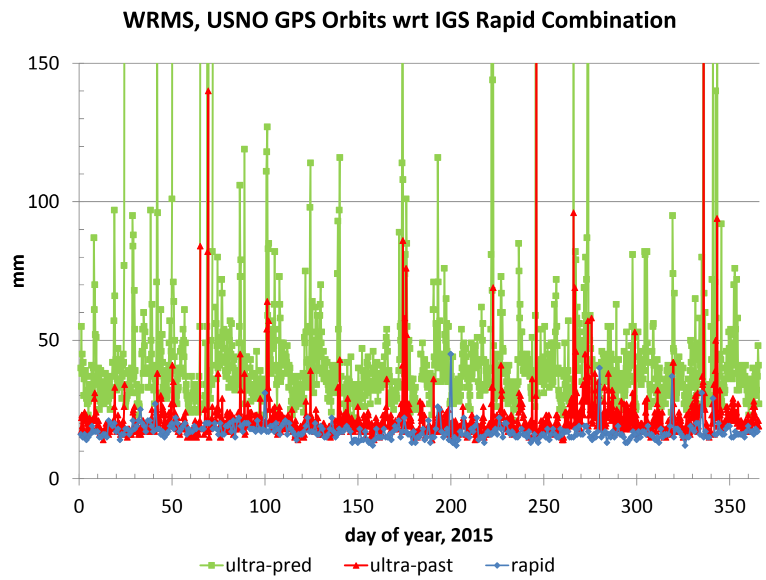

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2015. "Ultra–past" refers to 24–hour post–processed section of USNO ultra–rapid orbits. "Ultra– pred" refers to first six hours of ultra–rapid orbit prediction.

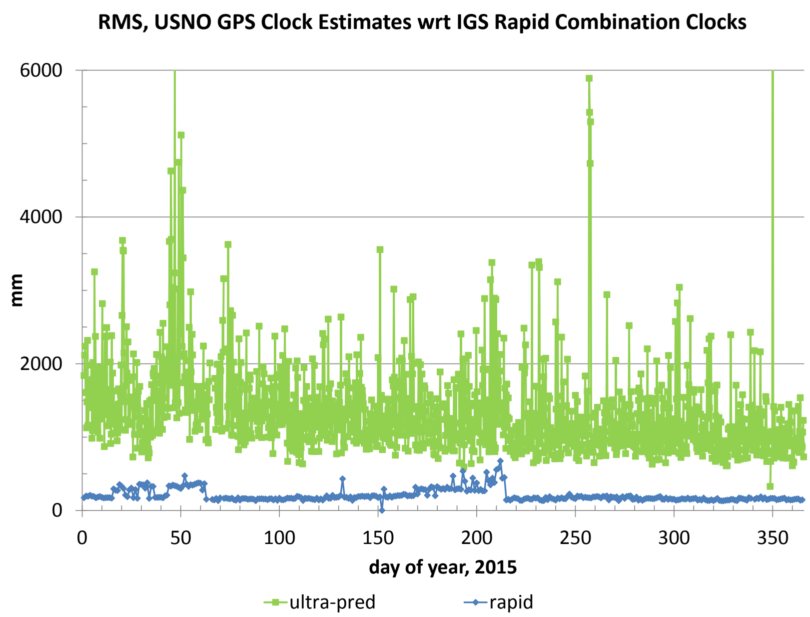

Figure 2: RMS of USNO GPS rapid clock estimates and ultra–rapid clock predictions with respect to IGS Rapid Combination, 2015.

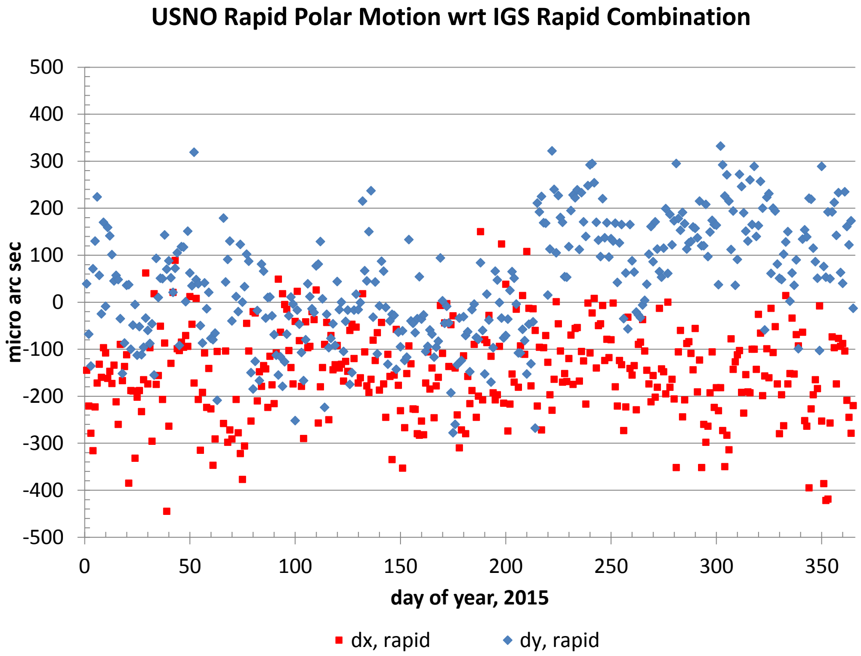

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2015.

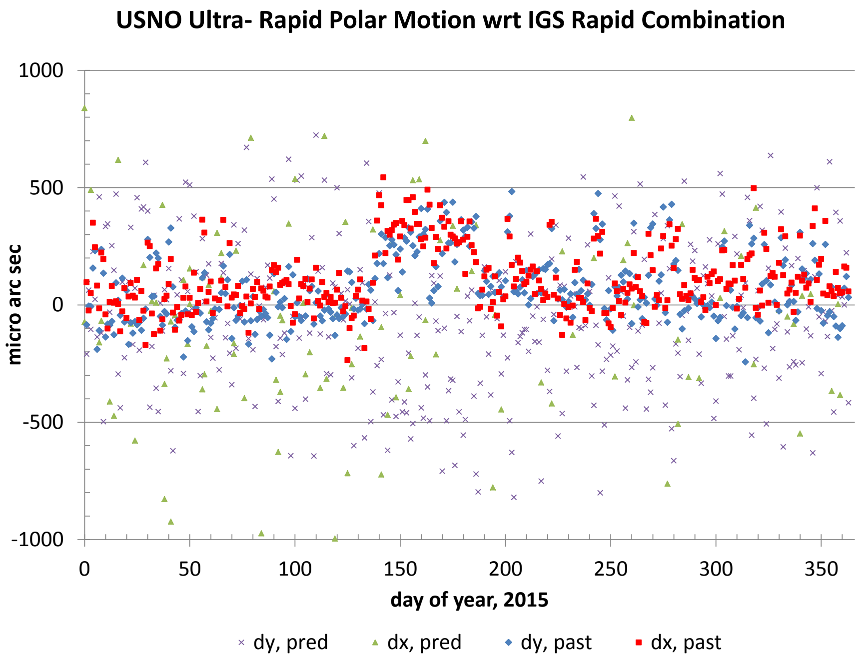

Figure 4: USNO ultra–rapid polar motion estimates minus IGS Rapid Combination values, 2015.

Table 2: Precision of USNO Ultra–Rapid GPS+GLONASS Test Products in 2014 (Orbit statistics computed with respect to IGV Combined Ultra–Rapid GPS+GLONASS Products. Polar motion statistics computed with respect to past–24–hr segment of IGU GPS–only values.)

USNO GLONASS satellite orbits			**USNO GPS+GLONASS polar motion estimates**	
Median RMS of 7–parameter Helmert transformation units: mm			RMS difference units: 10^{-6} arc sec	
dates	past 24h	24h predict	past 24h	pred 24h
1/1/2015 – 12/31/2015	31	68	x: 270 y: 166	x: 471 y: 309

USNO rapid polar motion estimates had (x, y) 178 and 131 micro arc sec RMS differences wrt IGS rapid combined values. USNO ultra–rapid polar motion estimates differed (RMS; x, y) from IGS rapid combined values (aka IGR) by 176 and 159 micro arc sec for the 24–h post–processed segment. The USNO ultra–rapid 24–h predict–segment values differed (RMS; x, y) from the IGS rapid combined values by 390 and 316 micro arc sec. The ultra–rapid polar motion values are skewed due to a ∼6 week bias that was a result of a processing issue.

The USNO AC began incorporating measurements from the Russian GLONASS GNSS into processing in 2011 (Byram and Hackman 2012a – 2012b) and has been computing a full set of test rapid and ultra–rapid combined GPS+GLONASS products since 2012.

In 2015, seven–parameter Helmert transformations computed between USNO and IGS ultra–rapid GPS+GLONASS orbits had median RMSs of 31 and 68 mmfor the 24–h post–processed and 6–h predict portions, respectively. Meanwhile, the USNO GPS+GLONASS ultra–rapid 24–h post–processed polar motion x and y values differed from the IGR values, RMS, by 270 and 166 micro arc sec, respectively. USNO GPS+GLONASS ultra–rapid 24–h predicted polar motion x and y values differed the IGR values, RMS, by 471 and 309 micro arc sec, respectively. The ultra–rapid polar motion values are skewed due to a ∼6 week bias that was a result of a processing issue. These data are shown in Tab. 2/Figs. 5–6.

The USNO AC acquired *Bernese 5.2 GNSS Software* in 2013 and plans to release official AC products generated using it in 2016. The GPS+GLONASS rapid and ultra–rapid solutions referenced above have been generated using *Bernese 5.2 GNSS Software* since December 2014.

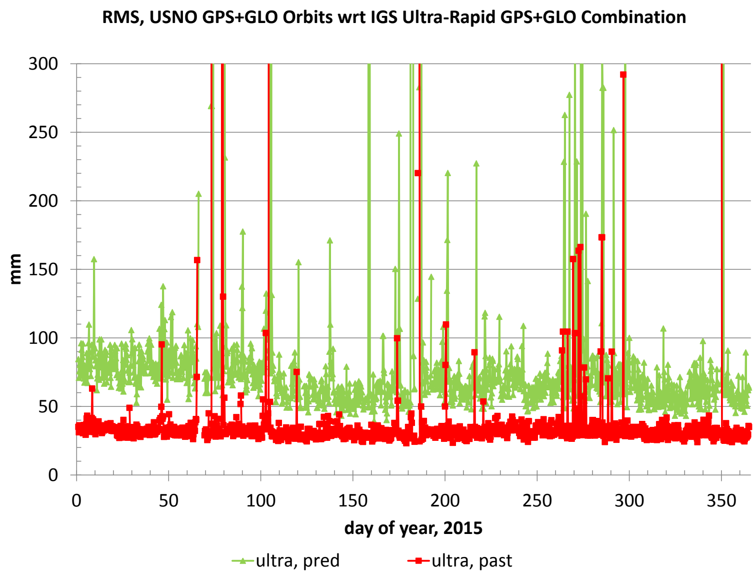

Figure 5: RMS of USNO ultra–rapid GLONASS orbit estimates with respect to IGS Combined Ultra–rapid GLONASS orbits, 2015. "Ultra, past" refers to 24–hour post–processed section of USNO ultra–rapid orbits. "Ultra, pred" refers to first six hours of ultra–rapid orbit prediction. Helmert transformations computed using Bernese 5.0 Software.

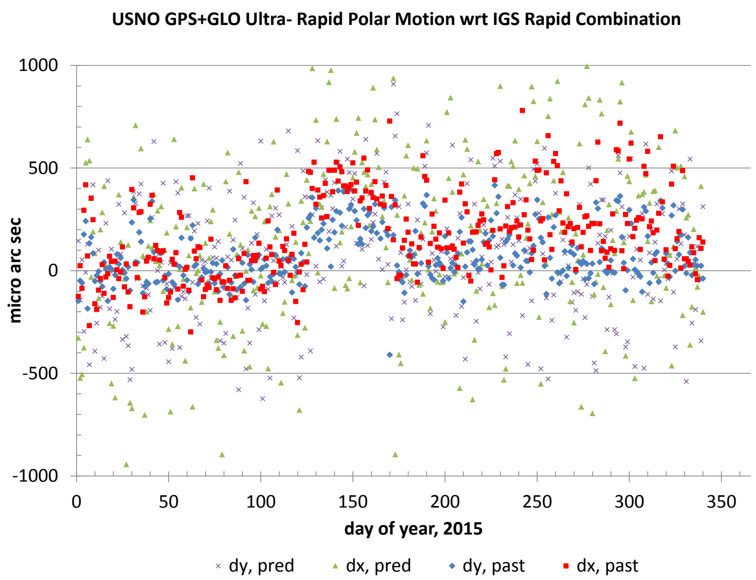

Figure 6: Difference between 24–h post–processed polar motion estimates in USNO test ultra–rapid GPS+GLONASS solution and IGS "IGU" GPS–only ultra–rapid solution, 2015.

3 USNO AC Conference Presentations/Publications

USNO AC members presentaitons/publications are as follows for 2015:

– S. Byram and C. Hackman, “Multi–GNSS Ultra–Rapid Orbit and Clock Products”. *2015 ION Pacific PNT*, Honolulu, HI, 2015.

– V. Slabinski, “Lense–Thirring Effect Measurement from LAGEOS Node: Limitation from Radiation Forces”. *2015 Meeting of the Division on Dynamical Astronomy*, American Astronomical Society, Pasadena, CA. 2015.

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WHU Analysis Center Technical Report 2015

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1 Introduction

The IGS Analysis Center of Wuhan University (WHU) has contributed to the International GNSS Service (IGS) since 2012 with a regular determination of the precise GPS+GLONASS ultra–rapid and rapid products. All the products are produced with the latest developed version of the Positioning And Navigation Data Analyst (PANDA) Software (Liu and Ge 2003; Shi et al. 2008).

In this report we give a summary of the IGS related activities at WHU during the year 2015.

2 PANDA software

PANDA software package is capable of simultaneously processing various types of measurements from GNSS, SLR, KBR, star trackers and accelerometers in order to estimate ground station coordinates, ZTDs, ERPs and orbits for GNSS satellites, LEOs and GEOs. Various methods for kinematic, dynamic and reduced–dynamic precise orbit determination of LEO satellite orbits are developed in this software package.

Both least–squares estimator (for post–processing) and square–root information filter (for real–time processing) are implemented in the state estimator module (Liu and Ge 2003) of PANDA. In order to speed up the data processing, an efficient approach of removal and recovery of station coordinate and ambiguity parameters is employed in the least–squares estimator (Shi et al. 2010). Besides, the ambiguity–fixing can also be performed in either network mode or precise point positioning mode, significantly improving the positioning accuracy of WHU final solutions.

3 WHU Analysis Products

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

Table 1: List of products provided by WHU

WHU rapid GNSS products	
whuWWWD.sp3	Orbits for GPS/GLONASS satellites
whuWWWD.clk	5–min clocks for stations and GPS/GLONASS satellites
whuWWWD.erp	ERPs
WHU ultra–rapid GNSS products	
whuWWWD_HH.sp3	Orbits for GPS/GLONASS satellites;provided to IGS every 6 hours
whuWWWD_HH.erp	observed and predicted ERPs provided to IGS every 6 hours

4 Ionosphere Activities

Ionosphere TEC is an important parameter for both satellite navigation and scientific studies of the ionosphere and space weather. TEC determines the first order ionosphere–induced range error, which is a dominant error source in GNSS navigation solutions. Measurement–based TEC estimation has gained much attention to meet the needs of practical applications. This is especially true since the proliferation of GNSS receivers has led to the establishment of various global and regional GNSS networks.

WHU are making efforts to boost the ability of processing GNSS data for generating global ionosphere maps over these years. Recently, WHU have implemented some algorithm for ionosphere modeling, such as spherical harmonics model, polynomial functions, Kriging interpolation and so on. Moreover, some algorithms are proposed to solve the problems in generating ionosphere maps. For instance, inequality–constrained least squares method was proposed to eliminate negative VTEC values in global ionosphere maps (Zhang et al. 2013). Meanwhile, the group of WHU use IRI model for providing VTEC values at where can't receive GNSS signals in ionosphere modeling to improve VTEC maps. Also, VTEC maps (from 2010 to 2014) are assessed through comparisons among our products and those of IAACs, as shown in Fig. 1. The VTEC maps in IONEX format can be downloaded on the IGS data center of WHU: ftp://igs.gnsswhu.cn/pub/whu/ionosphere.

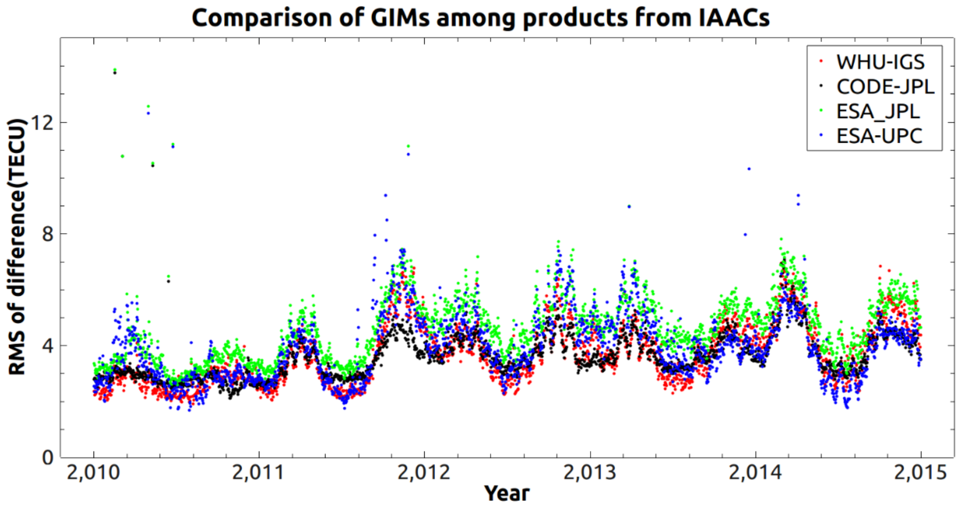

Figure 1: Comparison of GIMs from 2010 to 2014.

A software platform is built for data processing and analysis of ionosphere. This platform has kinds of function modules, including downloading global GNSS data, preprocessing and processing data, graphical visualization of TEC maps, releasing the ionosphere products, real–time delivering operating status of data processing as well as updating website. The website (`http://ionosphere.cn`) is established and maintained for the display of VTEC maps, DCB values and the other information. English version of the website will be updated soon.

Besides, the efficiency of global ionospheric modeling is improved by using multithreaded parallel computing with OpenMP. The time consumption of ionosphere modeling with different number of threads are presented in Fig. 2. It takes approximately 7 and 20 minutes to compute 1–day and 3–day solution, respectively. The efficiency of modeling is promoted nearly 8 times (which is approximately equal to the number of CPU cores). It's very helpful for algorithm testing of modeling, fast releasing of ionosphere products, post–time verification and prediction.

5 BeiDou Activities

According to recent publications, the BeiDou GEO satellites use the orbit–normal mode, whereas IGSO and MEO satellites employ yaw–steering and orbit–normal yaw attitude modes (Wang et al. 2013; Guo et al. 2013). As the exact attitude switch mechanism of IGSO and MEO satellites is not yet released, the reverse kinematic Precise Point Positioning (PPP) method was applied in this study. However, since the recent Precise Orbit Determination (POD) processing for GPS satellites could not provide suitable products

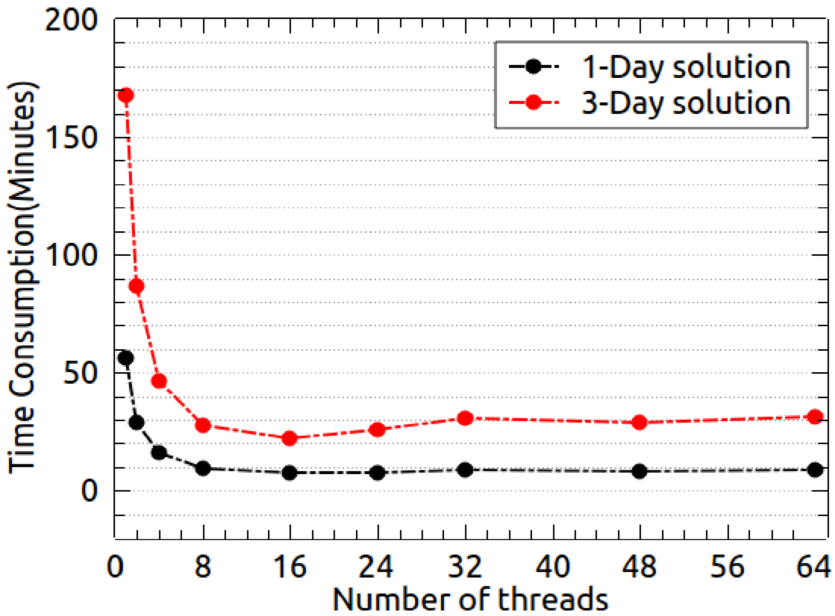

Figure 2: Time consumption of ionosphere modeling with different numbers of threads.

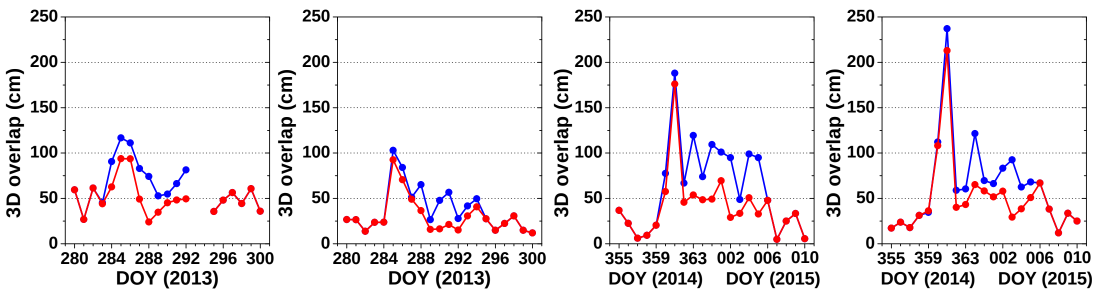

Figure 3: Daily RMS values of day–boundaries (3D) for IGSO (C09 and C06) and MEO (C11 and C12) satellites. The yaw–steering attitude mode solution is shown in blue, while the switch model–based solution in red. The shaded areas illustrate the duration of the orbit–normal regime.

for estimating BDS attitude using the reverse PPP because of the special attitude control switching between the nominal and the orbit–normal mode, a modified processing schema was proposed by WHU for studying the attitude behavior of the BDS satellites (Dai et al. 2015). In the modified processing, only data before the attitude switch is employed in the POD processing. This avoids the effect of the inaccurate attitude model on those parameters of the satellite orbit and ambiguities which are fixed in the phase center offset estimation later on. After this modification, yaw–angles of BeiDou satellites are estimated with the reverse PPP and a preliminary attitude switch model is established and validated. In general, the attitude–mode–switch occurs when the Sun elevation is about 4° and the actual orientation is very close to its target one (the threshold is empirically set to 5° based on lots of computation and analysis). In a special case that the Sun elevation is about 4° , while the yaw angle is empirically larger than 5 but smaller than 20° and the absolute value of yaw angle is increasing, the attitude–switch is executed too. Applying this preliminary attitude switch model to the BeiDou satellite orbit determination observables gives an improved performance compared with the yaw–steering model (Fig. 3)

Recently, WHU has been providing the BeiDou satellite attitude switch table and a FORTRAN function for the public to process BeiDou data. The table file and FORTRAN code are placed at the IGS data center of WHU: ftp://igs.gnsswhu.cn/pub/BDS. The files are described as follows:

(1) The table file bds_yaw lists the attitude mode employed by BeiDou IGSO and MEO satellites from DOY 001 2015, which is updated every day and predicted for two days.

(2) The FORTRAN code bds_yaw.f90 can read the table file bds_yaw to determine the BeiDou satellite attitude mode, and compute the attitude mode in real time when the table file is not available.

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EPN Regional Network Associate Analysis Center Technical Report 2015

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1 Introduction

The International Association of Geodesy (IAG) Regional Reference Frame sub–commission for Europe, EUREF, defines, provides access and maintains the European Terrestrial Reference System (ETRS89). This is done through the EUREF Permanent GNSS Network (EPN) which is a network of continuously operating GNSS reference stations maintained on a voluntary basis by EUREF members. 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 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 Experiment (MGEX). The EUREF Technical Working Group (TWG) defines the general policy of the EPN following proposals by the EPN Coordination Group. This Coordination Group consists of the Network Coordinator (managing the EPN Central Bureau (EPN CB)), Data Flow Coordinator, Analysis Coordinator, Reference Frame Coordinator, Troposphere Coordinator, and Chairs of the Real–time Analysis, Reprocessing, and multi–GNSS Working Groups. This report gives an overview of the main changes in the EPN during the year 2015.

2 Tracking Network and Network Coordination

At the end of 2015, the EPN network consisted of 278 continuously operating GNSS reference stations (Fig. 1) from which 32% also belong to the IGS. Individual calibrations were used at 16% of the EPN stations. Sixteen new stations were integrated in the EPN network in 2015 (see Tab. 1). They are indicated with stars in Fig. 1. The number of stations providing GPS+GLONASS data increased from 79% to 84% since last year and already 33% (91) of the EPN stations provide Galileo data.

Table 1: New stations included in the EPN in 2015

ID	Location	Real–Time	Tracked Satellite Systems	Antenna Calibration
BCLN	Sant VicencdelsHorts, ESP	Real–Time	GPS GLO GAL	Individual (GEO++)
BRMF§	Bron, FRA (replaces BRON)	Real–Time	GPS GLO GAL BDS SBAS	Type mean
CARG	Cartagena, ESP	Real–Time	GPS GLO GAL	Individual (GEO++)
DLF1*	Delft, NLD	Real–Time	GPS GLO GAL BDS QZSS SBAS	Individual (GEO++)
GOP6*	Ondrejov, CZE		GPS GLO GAL SBAS	Individual (GEO++)
GRAC*	Caussols, FRA	Real–Time	GPS GLO GAL BDS SBAS	Type mean
KNJA	Knjazevac, SRB		GPS	Type mean
MATG*	Matera, ITA	Real–Time	GPS GLO GAL SBAS	Type mean
NPAZ	Novi Pazar, SRB		GPS GLO	Type mean
OBE4*§	Oberpfaffenhofen, DEU (replaces OBE2)	Real–Time	GPS GLO GAL	Individual (BONN)
PASA	Pasaia, ESP	Real–Time	GPS GLO GAL BDS	Individual (GEO++)
RANT	Rantum / Island Sylt, DEU	Real–Time	GPS GLO SBAS	Individual (GEO++)
SABA	Sabac, SRB		GPS GLO	Type mean
SUN6	Sundsvall, SWE	Real–Time	GPS GLO	Individual (GEO++)
TARI	Tarifa, ESP	Real–Time	GPS GLO GAL	Individual (GEO++)
UCAG	Cagliari, ITA	Real–Time	GPS GLO GAL	Type mean

*: also an IGS station, §: replaced station

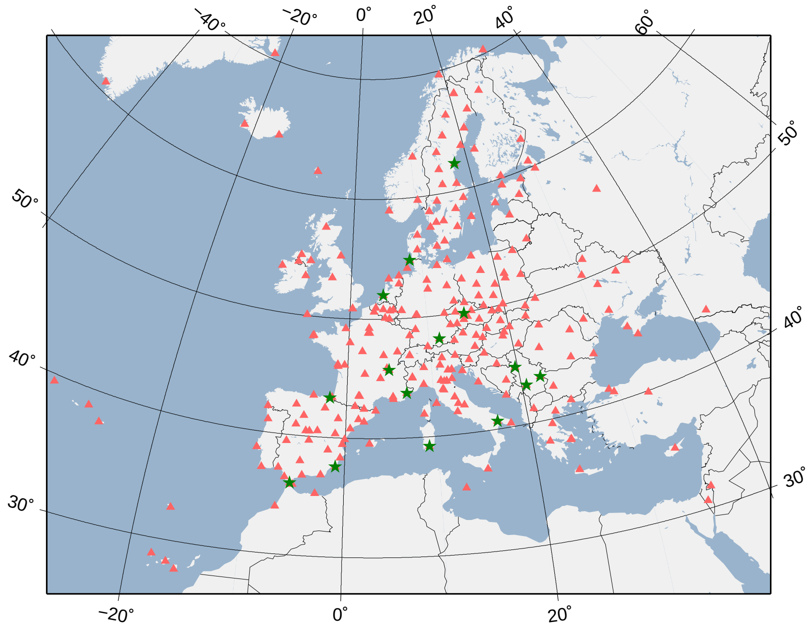

Figure 1: EPN tracking stations, status December 2015. (* indicates new stations included in the network in 2015.)

The EPN CB (http://epncb.oma.be) continued to perform daily data quality checks of the daily RINEX v2 data observations, checks of the meta–data of the daily RINEX (v2 and v3) data, 2–hourly checks of the meta–data and latency of the real–time EPN data streams; daily checks of the latency and availability of the hourly and daily RINEX data; daily updates of the residual position time series of the EPN stations, and regular updates of several EPN meta–data files such as station site logs files, antenna calibrations files, ocean loading parameters files, and site coordinates files in support of EPN data analysis. In 2015, the EPN CB was upgraded to perform additional monitoring tasks:

- Check the adherence of the EPN regional broadcasters to the newly released EPN broadcaster guidelines (see Section 6). This includes new verifications of the meta–data in the broadcasters' source–tables and cross–checking them with the observation streams and the site logs. A summary of the results is provided on the EPN ftp site (ftp://epncb.oma.be/pub/center/broadcasters/COMPARE_BRDC.txt).

- Verify the availability of the new RINEX 3 data in the EPN Data Centers, provide the information on the EPN CB web site, and inform station managers if data are missing.

- Verify the compliance between the satellite systems (e.g. GPS, GLONASS, and Galileo) included in the station observations files against the information in the site logs. After contacting station managers, the number of disagreements were reduced from 58 to 10.

EUREF also continued to actively stimulate station managers to provide multi–GNSS data to submit RINEX v3.02 (or later) data. This activity was supported by the release (Oct. 2015) of new "Guidelines for EPN stations and Operational Centers" (http://epncb.oma.be/_documentation/guidelines/guidelines_station_operationalcentre.pdf). At the same time, the EPN CB started evaluating if existing multi–GNSS RINEX (v2 and v3) data quality check software is able to detect known historical problems in EPN stations. Presently, the *ideal* match has not been found yet. Once it is found, the complete RINEX data quality web pages of the EPN CB will be *modernized*. The internal software and web pages of the EPN CB were already upgraded to switch to the new RINEX v3 standard 9–char station identification codes. Internal software and provided meta–data were also upgraded to allow the identification of the EPN antennas using their full serial number (instead of the last 5 digits) from May 2015 on. Finally, in support of the EPN densification Working Group (see Section 5), a complete new section of the EPN CB web site (http://epncb.oma.be/_densification) and associated software was created. Agencies from all over Europe were contacted to gather meta–data from their densification stations. Presently, more than 550 GNSS stations have already submitted meta–data.

3 RINEX v3

The EUREF Working Group on "Multi-GNSS" stimulates EUREF members to be actively involved in multi–GNSS activities, ranging from the introduction of the RINEX 3 format, the adaptation of the EPN data flow, the development of data quality checks to multi-GNSS data analysis. End of 2015, about 90 EPN stations are delivering RINEX v3 data (compared to 58 end of 2014). The majority of stations deliver data in format 3.02 (16 stations deliver data still in format 3.01). Additionally, about 15 stations in Europe contribute data to the IGS MGEX. The EPN Regional Data Centers (RDCs) at BKG and OLG follow the IGS strategy concerning acceptance of RINEX v3 observations. Station managers have been encouraged to submit RINEX v3 files additionally to RINEX v2 files. Both EPN RDCs are accepting RINEX v3 data with long as well as short files names. The files with the long names are stored in the "regular" download directories together with RINEX v2 files. RINEX v3 files with short names are kept separately until the IGS and EPN DC decide to rename to the long names and move them to the RINEX 2 directories. An important requirement for the routine utilization of the RINEX v3 observation files is the availability of quality check software. Working Group members are actively contributing to this effort by developing and using two software packages: G-Nut/Anubis [1.2.1] (Vaclavovic and Dousa 2015) and BNC [2.12] (Weber and Mervart 2009). Both allow RINEX header manipulation and the generation of data quality statistics. Several groups are running these programs and make the results available in form of plots available on their web pages, e.g. http://www.pecny.cz/GOP/index.php/gnss/data-center/euref-rnx3, http://www.swisstopo.admin.ch/swisstopo/geodesy/pnac/html/en/anubis_monitor_r3.html. At the 9th Workshop of the EUREF Analysis Centers (ACs), held in October 2015 in Bern, several presentations underlined the increasing complexity when analyzing multi-GNSS data. A technical introduction was given to the ACs on how to process multi–GNSS data using BSW 5.2 (Dach et al. 2015).

4 Data Analysis

4.1 Positions

In 2015 the number of ACs submitting routine solutions did not change: 16 (from 18 existing) ACs deliver SINEX solutions contributing to the weekly EPN combination. The GOP AC focuses on the EPN reprocessing activities. The DEO AC does not submit its solutions anymore since 2009, but is planning to restart routine analysis in 2016. Fourteen ACs analyze both GPS and GLONASS data with *Bernese GNSS Software 5.2* (Dach et al. 2015), the two remaining ACs use *Bernese GNSS Software 5.0* and *GIPSY–OASIS 6.2 software*. The routine solutions are combined by the Analysis Combination Center (ACC) run by a consortium of the Military University of Technology and the Warsaw University of Technology. All combinations are performed with Bernese 5.2. The weekly and daily final positions are delivered on the basis of 16 ACs solutions, while the rapid daily and ultra–rapid solutions use input from respectively ten and three ACs. Other ACs are encouraged to submit rapid and ultra–rapid solutions to strengthen the reliability of these products. Only stations processed by at least three ACs are used in the final daily and weekly solutions, which enables the detection of outliers and increases the reliability of the solutions. Exceptions are made for a few new stations: in the beginning of their lifetime it is accepted that they are processed by less than three ACs. Prior to the combination process, the SINEX files provided by the different ACs are automatically checked against possible metadata inconsistencies (e.g. antenna types and calibration models, receiver types) and problematic stations are excluded from the combination. The short reports from the final combinations are distributed using EUREF and LAC mail system (see http://epncb.oma.be/_newseventslinks/mails.php), while the full version of these reports is available at ftp://epncb.oma.be/pub/product/combin/WWWW. The EPN ACC webpage (http://www.epnacc.wat.edu.pl) shows results of the final, rapid and ultra–rapid combinations. For the final combination, it shows for all EPN stations the agreement between the AC solutions in the horizontal and vertical components, the Helmert transformation parameters (Fig. 2) of all input solutions wrt the combined solution, and time series of all station input residuals w.r.t. to the positions resulted from the combination.

The long–term combination, performed every 15 weeks, is compared to the national realizations of ETRF in the countries. The difference plots, available under http://epncb.

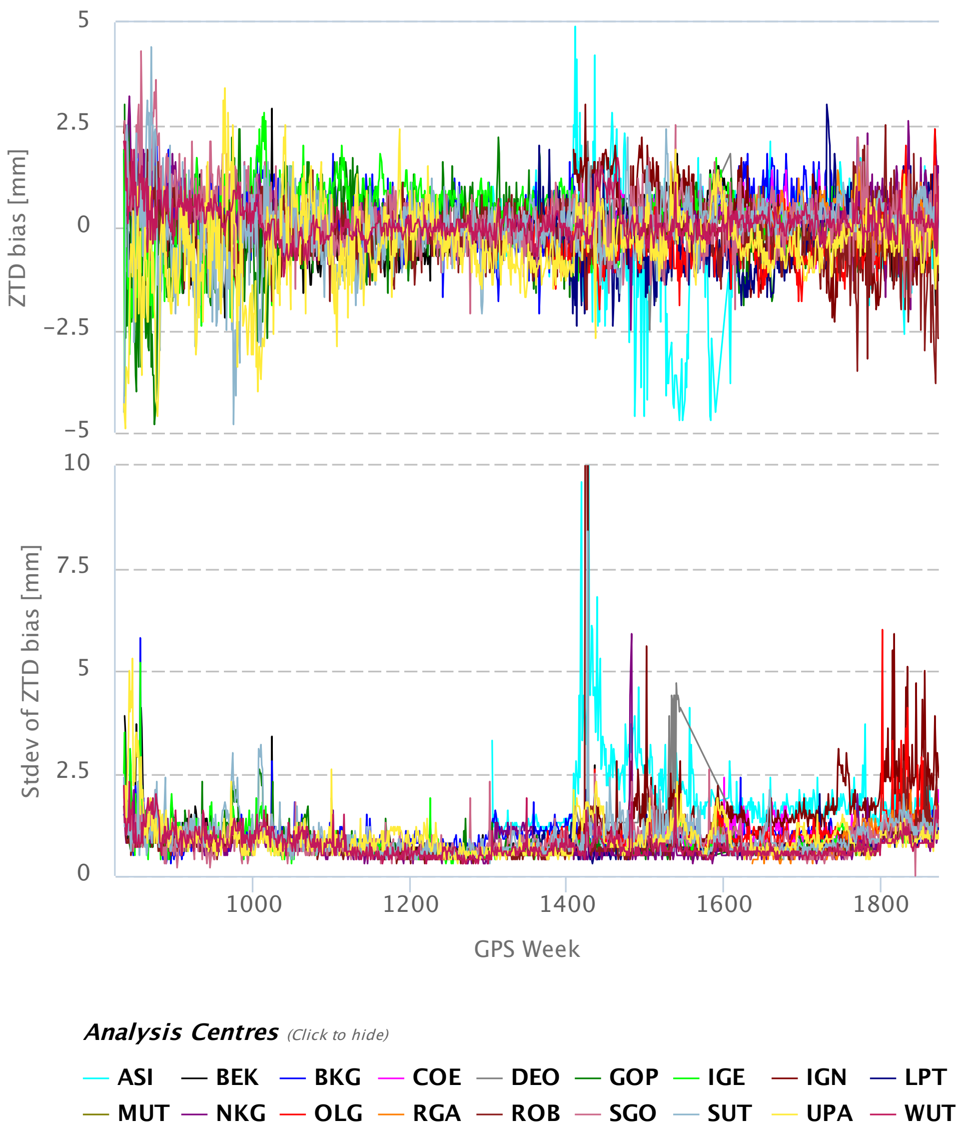

Figure 2: Agreement (RMS of Helmert transformation) between each weekly LACs solution and the weekly EPN combined solution.

oma.be/_productsservices/coordinates/img/ETRF_EPN_HOR.JPG and http://epncb.oma.be/_productsservices/coordinates/img/ETRF_EPN_UP.JPG show nicely the homogeneous implementation of the various ETRF realizations in Europe.

4.2 Troposphere

Beside station coordinates, the 16 ACs also submit ZTD parameters on a routine basis in SINEX–Tro format. Thirteen ACs are also submitting horizontal gradients. The ZTDs and horizontal gradients are delivered with a sampling rate of 1 hour, on a weekly basis but in daily files. As regard as the troposphere mapping function, five of the 16 ACs use the Vienna Mapping Function, ten the Global Mapping Function and one the Niell Mapping Function. The tropospheric combination is based on a generalized least square method, following Pacione et al. 2011. A report of the weekly combination is distributed using the EUREF LAC mail system. Thanks to the growing computation power, the individual ACs enlarged their networks in 2015. Even though all EPN stations are processed by at least three ACs (with exception described above), thus improving the outlier detection, in 2015 ZTD estimates are provided by more than three ACs for about 260 stations, by two ACs for about 11 stations and by one ACs for about 6 stations. The weekly mean bias (Fig. 3–top) and the related standard deviation (Fig. 3–bottom) (available at http://www.epncb.oma.be/_productsservices/sitezenithpathdelays) give insight into the agreement of the individual solutions with respect to the combined solution. The time series in Fig. 3 are based on EPN Repro1 solutions from GPS week 0834 to 1407 and on operational solutions afterwards. The jump in the standard deviation time series (Fig. 3) occurred at GPS week 1800 is related to the use of a different combination software starting from that GPS week, when the combination moved from BKG to ASI/CGS.

Alongside the ZTD combination, inter–technique comparisons have been added to the web site of the EPN CB. The time series of EPN ZTD differences with respect to radiosonde–derived ZTDs are computed for more than 180 stations. For the stations considered, the horizontal distance between radiosonde and GNSS location is varying from less than 1 km up to 75 km. The standard deviation of the differences is between 4 and 20 millimeters ZTD, with worse agreement if the distance is long. Moreover, for each EPN site plots showing monthly mean of ZTD values from 1996 to present are available.

4.3 Reprocessing

The Working Group "EPN Reprocessing" continued its effort in providing a new solution for the entire EPN based on reprocessed orbits (IGb08), clock products and ERP. The reprocessing activity covered all available data of the EPN spanning the years 1996 until 2013. The analysis was carried out either with the software *BERNESE 5.2*, *GAMIT 10.5* or *GIPSY 6.2*. First daily solutions have already been provided in spring 2015 by the five different ACs involved in this activity, either analyzing the complete network (three ACs)

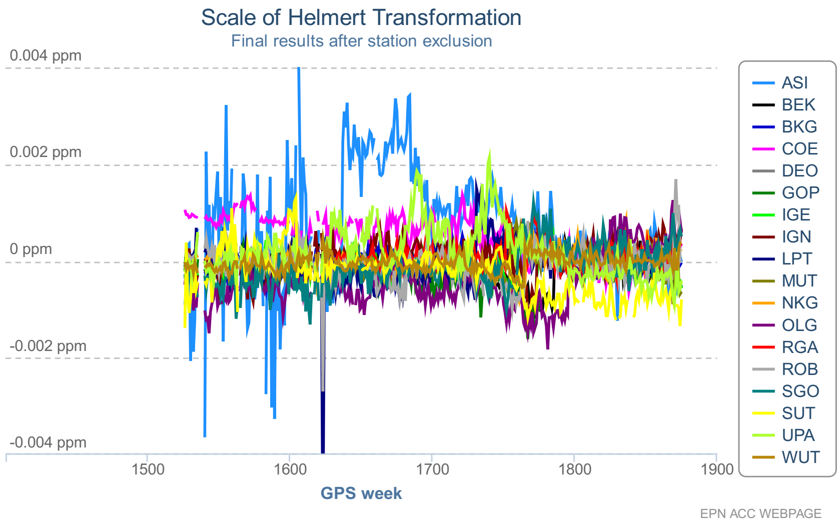

Figure 3: Top: Weekly mean biases of ACs individual ZTD contributions w.r.t. the combined ZTD solution (mm ZTD). Bottom: Standard deviation of weekly mean biases of ACs individual ZTD contributions w.r.t. the combined ZTD solution (mm ZTD).

or subnetworks (two ACs). Some ACs provided even different solutions that were based on different strategies. These different solutions were tested by the ACC and feedback was given to the working group. In order to homogenize the different solutions, it was necessary for some ACs to reprocess the solution again securing to a large extend that the same standards and conventions have been used in the solutions. In contrast to the IGS network, the EPN uses not only type mean but also individual antenna calibration models. Finally, in the end of 2015, the computations of the daily solutions have been finished. The next step requires now the combination of the five different solutions and this process will be conducted by the ACC at the Military University of Warsaw. Combined products of the five networks are expected in February 2016, while the multi–year–solution will hopefully be ready by the next EUREF symposium in June 2016. In parallel a first tropospheric combined solution for the period 1996–2013 has been carried out. This combined solution is based on all the available homogenously reprocessed contributions delivered by the five ACs. It offers the possibility to assess each contribution and in order to provide a GNSS climate data record with the high potential for climate monitoring over Europe.

5 Densification of the IGS and EPN

Based on the EPN combined weekly SINEX solutions (back to mid–1996), a multi–year EPN position and velocity solution is maintained as the densification of the IGS realization of the ITRS in Europe. This solution is computed with the CATREF software

Altamimi et al. 2007 and updated each 15 weeks, in accordance with the long–term combination (Section 4.1). Up to GPS week 1709, the multi–year solution was tied to IGS08, since that date the IGb08 was used. This reference frame alignment is based on the minimum constraint approach and the consistency of the frame realization is checked. When ITRF2014 and the EPN–Repro2 products will become available, the multi–year EPN solution will be updated to be compliant with the latest standards. The EPN multi–year product files (including a discontinuity table and associated residual position time series) are available at ftp://epncb.oma.be/pub/station/coord/EPN/. More details can be found in http://epncb.oma.be/_productsservices/coordinates. The densification of the EPN aims at providing a dense continental–scale homogeneous station position and velocity field to support the better realization of the ETRS89 over the non–stable regions of Europe (e.g. the Mediterranean). This activity is done in close co–operation with the geophysical community which will provide input for the tectonic interpretation and modelling. The densification activity is done in the frame of a Working Group lead by the EPN Reference Frame Coordinator. In that frame, EUREF combines the weekly SINEX solutions provided by European countries for their dense national active GNSS networks with the weekly EPN SINEX solution. Then, all available weekly combined solutions are stacked to obtain a consistent cumulative position/velocity solution. Both combinations (the weekly and the multi–year) are done using the *CATREF software* using exactly the same approach and parameters as for the generation of the EPN IGb08 densification ensuring full consistency from the global to local level. The total number of stations included in the EPN densification exceeded 2900 as of December 2015. Two contributions (IGN, France and BIGF, UK) are global solutions and therefore the EPN densification shall be considered as a global solution. Beyond the active networks a long term (1996–2015) Repro–2 campaign product of CEGRN (Central European GPS Geodynamic Network) has also been integrated. We devoted significant efforts to collect, harmonize and maintain station meta–data based on log files. Relying on the experiences, tools and web services we developed for EPN, dedicated web pages had been installed to handle EPN densification meta–data and products (http://www.epncb.oma.be/_densification). The densification products will be an essential contribution to several groups and projects as the European Plate Observing System (EPOS) and the European Positioning System (EUPOS). This work is still in progress (see Kenyeres et al. 2015).

6 Stream and Product Dissemination

As announced in last year's report, guidelines for the EPN broadcasters were prepared and released in 2015. For this, the guidelines for EPN Data Centers were extended (see http://epncb.oma.be/_documentation/guidelines/guidelines_data_centres.pdf). A new section 4 explains in detail the role and content of the broadcaster sourcetable with the three record types CAS, NET and STR. In particular, the mountpoint data fields should be as consistent as possible between the regional as well as the local broadcasters.

The process of homogenization of the three EUREF regional broadcasters (RBs) located at ASI (http://euref-ip.asi.it:2101/), BKG (http://www.euref-ip.net) and ROB (http://www.euref-ip.be/) continued in 2015. Besides the real–time monitoring of the status of each mountpoint at the three RBs (green–red differentiation), another tool, developed by the EPN CB, is testing the currently available observation types used in the streams against the –static– sourcetable entries. This way, the providers can see, e.g., if any of the message types have been lost or if update rates have been changed. Moreover, meta–data included in the sourcetables is checked against the most recent site logs. Finally, a script checking antenna height and antenna type contained in the data stream against the entries in the most recent skeleton file is running in a test mode at BKG.

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SIRGAS Regional Network Associate Analysis Center Technical Report 2015

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1 Introduction

The SIRGAS Reference Frame is currently composed of 396 continuously operating GNSS stations (Fig. 1). It comprises two hierarchy levels (Brunini et al. 2012): a core network (SIRGAS–C) providing the primary link to the global ITRF; and national reference networks (SIRGAS–N) improving the geographical density of the reference stations to ensure the accessibility to the reference frame at national and local levels. The SIRGAS reference stations are processed by 10 SIRGAS Processing Centers (Mackern and Brunini 2015):

- Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (Germany), Sánchez et al. 2015a
- CEPGE: Centro de Procesamiento de Datos GNSS del Ecuador, Instituto Geográfico Militar (Ecuador)
- CNPDG–UNA: Centro Nacional de Procesamiento de Datos GNSS, Universidad Nacional (Costa Rica), Moya et al. 2015
- CPAGS–LUZ: Centro de Procesamiento y Análisis GNSS SIRGAS de la Universidad del Zulia (Venezuela), Cioce et al. 2015
- IBGE: Instituto Brasileiro de Geografia e Estatistica (Brazil), Da Silva et al. 2015
- IGAC: Instituto Geográfico Agustín Codazzi (Colombia)
- IGM–Cl: Instituto Geográfico Militar (Chile), Parra 2015

- IGN–Ar: Instituto Geográfico Nacional (Argentina)
- INEGI: Instituto Nacional de Estadística y Geografía (Mexico)
- SGM: Servicio Geográfico Militar (Uruguay)

The SIRGAS processing centers follow unified standards for the computation of loosely constrained weekly solutions for the station positions. These standards are generally based on the conventions outlined by the IERS and the GNSS–specific guidelines defined by the IGS; with the exception that in the individual SIRGAS solutions the satellite orbits and clocks as well as the Earth orientation parameters (EOP) are fixed to the final weekly IGS values (SIRGAS does not estimate these parameters), and positions for all stations are constrained to ± 1 m (to generate the loosely constrained solutions in the SINEX format). INEGI (Mexico) and IGN–Ar (Argentina) employ the software GAMIT/GLOBK (Herring et al. 2010); the other local processing centers use the Bernese GPS Software V. 5.2 (Dach et al. 2015). The processing standards applied at present are described in Sánchez et al. 2015a. The individual solutions are combined by the SIRGAS Combination Centers operated by DGFI–TUM (Sánchez 2015a) and IBGE (Mantovani et al. 2015). In charge of the IGS Regional Network Associate Analysis Center for SIRGAS (IGS RNAAC SIRGAS), DGFI–TUM processed the entire SIRGAS reference network from June 1996 until August 2008 (Brunini et al. 2012, Sánchez et al. 2012). Now, it is responsible for

- processing the SIRGAS–C core network, Sánchez et al. 2015a;
- combining the core network with the national reference networks (Fig. 2), Sánchez 2015a;
- ensuring that the SIRGAS processing strategy meets the IERS standards and IGS guidelines (Fig. 3), Sánchez 2015b;
- developing strategies to guarantee the reliability of the reference frame over time, this includes
- estimation of the reference frame kinematics (Fig. 4), Sánchez 2015c;
- evaluation of the seismic impacts on the reference frame (Fig. 5), Sánchez et al. 2015b;
- modelling crustal deformation in the SIRGAS region (Fig. 6), Drewes and Sánchez 2015, Sánchez and Drewes 2015;
- making available the SIRGAS products via www.sirgas.org and ftp.sirgas.org.

At present, the SIRGAS efforts are concentrated on the second reprocessing of the reference network backwards until January 1997.

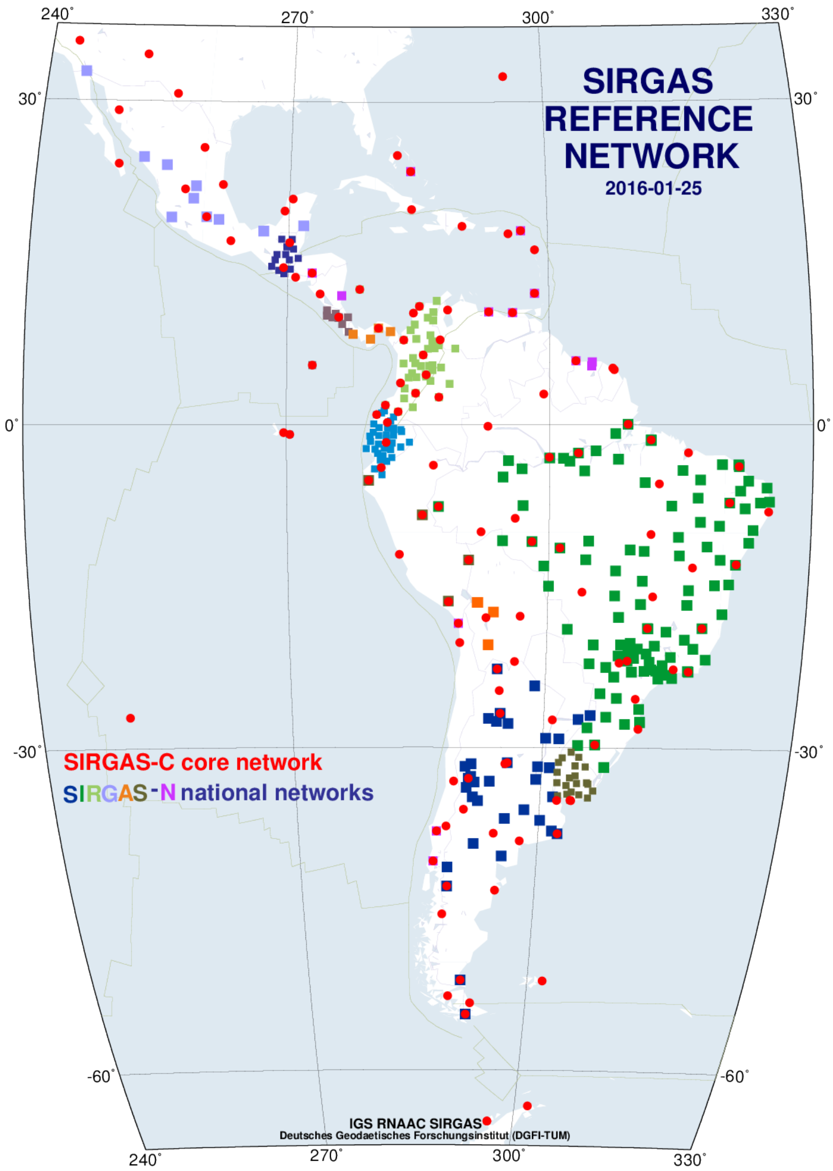
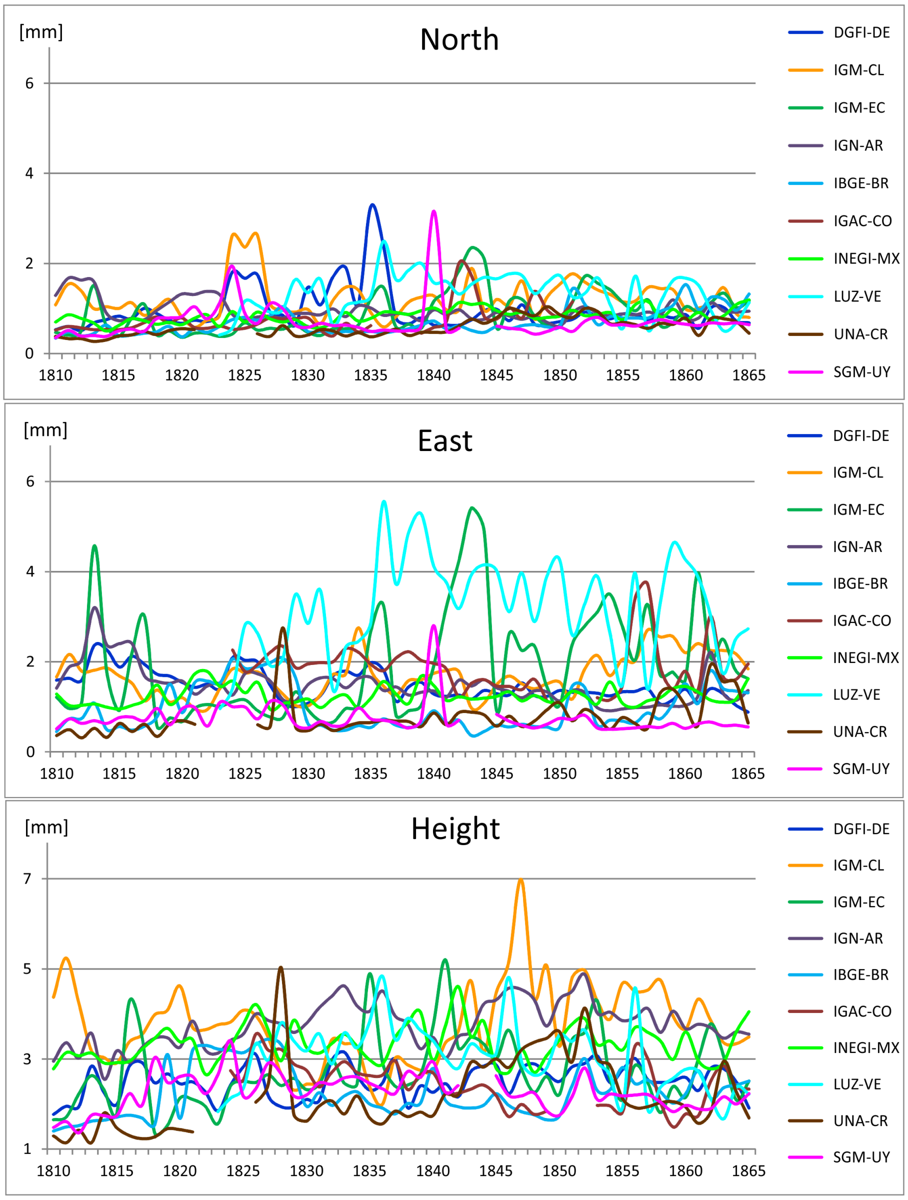
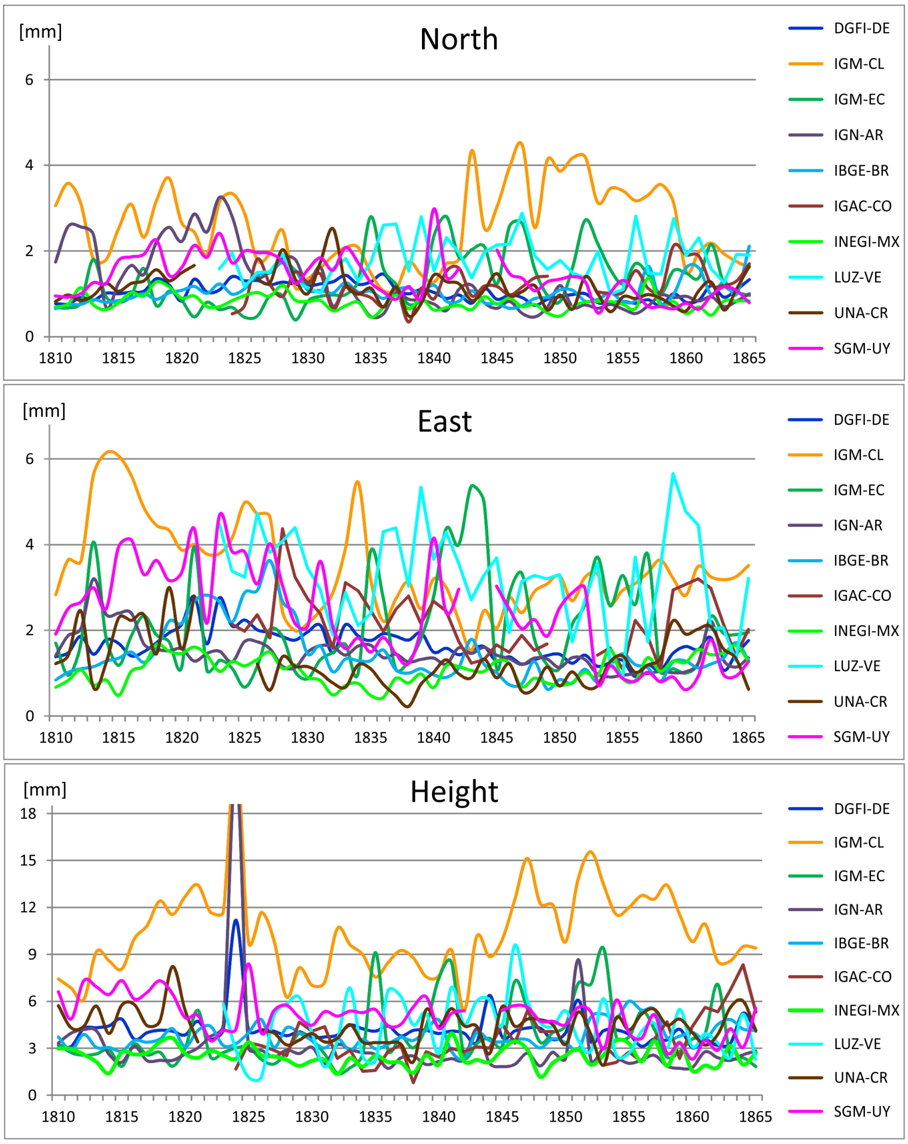


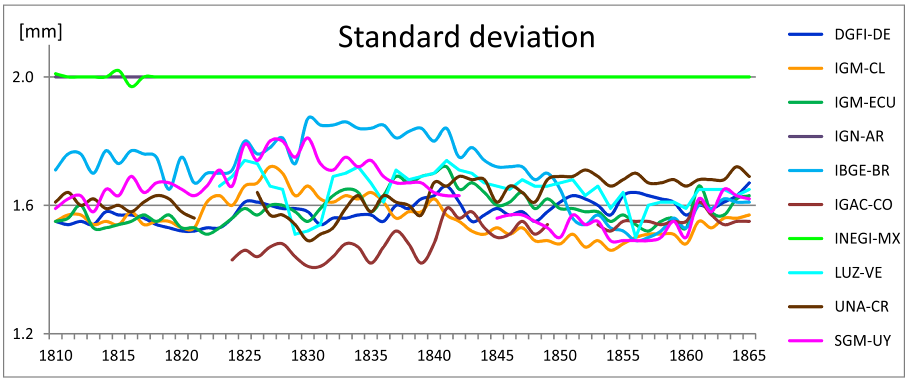
Figure 1: Core and national networks within the SIRGAS Reference Frame.



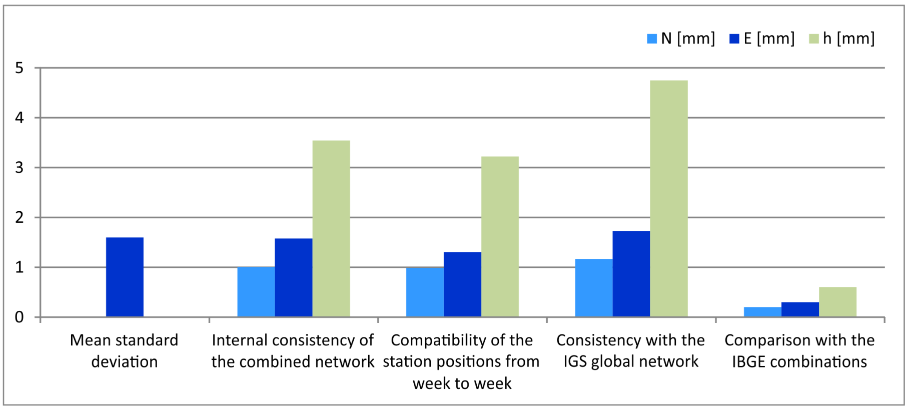
(a) Time series of the RMS of the station position residuals for each analysis center with respect to the SIRGAS weekly combined solutions. Outliers in the LUZ–VE series for the East component have to be further studied.



(b) Time series of the RMS of the station position residuals for each analysis center with respect to the IGS weekly final solutions. This comparison allows to assess the accuracy of the individual solutions: about ±2 mm in North and East, and ±5 mm in the vertical component. Outliers in the IGM–CL and LUZ–VE series have to be further studied.



(c) Standard deviation of station positions after solving the individual solutions with respect to the IGS reference frame. These values represent the formal errors of the individual solutions. Analysis Centers applying the Bernese GNSS Software achieve values of about ±1.6 mm, while Analysis Centers using GAMIT/GLOBK have values of ±2.0 mm.



(d) Quality evaluation of combined SIRGAS solutions: The coordinate repeatability of the weekly combinations provides an estimate for the accuracy (internal consistency) of the weekly combinations of about ±1.2 mm in the horizontal component and about ±3.5 mm in the vertical one. The RMS values derived from the time series for station positions and with respect to the IGS weekly coordinates indicate that the reliability of the network (external precision) is about ±1.5 mm in the horizontal position and ±4.0 mm in the height. The differences with respect to the IBGE weekly combinations are at the expected level (less than 0.5 mm).

Figure 2: Quality control of the individual solutions delivered by the SIRGAS Analysis Centers as well as of the combined solutions computed by the IGS RNAAC SIRGAS (GPS weeks 1810 – 1865)

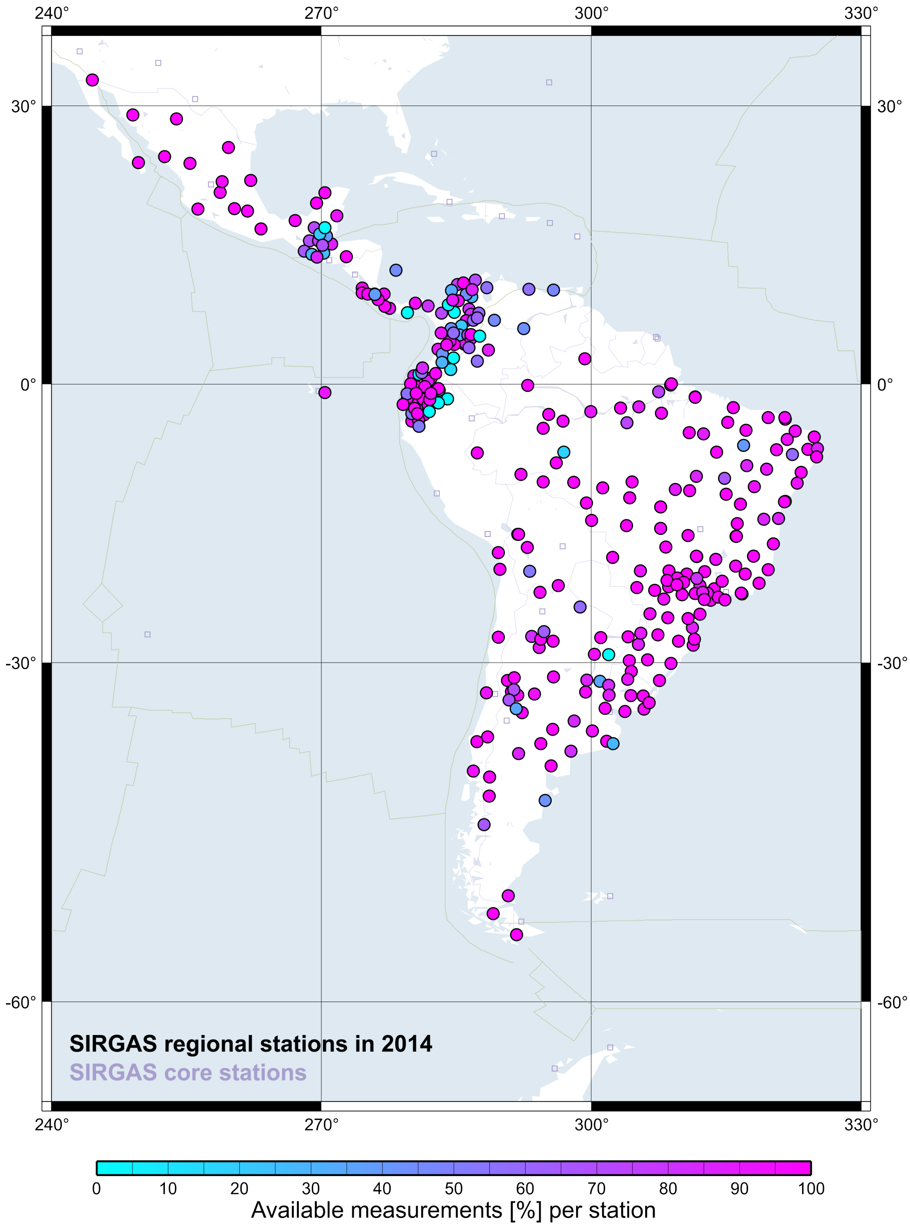


Figure 3: Inventory for the second SIRGAS reprocessing. It is necessary to compute all daily and weekly normal equations of the reference frame applying the new IERS and IGS guidelines. This inventory was performed from 1997 until 2014; as an example, the RINEX availability for the year 2014 is shown.

Figure 4: Multi-year solution SIR15P01. It covers the time span from 2010.2 to 2015.2, includes 303 stations and refers to the IGb08, epoch 2013.0. Its accuracy is estimated to be ± 1.8 mm in the horizontal position, ± 3.5 mm in the vertical position, ± 1.0 mm/a in the horizontal velocities and ± 1.2 mm/a in the vertical velocities.

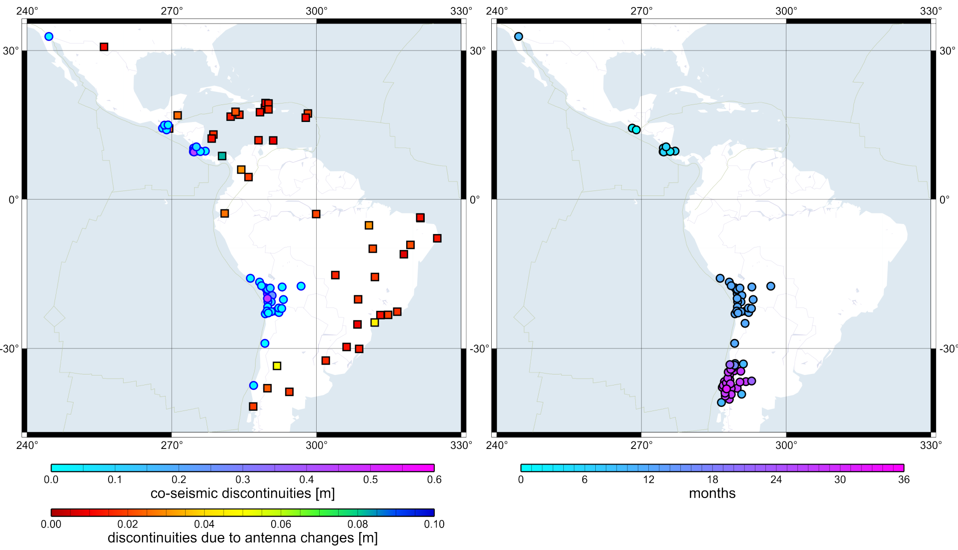


Figure 5: Station discontinuities (left) and post–seismic relaxation movements (right) identified in the SIRGAS region from March 2010 to April 2015.

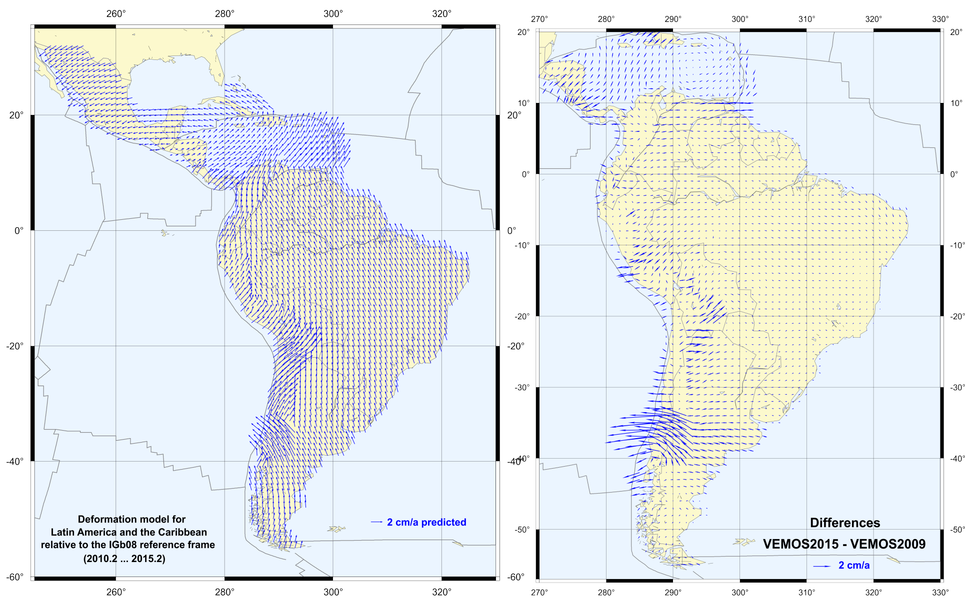


Figure 6: Post–seismic deformation model VEMOS2015 and comparison with the pre–seismic model VEMOS2009.

2 Acknowledgements

The operational infrastructure and results described in this report are only possible thanks to the active participation of many Latin American and Caribbean colleagues, who not only make the measurements of the stations available, but also operate SIRGAS Analysis Centers processing the observational data on a routine basis. This support and that provided by the International Association of Geodesy (IAG) and the Pan–American Institute for Geography and History (PAIGH) is highly appreciated. More details about the activities and new challenges of SIRGAS, as well as institutions and colleagues working on can be found at www.sirgas.org.

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Part III

Data Centers

Infrastructure Committee Technical Report 2015

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1 Summary of Activities in 2015

The Infrastructure Committee consists of the members listed in Tab. 1. The Infrastructure Committee worked on the implementation of the RINEX 3 transition plan drafts and revised it as needed after more revisions:

- Collaborated with the Network Coordinator (NC) to create all the IGS station long names and adapt the SLM.
- Collaborated with the Data Centers (DC) to accept long name RINEX 3 files into the regular data file repository and to rename files.

The Infrastructure Committee also helped to bring into the IGS network two new stations in Hong Kong (HKSL, HKWS) and helped the NC to introduce new stations from Taiwan, Macau and Malaysia. We collaborated with the Data Centers on the XML Metadata exchange project.

Table 1: Current Members: re–appointed in December 2013 for terms up to December 2015

Name	Affiliation
Carine Bruyninx	ROB
Lou Estey	UNAVCO
Gary Johnston	GA
Nacho Romero (Chairman)	ESOC
Mike Schmidt	NRCan
Axel Ruelke	BKG

Table 2: Ex–officio Members

Name	Affiliation
Steve Fisher	Central Bureau
Kevin Choi	Analysis Coordinator
Mark Caissy	Real time Working Group Chair
Bruno Garayt	Reference Frame Coordinator
Carey Noll	Data Center Working Group Chair
Michael Coleman	Clock Products Coordinator

2 Activity plan in 2016

- Continue supporting the implementation of the RINEX 3 transition plan
- Continue supporting the DC WG on the XML Metadata exchange project
- Participate in the IGS Workshop
- To support the Network Coordinator by having telecons between the IC Chair and the NC, so as to coordinate the inclusion of all used stations into the IGS network to return to "one network" and to more effectively monitor the Data Center file holdings.

CDDIS Global Data Center Technical Report 2015

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1 Introduction

The Crustal Dynamics Data Information System (CDDIS) is NASA's data archive and information service supporting the international space geodesy community. For over 35 years, the CDDIS has provided continuous, long term, public access to the data (mainly GNSS[1], SLR[2], VLBI[3], and DORIS[4]) and products derived from these data required for a variety of science observations, including the determination of a global terrestrial reference frame and geodetic studies in plate tectonics, earthquake displacements, volcano monitoring, Earth orientation, and atmospheric angular momentum, among others. The specialized nature of the CDDIS lends itself well to enhancement to accommodate diverse data sets and user requirements. The CDDIS is one of NASA's Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs); EOSDIS data centers serve a diverse user community and are tasked to provide facilities to search and access science data and products. The CDDIS is also a regular member of the International Council for Science (ICSU) World Data System (WDS).

The CDDIS serves as one of the primary data centers and core components for the geometric services established under the International Association of Geodesy (IAG), an organization that promotes scientific cooperation and research in geodesy on a global scale. The system has supported the International GNSS Service (IGS) as a global data center since 1992. The CDDIS activities within the IGS during 2015 are summarized in this report; this report also includes any recent changes or enhancements made to the CDDIS.

[1] Global Navigation Satellite System
[2] Satellite Laser Ranging
[3] Very Long Baseline Interferometry
[4] Doppler Orbitography and Radiopositioning Integrated by Satellite

2 System Description

The CDDIS archive of IGS data and products are accessible worldwide through anonymous ftp (ftp:/cddis.gsfc.nasa.gov). The CDDIS has also implemented web–based access to the archive (http:/cddis.gsfc.nasa.gov/archive). The CDDIS is located at NASA's Goddard Space Flight Center (GSFC) and is available to users 24 hours per day, seven days per week.

The CDDIS computer system is fully redundant with primary and secondary/failover systems. Each system utilizes a distributed functionality (incoming, outgoing, processing, database, and map servers) and is configured with a local backup system as well as a full backup system located in a third building at GSFC. The archive is equipped with a multi–Tbyte RAID storage system and is scaled to accommodate future growth. All ftp and web access is performed on the outgoing servers. Data centers, stations, and analysis centers push files to the CDDIS incoming servers. Processing of incoming files for the on–line archive is performed in a separate environment that also includes database servers for managing metadata extracted from incoming data.

3 Archive Content

As a global data center for the IGS, the CDDIS is responsible for archiving and providing access to GNSS data from the global IGS network as well as the products derived from the analyses of these data in support of both operational and working group/pilot project activities. The CDDIS archive is approximately 15.1 Tbytes in size of which 14.5 Tbytes (95%) is devoted to GNSS data (13.5 Tbytes), products (1 Tbytes), and ancillary information. All data and products are accessible through subdirectories of ftp:/cddis.gsfc.nasa.gov/gnss.

3.1 GNSS Tracking Data

3.1.1 Operational Data Archive

The user community has access to GNSS data available through the on–line global data center archives of the IGS. Over 70 operational and regional IGS data centers and station operators make data (observation, navigation, and meteorological) available in RINEX format to the CDDIS from selected receivers on a daily, hourly, and sub–hourly basis. The CDDIS also accesses the archives of the other three IGS global data centers, Scripps Institution of Oceanography (SIO) in California, the Institut Géographique National (IGN) in France, and the Korea Astronomy and Space Science Institute (KASI) to retrieve (or receive) data holdings not routinely transmitted to the CDDIS by an operational or regional

Table 1: GNSS Data Type Summary

Data Type	Sample Rate	Data Format	Available On–line
Daily GNSS	30 sec.	RINEX and compact RINEX	Since 1992
Hourly GNSS	30 sec.	Compact RINEX	10+ years
High–rate GNSS	1 sec.	Compact RINEX	Since May 2001
Satellite GPS	10 sec.	Compact RINEX	Since 2002

Table 2: GNSS Data Archive Summary for 2015

Data Type **GNSS**	Average # Sites/Day	# Unique Sites	Average Vol./Day	Total Vol./Year	# Files	Directory Location
Daily	485	566	1,300 Mb	400 Gb	735K	`/gnss/data/daily`
Hourly	325	384	485 Mb	140 Gb	6,705K	`/gnss/data/hourly`
High–rate	185	224	3,100 Mb	765 Gb	9,750K	`/gnss/data/highrate`

#: Number

data center. Tab. 1 summarizes the types of IGS operational GNSS data sets archived at the CDDIS.

Data, in RINEX V2.10 or V2.11 format, from GPS and GPS+GLONASS receivers are archived within the main GNSS directory structure `/gnss/data`.

The CDDIS archives four major types/formats of GNSS data, all in RINEX format, as described in Tab. 1. Daily RINEX data are quality–checked, summarized, 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. Over 177K daily station days from 566 distinct GNSS receivers were archived at the CDDIS during 2015. A complete list of daily, hourly, and high–rate sites archived in the CDDIS can be found in the yearly summary reports at URL `ftp:/cddis.gsfc.nasa.gov/reports/gnss`.

Within minutes of receipt, 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. A total of 384 unique hourly sites (over 6.7 million files) were archived during 2015.

High–rate (typically 1–second sampling) GNSS data are archived in files containing fifteen minutes of data and in subdirectories by year, day, file type, and hour. Many of these data files are created from real–time streams. Data from 224 unique high–rate sites (nearly 10 million files) were also archived in the CDDIS in 2015.

The CDDIS generates global broadcast ephemeris files (for both GPS and GLONASS) on an hourly basis. These files are derived from the site–specific ephemeris data files for each day/hour. These files 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 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 broadcast files are then copied to the corresponding subdirectory under the daily file system. Users can thus download this single, daily (or hourly) file to obtain the unique navigation messages rather than downloading multiple broadcast ephemeris files from the individual stations.

The CDDIS generates and updates "status" files, (`/gnss/data/daily/YYYY/DDD/YYDD.status`) that summarize the holdings of daily GNSS data. These files include a list of stations. The archive 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. The user community can thus view a snapshot of data availability and quality by checking the contents of such a summary file.

3.1.2 RINEX V3 (MGEX) Archive

During 2015 the CDDIS continued the archiving of data in RINEX V3 format from multi–GNSS receivers participating in the Multi–GNSS Experiment (MGEX) as well as products derived from the analysis of these data. The data include all available multi–GNSS signals (e.g., Galileo, QZS, SBAS, and BeiDou) in addition to GPS and GLONASS. The data are currently archived in a campaign directory structure at CDDIS (`/gnss/campaign/mgex/data`). The summary of the MGEX data holdings at the CDDIS is shown in Tab. 3. Daily status files are also provided that summarize the MGEX data holdings; however, data quality information, generated for operational GNSS data holdings, is not available through the software used by CDDIS to summarize data in RINEX V3 format. CDDIS continues to investigate and evaluate software capable of providing data summary/QC information for RINEX V3 data. Products derived in support of MGEX by three to six ACs are also available through the CDDIS (`/gnss/products/mgex/WWWW`).

Table 3: GNSS MGEX Data Archive Summary for 2015

Data Type **GNSS**	Average # Sites/Day	# Unique Sites	Average Vol./Day	Total Vol./Year	# Files	Directory Location
Daily	110	137	35.1K	710 Mb		`/gnss/data/campaign/mgex/daily`
Hourly	50	58	17.1K	190 Mb		`/gnss/campaign/mgex /data/hourly`
High–rate	45	52	13.6K	2,300 Mb	740 Gb	`/gnss/campaign/mgex /data/highrate`

#: Number

The CDDIS also added a merged, multi–GNSS broadcast ephemeris file containing GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS ephemerides from MGEX stations. This file, generate by colleagues at the Technical University in Munich (TUM) and Deutsches Zentrum für Luft– und Raumfahrt (DLR), is similar to the daily and hourly concatenated broadcast message files in RINEX V2 format provided by the CDDIS for the operational GPS+GLONASS data sets; it contains all the unique broadcast navigation messages for the day. The file is named `brdmDDD0.YYp.Z` and found in daily subdirectories within the MGEX campaign archive at CDDIS (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/DDD/YYp`) and in a yearly top level subdirectory (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/brdm`).

In order to promote usage of RINEX V3 and allow users (and data centers) to become familiar with the format and file naming conventions, several data providers are now delivering data from MGEX stations using both RINEX V2 and V3 filename formats. The CDDIS established a daily subdirectory for the files containing observation or navigation data files using the RINEX V3 filename format within the daily MGEX directory structure (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/DDD/crx`).

Colleagues at TUM and DLR are also providing GPS and QZSS CNAV (civilian navigation) data on an operational basis within MGEX. These messages are collected from a sub–network (ten stations) of MGEX stations and are provided in a merged daily file in a format similar to RINEX. These files are named `brdxDDD0.YYx.Z` and stored in a daily subdirectory within the MGEX archive at CDDIS (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/cnav`).

Colleagues at DLR and the Chinese Academy of Sciences (CAS) provide differential code biases (DCBs) products for the MGEX campaign. This product was derived from GPS, GLONASS, Galileo, and BeiDou ionosphere–corrected pseudorange differences and is available in the bias SINEX format. DLR has provided two files per year, daily satellite and daily satellite and station biases, for the 2013–2016 time period in CDDIS directory `/gnss/products/mgex/dcb`; CAS provides daily files. 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 new RINEX V3 file naming convention.

3.2 IGS Products

The CDDIS routinely archives IGS operational products (daily, rapid, and ultra–rapid orbits and clocks, ERP, and station positions) as well as products generated by IGS working groups and pilot projects (ionosphere, troposphere, real–time). Tab. 4 summarizes the GNSS products available through the CDDIS. The CDDIS currently provides on–line access through anonymous ftp to all IGS products generated since the start of the IGS Test Campaign in June 1992 in the file system /gnss/products; products from GPS+GLONASS products are available through this filesystem. Products derived from GLONASS data only continued to be archived at the CDDIS in a directory structure within the file system `/glonass/products`.

Table 4: GNSS Product Summary

Product Type	Number of ACs/AACs	Volume	Directory
Orbits, Clocks, ERP, Positions	14+Combinations	1.2 Gb/week	`/gnss/products/WWWW` (GPS, GPS+GLONASS) `/glonass/products/WWWW` (GLONASS only)
Troposphere	Combination	2.6 Mb/day 940 Mb/year	`/gnss/products/troposphere/YYYY`
Ionosphere	5+Combination	4 Mb/day 1.5 Gb/year	`/gnss/products/ionex/YYYY`
Real–time clocks	Combination	6.0 Mb/week	`/gnss/products/rtpp/YYYY`
Repro2 products	9+Combination	500 Mb/week	`/gnss/products/WWWW/repro2`

`WWWW`: 4–digit GPS week number; `YYYY`: 4–digit year

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

In 2015, the IGS analysis centers completed the upload of products for the second IGS reprocessing campaign (`repro2`). The CDDIS provided support through upload of files from the ACs and online archive of these products (`/gnss/products/WWWW/repro2`).

3.3 Real–Time Activities

In 2013, the CDDIS staff configured a server and began testing a real–time caster to provide a real–time streaming capability at GSFC and support the IGS Real–Time Service (IGS RTS). The CDDIS successfully tested obtaining product streams from the BKG and IGS casters and providing access to these streams to authorized users; additional streams from NRCan and GA were later added to the caster. Work was completed in spring 2015 and the CDDIS caster became fully operational, broadcasting nearly 40 product and 165+ data streams in real–time. The caster runs the NTRIP (Network Transport of RTCM via internet Protocol) format. Fig. 1 shows the distribution of stations providing real–time streams to the CDDIS caster.

As stated previously, the CDDIS is one of NASA's EOSDIS DAACs and through EOSDIS, has access to a world–class user registration process, the EOSDIS User Registration System (URS), with over 140K users in its system. Since the NTRIP–native registration/access software was not compatible with NASA policies, the CDDIS developed software to interface the caster and the URS within a generic Lightweight Directory Access Protocol (LDAP) framework. The module was specifically developed to easily interface with multiple user verification systems and was given back to the NTRIP community for possible

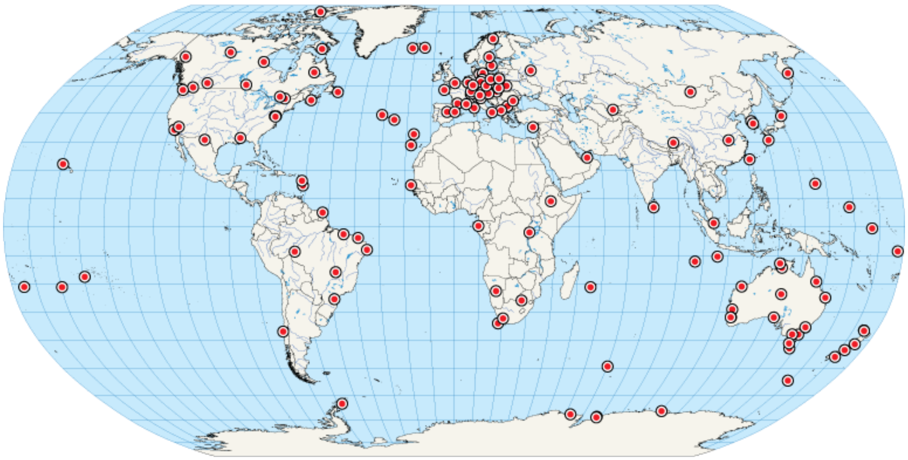

Figure 1: CDDIS is operationally supporting the dissemination of data from over 160 real–time GNSS sites as well as near real–time products derived from these data.

inclusion in future releases. The user registration form is available on the CDDIS website; once completed, the data are passed to the URS, which generates an email to the user with a validation link. The user accesses the link and the URS validates the form's data; this process is accomplished within a minute or less. The user's validated access request is submitted to CDDIS staff for access authorization to the CDDIS caster. This second step is not yet automated and can take several hours to configure depending on the time of day. In addition, users registering in this system have access to the entire suite of EOSDIS products across all 12 EOSDIS DAACs.

Initially, the CDDIS caster is providing access to product streams from several regional real–time casters. Data streams have also been tested, provided through JPL for receivers in NASA's Global GPS Network. In the near future, an additional set of stations from JPL's Global Differential GPS (GDGPS) network will be added to the CDDIS caster. This network of globally distributed, geodetic quality, dual frequency receivers, will provide additional 1 Hz data streams to those current available from the IGS RTS.

Now that the CDDIS caster is operational, the system 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 and BKG will be required to register through the CDDIS registration process in order to use the CDDIS caster. By the end of 2015, over 50 users from 16 countries have registered to use the CDDIS caster. More information about the CDDIS caster is available at `https://cddis-casterreg.gsfc.nasa.gov/index.html`.

The CDDIS has also developed software to capture real–time data streams into fifteen–minute high–rate files. This capability requires further testing and coordination with the IGS Central Bureau and Infrastructure Committee.

3.4 Supporting Information

Daily status files of GNSS data holdings, reflecting timeliness of the data delivered as well as statistics on number of data points, cycle slips, and multipath, continue to be generated by the CDDIS for RINEX V2 data. By accessing these files, the user community can receive a quick look at a day's data availability and quality by viewing a single file. The daily status files are available through the web at URL ftp:/cddis.gsfc.nasa.gov/reports/gnss/status. The daily status files are also archived in the daily GNSS data directories.

In preparation for the analysis center's second reprocessing campaign, the CDDIS developed site–specific reports detailing missing data. Station operators and operational data centers can consult these lists (ftp:/cddis.gsfc.nasa.gov/gnss/data/daily/reports/missing) and if available, supply missing files to the CDDIS for inclusion in the global data center archives.

Ancillary information to aid in the use of GNSS data and products are also accessible through the CDDIS. Daily, weekly, and yearly summaries of IGS tracking data (daily, hourly, and high–rate) archived at the CDDIS are generated on a routine basis. These summaries are accessible through the web at URL ftp:/cddis.gsfc.nasa.gov/reports/gnss. The CDDIS also maintains an archive of and indices to IGS Mail, Report, Station, and other IGS–related messages.

4 System Usage

Figure 2 summarizes the usage of the CDDIS for the retrieval of GNSS data and products in 2015. This figure illustrates the number and volume of GNSS files retrieved by the user community during 2015, categorized by type (daily, hourly, high–rate, MGEX data, products). Nearly 930 million files (nearly 100 Tbytes), excluding robot downloads, were transferred in 2015, with an average of nearly 80 million files per month. Figure 3 illustrates the profile of users accessing the CDDIS IGS archive during 2015. The majority of CDDIS users were once again from hosts in North America, Asia, and Europe.

5 Recent Developments

5.1 CDDIS Website

The CDDIS developed two applications for querying site information or archive contents. The Site Log Viewer (http://cddis.gsfc.nasa.gov/SLV2/network/QuerySiteLogs.action) is an application for the enhanced display and comparison of the contents IAG service site logs; currently the IGS, ILRS, and IDS site logs are viewable through this application.

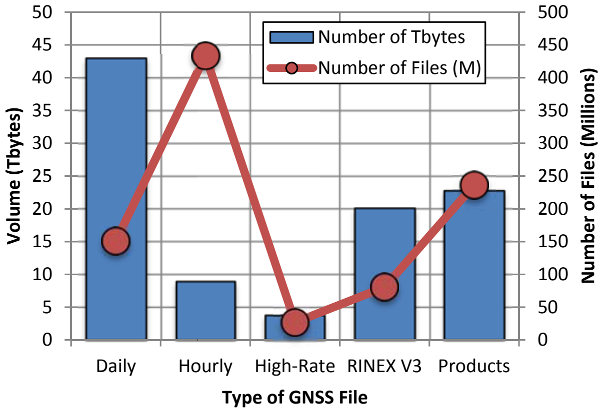

Figure 2: Number and volume of GNSS files transferred from the CDDIS in 2015.

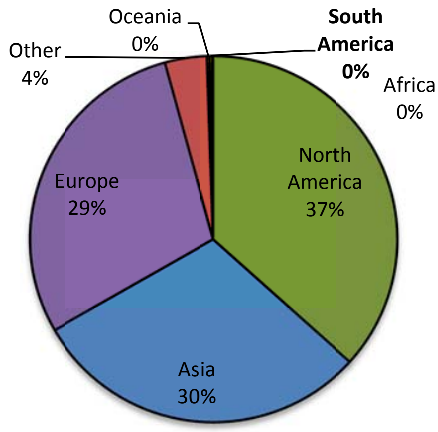

Figure 3: Geographic distribution of IGS users of the CDDIS in 2015.

Through the Site Log Viewer application, users can display a complete site log, section by section, display contents of one section for all site logs, and search the contents of one section of a site log for a specified parameter value. Thus, users can survey the entire collection of site logs for systems having particular equipment or characteristics.

Development of a second application, the CDDIS Archive Explorer, was completed in 2015; this application allows users to discover what data are available through the CDDIS. The application (accessible at `http://cddis.gsfc.nasa.gov/Data_and_Derived_Products/CddisArchiveExplorer.html`) allows users, particularly those new to the CDDIS, the ability to specify search criteria based on temporal, spatial, target, site designation, and/or observation parameter in order to identify data and products of interest for download. Results of these queries include a listing of sites and additional metadata satisfying the user input specifications. Such a user interface also aids CDDIS staff in managing the contents of the archive. Future plans for the application include adding a list of data holdings/URLs satisfying the search criteria.

5.2 Next Generation Hardware

The current CDDIS server configuration consists of multiple incoming and outgoing servers dedicated to specific functions; the system is equipped with 32 Tbytes of online RAID storage. A new virtual–machine based system was installed within the EOSDIS computer facility and network infrastructure and is currently under testing with expected operations in spring 2016. This new system configuration will provide a more reliable/redundant environment (power, HVAC, 24–hour on–site emergency personnel, etc.) and network connectivity; a disaster recovery system will be installed in a different location on the GSFC campus. The new system location will address the number one operational issue

CDDIS has experienced over the past several years, namely, the lack of consistent and redundant power and cooling in its existing computer facility. Multiple redundant 40G network switches will also be utilized to take full advantage of a high–performance network infrastructure by utilizing fully redundant network paths for all outgoing and incoming streams along with dedicated 10G network connections between its primary operations and its backup operations. The CDDIS will also transition approximately 85% of its operation services over to virtual machine (VM) technology for both multiple instance services in a load balancing configuration which will allow additional instances to be increased or decreased due to demand and will allow maintenance (patching, upgrades, etc.) to proceed without interruption to the user or any downtime. CDDIS will be utilizing a unified storage system (100 Tbytes in size) to easily accommodate future growth of the archive and facilitate near real–time replication between its production and disaster recovery sites.

5.3 Metadata Developments

The CDDIS continues to make modifications to the metadata extracted from incoming data and product files pushed to its archive. These enhancements have facilitated cross discipline data discovery by providing information about CDDIS archive holdings to other data portals such as Earth Observing System search client and future integration into the Global Geodetic Observing System (GGOS) portal. The staff has begun a metadata evolution effort, re–designing the metadata extracted from incoming data and adding information that will better support EOSDIS applications such as its search client and the metrics collection effort. The CDDIS is also participating in GGOS metadata efforts within the Bureau of Networks and Communications.

The CDDIS continues to implement Digital Object Identifiers (DOIs) to select IGS data sets (GNSS data and products). DOIs can provide easier access to CDDIS data holdings and allow researchers to cite these data holdings in publications. Landing pages are available for each of the DOIs created for CDDIS data products and linked to description pages on the CDDIS website; an example of a typical DOI description (or landing) page, for daily Hatanaka–compressed GNSS data files, can be viewed at: http:/cddis.gsfc.nasa.gov/Data_and_Derived_Products/GNSS/daily_gnss_d.html. DOIs will be assigned to additional GNSS data and product sets in the near future.

6 Publications

The CDDIS staff attended several conferences during 2015 and presented papers on or conducted demos of their activities within the IGS, including:

- P. Michael, C. Noll, J. Roark. "CDDIS Near Real–Time Data for Geodesy Based

Applications", Abstract IN43C–3709 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.

- M. Pearlman, C. Ma, C. Noll, E. Pavlis, H. Schuh, T. Schoene, R. Barzaghi, S. Kenyon, "The GGOS Bureau of Networks and Observations and an Update on the Space Geodesy Networks", Abstract EGU2015–7420 presented at EGU 2015, April 13–17, 2015, Vienna, Austria, April 12-17, 2015.
- C. Noll, P. Michael, L. Tyahla, "Distributing Real-Time GNSS Data and Derived Products at the CDDIS", NASA Earthdata Webinar Series, July 22, 2015.
- C. Noll, P. Michael, N. Pollack, "Recent Developments at the CDDIS in Support of GGOS", Abstract No. G43A–1023 presented at 2015 Fall AGU meeting, San Francisco, CA USA, December 14–18, 2015.

Electronic versions of these and other publications can be accessed through the CDDIS on–line documentation page on the web at URL http:/cddis.gsfc.nasa.gov/Publications/Presentations.html.

7 Future Plans

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

The CDDIS will continue to add real–time data and product streams to its operational caster in support of the IGS Real–Time Service. Future activities in the real–time area include capturing the streams for generation of 15–minute high–rate files for archive. This capability requires further testing as the CDDIS caster becomes operational and data streams from real–time stations are added and coordination with the IC. The staff will also investigation automating the process of adding users to the CDDIS caster configuration files.

CDDIS has traditionally used ftp for delivery of data for the archive from both data centers and analysis centers. While this has worked well over the years, transition to the new system provides an opportune time to look at updating this method to a web–based approach that can utilize the EOSDIS URS infrastructure. CDDIS will further pursue incorporating a web–based approach that will continue to allow suppliers to use existing scripts without significant modification but also tie authentication into the URS.

8 Contact Information

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

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9 Acknowledgments

Funding for the CDDIS, and its support of the IAG, IGS and other services, is provided by NASA through the Earth Science Data and Information System (ESDIS) project, which manages the EOSDIS science systems and DAACs.

The author would like to thank the CDDIS senior staff, Patrick Michael, and the contractor staff, Maurice Dube, Nathan Pollack, Rebecca Limbacher and Carlysle McNaught (Science Systems and Applications, Inc./SSAI), Lori Tyahla (Stinger Ghaffarian Technologies/SGT), Justine Woo (Sigma Space Inc.) and James Roark and Jennifer Ash (ADNET Systems). The success of the CDDIS and its recognition in the many international programs supported by the system can be directly attributed to the continued dedicated, consistent, professional, and timely support of its staff.

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Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2015

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1 IGS-specific spacecraft axis convention

At the IGS Workshop 2014 in Pasadena, the following recommendation was made: "Adopt GPS-style spacecraft axes conventions for Galileo/BeiDou/QZSS to achieve a consistent handling of the yaw-steering mode across all constellations and satellites." This IGS-specific axis convention is described in detail by Montenbruck et al. 2015:

- The $+z$-axis is the principal body axis closest to the antenna boresight direction (i.e., the direction of the maximum beam intensity).
- The y-axis is parallel to the rotation axis of the solar panels. The positive y-direction is defined through the corresponding x-axis orientation.
- The $+x$-direction is chosen such that the $+x$-panel is permanently sunlit during nominal yaw-steering, while the $-x$-panel remains dark at all times.

As this coordinate system is strictly body-fixed, the directions of the three axes are not directly referred to the positions of the Earth and the Sun. Montenbruck et al. 2015 also provide drawings and verbal descriptions of both the manufacturer- and the IGS-specific axis conventions for all types of GNSS satellites.

2 Updates and content of the antenna phase center model

Table 1 lists 15 updates of the absolute IGS antenna phase center model `igs08_wwww.atx` (Schmid et al. 2016) that were released in 2015. Eleven of them are related to changes of

Table 1: Updates of the phase center model `igs08_wwww.atx` in 2015 (`wwww`: GPS week of the release date; model updates restricted to additional receiver antenna types are only announced via the *IGS Equipment Files* mailing list)

Week	Date	IGSMAIL	Change
1830	02-FEB-15	7044	Added G032 (G26)
			Decommission date: G026
			Added `TIAPENG3100R2 NONE`
1832	18-FEB-15	—	Added `STXS8PX003A NONE`
1835	13-MAR-15	7067	Added G027 (G26)
			Decommission date: G032 (G26)
1837	26-MAR-15	7071	Added G071
			Decommission date: G027 (G26)
			Added `JNSCR_C146-22-1 NONE`
1840	15-APR-15	7082	Added R714 (R17)
			Decommission date: G038, R746
			Added `JAV_RINGANT_G3T JAVC`
1842	30-APR-15	7089	Added G049 (G08)
			Added `GMXZENITH10 NONE`
			`GMXZENITH20 NONE`
			`GMXZENITH25 NONE`
			`GMXZENITH25PRO NONE`
1844	15-MAY-15	—	Added `STXS10SX017A NONE`
1848	12-JUN-15	—	Added `JAVRINGANT_DM SCIS`
			`JAVRINGANT_G5T NONE`
			`JAVRINGANT_G5T JAVC`
			`TRM57971.00 SCIT`
1850	26-JUN-15	—	Added `SEPCHOKE_B3E6 NONE`
			`SEPCHOKE_B3E6 SPKE`
			`TRMR8S NONE`
1852	10-JUL-15	7121	Decommission date: G049 (G08)
1853	16-JUL-15	7124	Added G072
			Added `CHCC220GR CHCD`
			`CHCC220GR2 CHCD`
1854	21-JUL-15	7126	Added C001, C003, C004, C005, C006, C007, C008, C009, C010, C011, C012, C013, C014, C015, C016, E001, E002, E101, E102, E103, E104, E201, E202, E203, E204, I001, I002, I003, I004, J001
			x-offset UPDATED: G001, G002, G003, G004, G005
1861	10-SEP-15	7154	Added G036 (G10)
			Decommission date: G040
1864	29-SEP-15	7164	Added E205, E206
			Added `GMXZENITH35 NONE`
			`TPSG5_A1 NONE`
1869	03-NOV-15	7181	Added G073
			Decommission date: G036 (G10)

Table 2: Number of data sets in `igs08_1869.atx` (released in November 2015)

Satellite antennas	Number	Receiver antennas	Number
GPS	90	`ROBOT`	146
GLONASS	93	`FIELD`	90
Galileo	12	`COPIED`	34
BeiDou	15	`CONVERTED`	14
QZSS	1		
IRNSS	4		

the satellite constellation, and four times an update of the model was released, when new receiver antenna calibrations became available. Further details on all model changes can be found in the corresponding IGSMAILs whose numbers are also given in Table 1.

Table 2 gives an overview of the data sets contained in the IGS phase center model. The numbers refer to `igs08_1869.atx` that was released in November 2015. For GPS and GLONASS, there are 90 and 93 file entries, respectively. These numbers are bigger than the number of actual satellites, as certain satellites were assigned with different PRN codes or almanac slots, respectively.

Making use of the IGS-specific axis convention described in Sect. 1, conventional phase center offset (PCO) values for Galileo, BeiDou-2, QZSS, and IRNSS satellites could be added to the model in July 2015 (Montenbruck and Schmid 2015). The initial values can be found in Table 3 of Montenbruck et al. 2015. In all cases, the phase center variations (PCVs) were set to dummy (zero) values over the required range of nadir angles.

As the four new systems are still under construction, the number of satellites is limited. As regards BeiDou, the new generation of BeiDou-3 satellites launched in 2015 could not be considered for the IGS model, as no PCO information is available so far. Galileo and BeiDou-2 PCO estimates derived from terrestrial data will have to be evaluated by the Multi-GNSS Working Group, before they can replace the conventional values.

Apart from the satellite antennas, the IGS model meanwhile contains phase center calibration values for 284 different receiver antenna types. 92 of them are certain combinations of an antenna and a radome, whereas the remaining 192 antenna types are not covered by a radome. As Table 2 shows, `igs08_1869.atx` contains, among others, 146 absolute robot calibrations and 90 converted field calibrations.

As elevation- and azimuth-dependent calibration values down to 0° elevation are mandatory for new or upgraded IGS stations, altogether 183 different antenna types (146 `ROBOT` + 34 `COPIED` + 3 `CONVERTED`) are currently approved for installation. The remaining 101 types (90 `FIELD` + 11 `CONVERTED`) are no longer allowed, but their calibration values are still necessary for existing installations (see Sect. 3) as well as for reprocessing purposes.

Table 3: Calibration status of 493 stations in the IGS network (`logsum.txt` of 12 January 2016, `igs08_1869.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%**

3 Calibration status of the IGS network

Table 3 shows the percentage of IGS tracking stations with respect to certain calibration types. For this analysis, 493 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general/`) on 12 January 2016 were considered. At that time, 97 different antenna/radome combinations were in use within the IGS network. The calibration status of these antenna types was assessed with respect to the phase center model `igs08_1869.atx` that was released in November 2015.

Nine years after the adoption of absolute robot calibrations by the IGS in November 2006, state-of-the-art calibrations comprising elevation- and azimuth-dependent PCVs down to the horizon are available for about 83% of all IGS stations. The increase of about 3% compared to the previous year mainly results from the integration of a big number of MGEX stations equipped with properly calibrated antennas into the IGS network. In 2016, a further increase can be expected, as the upcoming `igs14.atx` model will allow to replace about 10 converted field calibrations for antenna types that are in use within the IGS network.

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Bias & Calibration Working Group Technical Report 2015

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1 Introduction

The IGS Bias and Calibration Working Group (BCWG) coordinates research in the field of GNSS bias retrieval and monitoring. It defines rules for appropriate, consistent handling of biases which are crucial for a "model-mixed" GNSS receiver network and satellite constellation, respectively. At present, we consider: P1–C1, P2–C2, and P1–P2 differential code biases (DCB). Potential quarter-cycle biases between different phase observables (specifically L2P and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and upcoming GNSS, like the European Galileo and the Chinese BeiDou, an increasing number of types of biases is expected.

The IGS BCWG was established in 2008. More helpful information and related internet links may be found at http://igs.org/projects-working-groups/bcwg. For an overview of relevant GNSS biases, the interested reader is referred to (Schaer 2012).

2 Activities in 2015

- Regular generation of P1–C1 bias values for the GPS constellation (based on *indirect* estimation) and maintenance of receiver class tables was continued at CODE/AIUB.
- The organization and realization of the second **IGS Workshop on GNSS Biases** was a key challenge and achievement in 2015 (see also Sect. 4).
- P1–P2 bias values for GPS and GLONASS are generated as a by-product of the ionosphere analysis.

- The tool developed for *direct* estimation of GNSS P1–C1 and P2–C2 DCB values is used to generate corresponding GPS and GLONASS bias results on a regular basis.
- The ambiguity resolution scheme at CODE was extended (in 2011) to GLONASS for three resolution strategies. It is essential that *self-calibrating* ambiguity resolution procedures are used. Resulting GLONASS DCPB(differential code-phase bias) results are collected and archived regularly.
- More experience could be gained concerning station-specific GLONASS-GPS inter-system translation parameters, which are estimated and accumulated as part of CODE's IGS analysis (but completely ignored for all submissions to IGS).
- CODE's enhanced RINEX observation data monitoring was continued. Examples may be found at:

  ftp://ftp.unibe.ch/aiub/igsdata/odata2_day.txt

  ftp://ftp.unibe.ch/aiub/igsdata/odata2_receiver.txt

  ftp://ftp.unibe.ch/aiub/igsdata/y2015/odata2_d335.txt

  ftp://ftp.unibe.ch/aiub/igsdata/y2015/odata2_d335_sat.txt

  Internally, the corresponding information is extracted and produced using metadata stored in an xml database (established in December 2014).
- This RINEX monitoring service is provided in addition for MGEX observation data (available in RINEX3 format). See ftp://ftp.unibe.ch/aiub/mgex/y2015/.

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. Analysis and combination of these remarkably long time series must be seen as a medium-term (or long-term) goal.

4 IGS Workshop on GNSS Biases 2015

This workshop was held at the University of Bern on 5–6 November 2015. All related information, including all presentations, may be found at:

http://www.biasws2015.unibe.ch

The main focus of this workshop was on:

- **Characteristics and handling of GNSS biases:** Most of the presentations addressed related topics and provided corresponding updates.
- **Bias-SINEX Format Version 1.00:** A first draft format document was prepared and presented at the workshop. Essential format aspects and issues were discussed in the plenum. An accordingly updated format document will be prepared for the upcoming IGS Workshop in Sydney.

References

Schaer, S. 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. Bias and Calibration Working Group Technical Report 2014. In: Y. Jean and R. Dach (Eds): *IGS Technical Report 2014*, Astronomical Institute, University of Bern, May 2015, pp. 133–140.

IGS Workshop on GNSS Biases 2015

5–6 November 2015
University of Bern, Switzerland (Hauptgebäude Universität Bern, Kuppelraum)
www.biasws2015.unibe.ch/programme_biasws2015.pdf

Programme and Oral Presentations

Thursday 5 November

08:30–09:00	Registration
09:00–09:30	**Opening Session**
	Welcome by the Dean (of the Philosophical Natural Sciences Faculty of the University of Bern) – Prof. Dr. G. Colangelo
	Introduction by the Director of the AIUB – Prof. Dr. A. Jäggi
	Organizational Issues – Rolf Dach
	Goals of the Workshop – Stefan Schaer
09:30–10:00	**Introduction– Chair: Rolf Dach**
	Introduction, Overview, Current Status, Bias Products – Stefan Schaer
10:00–10:30	Coffee Break
10:30–11:40	**Characteristics of GNSS Biases – Chair: Rolf Dach**
	(15') *Correlator- and Front-End-Dependency of GNSS Pseudorange Biases for Geodetic Receivers* – André Hauschild
	(15') *Nadir angle and elevation angle dependent GPS code delay variations* – Lambert Wanninger
	(15') *Receiver type depending part of observed satellite wide lane delays* – Sylvain Loyer
11:45–11:50	Photo session
12:00–13:15	Lunch at UNIESS Bistro Bar Lounge
13:30–14:00	**Continuation**
	(15') *Code Inter-Frequency Biases in GNSS Receivers* – Jean-Marie Sleewaegen
	(15') *Determination of Phase Biases with zero-baseline common clock setups* – Steffen Schön
14:00–15:00	**Treatment of GNSS Biases – Chair: Peter Steigenberger**
	(15') *RTCM-SSR Strategy of Bias Treatment* – Wübbena Gerhard
	(30') *Generalized Bias Handling in the Bernese GNSS Software and First Examples* – Arturo Villiger
	(10') *Outlook Concerning New Bias Products From CODE* – Stefan Schaer
15:00–15:30	Coffee Break
15:30–17:00	**Continuation**
	(15') *Correction for Code-Phase Clock Bias in PPP*– Pascale Defraigne
	(15') *Coupled satellite/receiver biases* – Laurent Lestarquit
	(10') *Absolute DCB determination* – Laurent Lestarquit
	(20') *Comparison of MGEX bias products* – Rolf Dach
	Bias-SINEX Version 1.00:Main Issues – Stefan Schaer
19:00–22:00	Dinner at Restaurant Beaulieu

Friday 6 November

09:00–10:30	**New GNSS and signals (e.g. IGS MGEX) – Chair: Oliver Montenbruck**
	(20') *MGEX DCB products* – Oliver Montenbruck
	(20') *Multi-GNSS Differential Code Biases (DCB) Process at* IGG –Ningbo Wang (presented by Oliver Montenbruck)
	(20') *GFZ Analysis Centre: Multi-GNSS Processing and Products* –Mathias Fritsche
	(10') *Handling of modernized signal DCBs* – Laurent Lestarquit
10:30–11:00	Coffee Break
11:00–12:15	**Continuation**
	(20') *MGEX Clock Determination at CODE* – Etienne Orliac
	(10') *GNSS Receiver Test Site at NRCan* – Ken MacLeod (presented by Simon Banville)
	(20') *Impact of PCV corrections on bias determination for multi GNSS* –Steffen Schön
	Format Discussion Concerning Bias-SINEX 1.00 and IONEX 1.1: General Rules – Stefan Schaer
12:30–13:45	Lunch at UNIESS Bistro Bar Lounge
14:00–15:30	**Standardization – Chair: Stefan Schaer**
	Data Format Issues: IONEX Version 1.1 – Stefan Schaer
	Data Format Issues: Bias-SINEX Version 1.00 – Stefan Schaer
15:30–16:00	Coffee Break
16:00–16:30	**Continuation**
	Data Format Issues: Bias-SINEX Version 1.00 – Stefan Schaer
16:30–17:00	**Closing Session – Chair: Stefan Schaer**
	Summary (Key Issues) – Stefan Schaer

Figure 1: Programme of the second IGS Workshop on GNSS Biases 2015.

Figure 2: The 31 participants of the IGS Workshop on GNSS Biases on 5$^{\text{th}}$ November 2015 in front of the main building of the University of Bern, Switzerland.

Clock Products Working Group Technical Report 2015

Michael J. Coleman

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1 Introduction

The clock products working group continues to provide a stable time scale reference for the IGS rapid and final clock products. These time scales are based on the combinations formed from clock solutions of the individual Analysis Centers (AC). The time scale product exchanges the reference clock for both the rapid (IGR) and final (IGS) clock product combinations. It should be noted that clock products for the ultra rapid products (and other more frequent products, such as the real time) are not influenced or computed by this group as of this year.

Improvements to the IGS timescale as well as publication of clock predictions and frequency states will be considered in the coming years. There have been a variety of advances in time scale analysis and computation methods over the past five years which will likely benefit the stability of the time scale product as well as enhance its use for satellite clock estimation.

Meetings among various members for this group are typical at a variety of venues including EFTF, PTTI, AGU, EGU, etc. Formal declared meetings for this group (as a whole) are rare, however. As a result, the membership list often goes unchecked for many years at a time. This year, the list of membership is being recertified and is summarized later in this report. Some former members have renewed their interest in participating in this working group while others have suggested younger members of their teams to join this working group.

2 Existing Timescale Product

An update of the IGS timescale was presented to the Consultative Committee on Time and Frequency at the BIPM in September 2015. The central point made was the loss of UTC clocks in the IGS combinations. Although the IGS timescale can be formed using any collection of clocks, absence of the best ground station reference clocks can jeopardize the stability of the IGS time scale. When Analysis Centers change the ground network used from one day to the next, the composition of ground clocks that pass through the combinations is changed. From the previous day to the current, some clocks disappear– a phenomena we call a clock “drop–out”.

These clock contribution losses are particularly detrimental when clocks that are steering references or stable UTC(k) clocks are lost. Unfortunately, the existing steering algorithm requires at least one steering target in order to process the IGS timescale and maintain reasonable alignment to UTC. When fewer clocks that are designated as steering targets are available, UTC alignment can drift (sometimes sharply); see Figure 1.

A parallel issue is the subsequent increase of GPS satellite clocks in the time scale average.

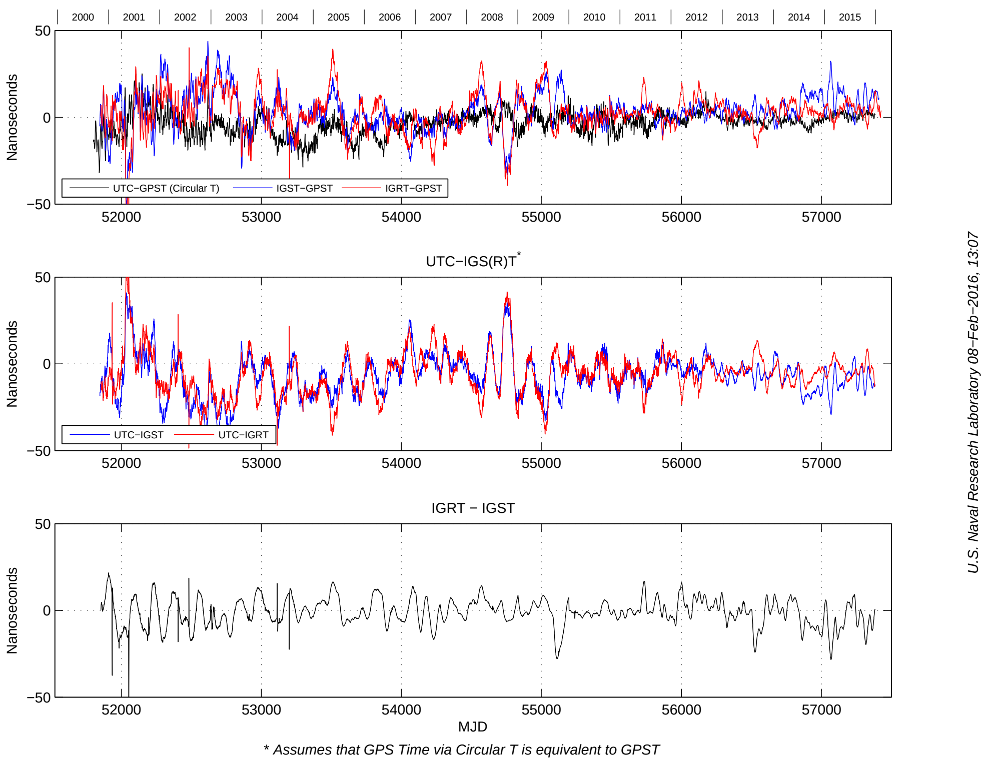

Figure 1: Offset of IGS Timescales versus UTC.

Historically, the total contribution of the satellite clocks has been low as older clocks on Block IIA and early Block IIR satellites possessed lower stability and occasional frequency breaks. Now, with improving satellite clocks in the Block IIF satellites, these GPS clocks often supplant ground station masers when those stations are drop–outs for the day. This has lead to a decreased weight of overall ground stations. Figure 2 shows the steadily increasing presence of GPS clocks in the IGS timescale over the past several years.

The positive side of this issue is that satellite clocks are improving. These newer satellite clocks are being recognized by the automated weighting algorithm as being healthy, and stable clocks. This is, of course, a desirable trend for the precision of the GPS system for ground users. In terms of the time scale, the existing algorithm does not have new and corrected models compiled for the satellite clocks that have been developed in the past two years. As a result, the historical reliance on solid and stable ground clocks is still necessary to maintain stability. We seek to include the new satellite clock model in the future; see Section 4 for further details.

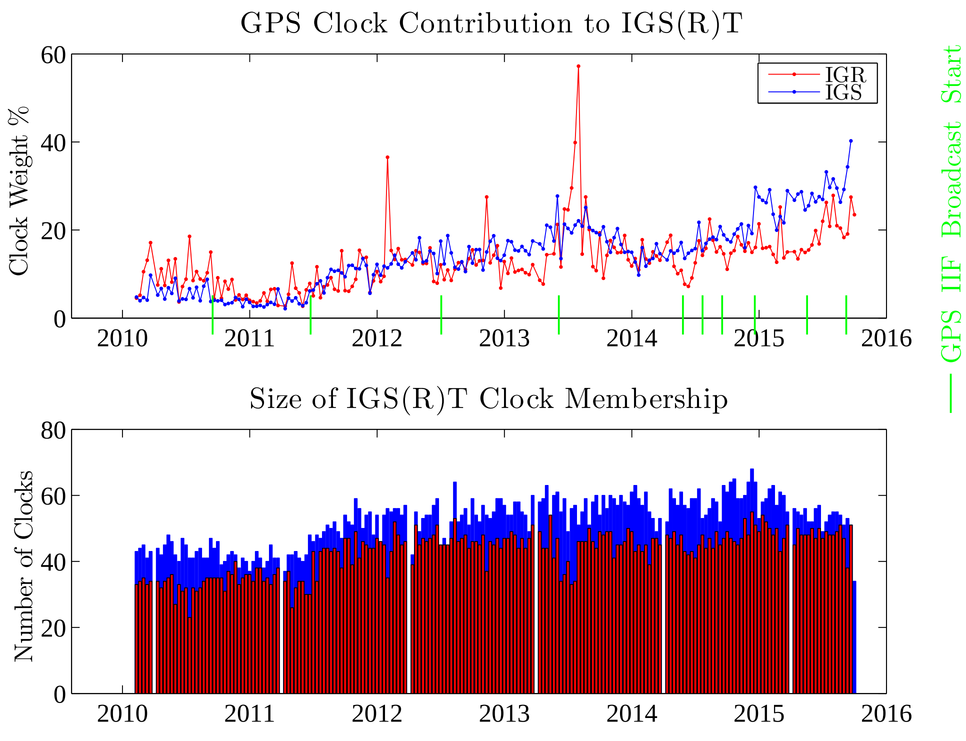

Figure 2: Upper plot shows total contribution of the GPS constellation (by weight) to the IGS(R)T ensemble. The lower plot shows the total number of clocks contributing weight to the ensemble sampled weekly. There may be many more clocks in the combinations, but some do not contribute weight to the time scale.

Table 1: Partial list of stations with IGS & UTC as well as the number of days each clock in an ensemble member of the IGS(R)T time scales (The two weights, w_p and w_f are the average phase and frequency weight contributed by the clock over the set of days that it is an ensemble member.)

Station			**IGST**			**IGRT**		
IGS	UTC	Location	Days	w_p	w_f	Days	w_p	w_f
BJNM	NIM	Beijing CHINA	104	4.36	4.71	0	–	–
IENG	IT	Torino ITALY	45	2.20	0.88	333	1.94	0.43
NIST	NIST	Boulder CO USA	0	–	–	212	4.94	4.93
OPMT	OP	Paris FRANCE	335	4.23	4.37	81	4.17	4.17
PTBB	PTB	Braunschweig GERMANY	354	4.68	4.68	355	5.00	5.00
SFER	ROA	San Fernando SPAIN	333	4.20	2.14	10	4.74	3.47
SPT0	SP	Boras SWEDEN	130	3.69	3.68	194	4.66	4.66
TWTF	TL	Chung-Li TAIWAN	181	2.97	3.01	155	4.40	4.46
USNO	USNO	Washington DC USA	73	3.58	1.09	58	4.37	4.36
WAB2	CH	Bern SWITZERLAND	340	2.58	2.45	327	2.97	0.15

Fewer clocks are present in the rapid (IGR) timescale product than in the final (IGS) since the collection of analysis centers contributing solutions for each differs. For example, MIT commits a solution to the final, but not rapid product. For a variety of reasons, the composition of the IGR and IGS timescales is not the same and total weight of GPS clocks likewise also differs. Spikes can be noticed in the GPS weight contribution in the IGR timescale since new combinations (and hence the ground network) are refreshed daily.

Clock drop–outs are of greatest concern among the set of stations listed in Table 1 since they are stable clocks that each provide direct traceability to UTC. Figure 3 shows the clock offset (with a small quadratic removed) for station IENG. An increase in clock state uncertainty along with reduced weight is seen on dates when the clock is dropped.

3 Timing Site Designations

In an effort to improve the performance of the reference time frame for the IGS clocks in both the rapid and final products, it has been suggested that the IGS add a new designation to its network. This designation will tag several of the stations within the IGS network as *Timing Stations*. Better publicity of these stations' timing abilities will enhance the chances that AC solutions utilize these sites in their ground network selection.

Timing Stations will consist only of sites that contribute their master clock data to the Bureau International des Poids et Mesures (BIPM) for computation in the monthly CircularT– the official dissemination of UTC. Even among these 73 sites, we only designate those sites that have confirmed that their receiver clock is traceable to the clock

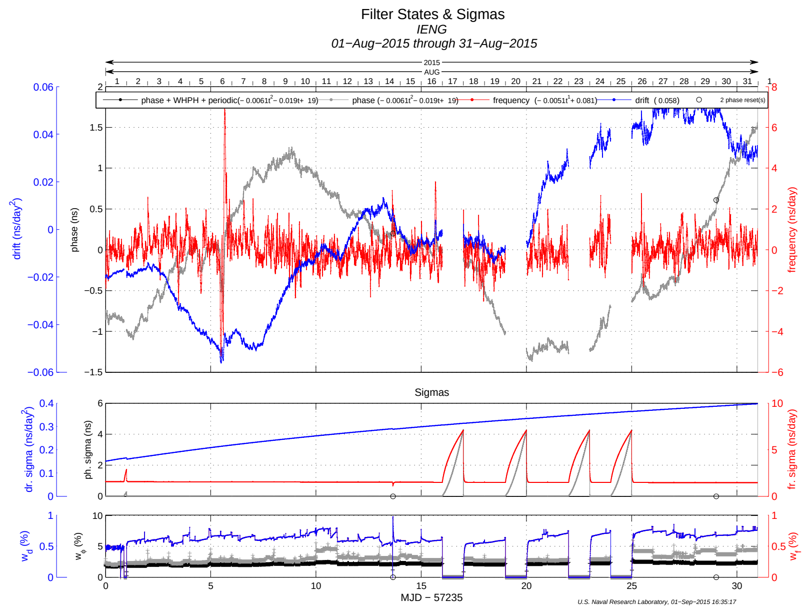

Figure 3: IGS clock product estimates of station clock at IENG site. Absence of this clock on dates 16, 19, 22 and 24 August lead to a loss of this clock's contribution to the IGRT on these dates.

signal of that UTC(k) and which are also IGS stations.

At the 45th Governing Board Meeting and associated Analysis Center Splinter Meeting, it was suggested that a list of UTC reference stations be developed. This list in Tab. 2 has been created and includes the following clocks, ranked by their order of preference for inclusion with the corresponding UTC designations.

Table 2: List of UTC reference stations (Names in IGS and UTC)

IGS	PTBB	USN7	OPMT	IENG	BJNM	SPT0	SFER	WAB2	NIST	TWTF	NRC1
UTC	PTB	USNO	OP	IT	NIM	SP	ROA	CH	NIST	TL	NRC

It was emphasized to ACs that the four sites PTBB, USN7, OPMT and IENG should be considered the most important selections. The loose criteria for selecting these particular sites are:

- Station is a timing laboratory that participates in the computation of TAI and is listed in the BIPM's CircularT.
- Confirmation that the clock signal supplied to the antenna utilized for IGS as well as UTC(k) is the same (possibly with a known calibrated bias).
- Stable performance in the CircularT with a reliably low value for |UTC – UTC(k)|.

- Geographic distribution. Lower density in this group of Timing Stations increases the likelihood of their selection among ACs.

Despite this advance, it is still expected that some analysis centers will be unable to add all or even many of these timing stations given the requirements imposed by the existing analysis done there. Additional stations can dramatically tax the processing of any one solution and it is often desirable to keep the number of ground stations low. Some solutions may also require some degree of separation of the ground stations for the benefit of other IGS products.

In the coming year, a parallel IGS timescale (unofficial) will be test an improved steering approach that utilizes UTC(k) clocks whenever they are available. It is expected that the UTC alignment can still be tightened as a result of such efforts.

4 Future Consideration: Satellite Models

The timescale is formed by a standard Kalman Filter approach utilizing a wide array of auxiliary functions that handle clock anomalies in an automated fashion. Some of the details of this timescale have been presented in the past and are available in Senior et al. 2003 and Coleman and Senior 2011, for example.

Many of the new Block IIF clocks are approaching the performance of masers in the mid to longer term; see Vannicola et al. 2013 and Senior and Coleman 2014. Clocks of this type tend to perform well even with the existing IGS timescale; see Fig. 4 for an example. Note in this figure, that clock's phase, frequency and drift state are well determined and that 1/rev and 2/rev periodics also superimpose as expected over the clock's phase. For this reason, inclusion of this clock can benefit stability. Predictions of this clock could also be made if clock data is needed at a data rate higher than the publication latency.

The existing products do not always detect clock breaks, or accurately converge on satellite clock harmonics. This can be seen clearly in Fig. 5, for example. There, a break in frequency is followed by a period of misalignment between the phase and its associated total phase value (which incorporates periodics). Improvements in the satellite clock models and initialization routines are expected to be implemented to the IGS timescale in the coming years and can help to improve estimate anomalies such as this one. Some developments on satellite clock models can be found in Coleman and Senior 2011.

The IGS timescale also stands to benefit when the products include solutions of clocks from other GNSS systems. A common time reference for all member satellite clocks could make clock comparisons easier between satellite systems. The Clock Products Working Group should endeavor to grow the timescale membership following the MGEX project and potential inclusion of all GNSS into the IGS products.

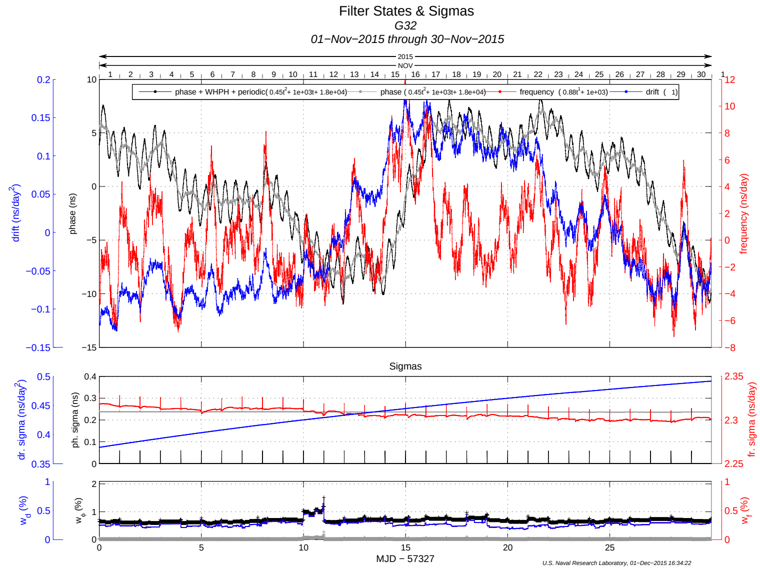

Figure 4: IGS clock product for G32 satellite clock (PRN 32). All states are relatively well determined and this clock contributes approximately 1% of the total IGS time scale weight.

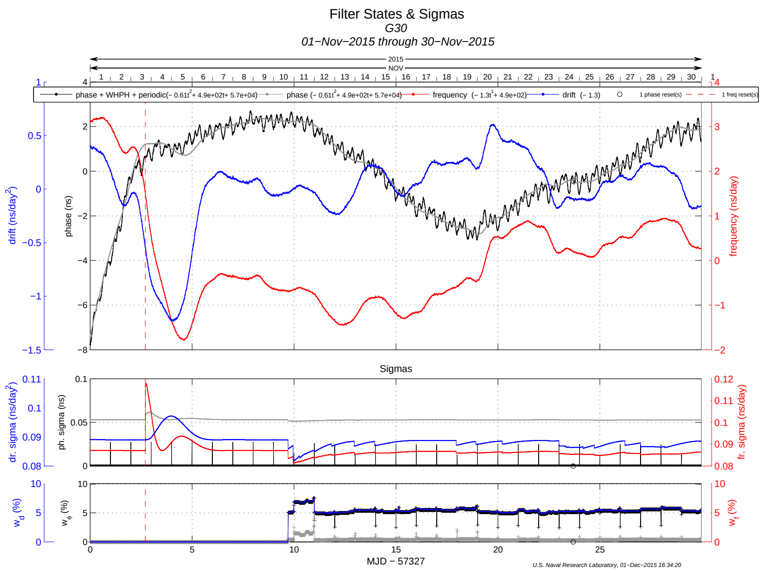

Figure 5: IGS clock product for G30 satellite clock (PRN30). Immediately following a frequency break on Nov 03, a period of poor estimation for harmonics and phase ensues. Note that the weight drops to zero as this clock is removed from the ensemble. It returns when the states stabilize, but not for several days.

5 Membership

The membership list for this working group has been revisited this year and updated to reflect those interested in clock products from the IGS. Table 3 is a table of the members and their affiliations. Those in this group consist of research scientists who have expertise in timing and frequency and are periodically present at international meetings. Membership to this working group may be expanded upon request of the coordinator.

Table 3: Membership of Clock Working Group

Last Name	First Name	Affiliation	Country
Arias	E. Felicitas	Bureau International des Poids et Mesures	International
Bertiger	William	Jet Propulsion Laboratory	US
Coleman	Michael	Naval Research Laboratory	US
Dach	Rolf	Astronomisches Institut, Universität Bern	Switzerland
Defraigne	Pascale	Observatoire Royal de Belgique	Belgium
Griffiths	Jake	Naval Research Laboratory	US
Lin	Calvin	National Time and Frequency Standard Laboratory	Taiwan
Petit	Gérard	Bureau International des Poids et Mesures	International
Rovera	Daniele	Observatoire de Paris	France
Romero	Ignacio	ESA / European Space Operations Center	Germany
Senior	Ken	Naval Research Laboratory	US
Sessia	Ilaria	Istituto Nazionale di Ricera Metrologica	Italy

References

Michael J. Coleman and Ken Senior. A comparison of GPS clock models for the next generation GPS system timescale. In *Proceedings of the 43rd Annual Precise Time and Time Interval Systems and Applications Meeting*, Long Beach, California, 2011.

Ken Senior and Michael J. Coleman. Generation of ensemble timescales for clocks at the naval research laboratory. In *Proceddings of the 46th Annual Precise Time and Time Interval Systems Applications Meeting, ION*, pages 98–105, Boston, Massachusetts, 2014.

Ken Senior, Paul Koppang, and Jim Ray. Developing an IGS time scale. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 50:585–593, 2003.

Francine Vannicola, Ronald Beard, Douglas Kock, Anthony Kubik, and David Wilson. GPS Block IIF atomic frequency standard analysis. In *Proceedings of the 45th Annual*

Precise Time and Time Interval Systems and Applications Meeting, pages 244–249, Bellevue, Washington, 2013.

Data Center Working Group Technical Report 2015

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1 Introduction

The IGS Data Center Working Group (DCWG) was established in 2002. The DCWG tackles many of the problems facing the IGS data centers as well as develops new ideas to aid users both internal and external to the IGS. The direction of the IGS has changed since its start in 1992 and many new working groups, projects, data sets, and products have been created and incorporated into the service since that time. The DCWG was formed to revisit the requirements of data centers within the IGS and to address issues relevant to effective operation of all IGS data centers, operational, regional, and global.

2 Recent Activities

2.1 RINEX V3 Integration

The DCWG continues to work with the IGS Infrastructure Committee (IC) on various topics of mutual interest. One primary area is the support of GNSS data in RINEX V3 format, initially utilized in the data holdings of the Multi–GNSS Experiment (MGEX) but becoming increasingly important in IGS activities in general. The following recommendations were generated from the June 2015 DCWG meeting, held during the 2014 IGS Workshop in Pasadena, CA:

- Develop a transition plan that will integrate RINEX V3, including the V3 filename convention, into the operational IGS archives by the end of 2015. (IC, DCs, ACs, MGEX WG)

– Progress: This recommendation supports the IC goal of "one network one archive." The current parallel "campaign" structure found at the DCs supporting MGEX limits the motivation of the ACs to switch to the RINEX V3 format. Integration of the two data archives (operational and campaign) will promote use of multi–GNSS data and the new format. Thus, the MGEX Working Group recommended the development of a transition plan that outlined the steps necessary for integrating the MGEX/RINEX V3 data into the operational archives. During 2015, the IC developed and circulated the draft plan, which was approved at the IGS Governing Board meeting in December 2015.

The way forward on this task was to have stations/operations centers utilize the file naming convention outlined in the RINEX V3 format documentation for any data in RINEX V3 format supplied to the IGS. Messages were sent to the IGS Analysis Centers (AC) and the user community in general, presenting the steps outlined in the transition plan, and informing users of the impending updates to the data center structure. A few GDCs, the CDDIS and IGN, began implementation of the recommendations in the plan in late December 2015 by agreeing to include any RINEX V3 data (starting with 2016 data) supplied with the V3 file naming convention in the operational archives. Thus, both RINEX V2 and V3 data can be found in the main GNSS data directories at these data centers. The campaign directories, e.g., for MGEX, continue to contain data in RINEX V3 format utilizing the older, 8.3 filename format.

- Provide software tools that DCs can use to continue to provide needed QC and metadata extraction enabling creation of data status information.

  – Progress: During the past year, a candidate tool for the DCs that can provide QC and generate reports from data in RINEX V3 format was suggested. The IC has had some success with G–Nut/Anubis, a command line tool developed by the Geodetic Observatory Pecny (GOP) for multi–GNSS data in RINEX V3 format. Tests are underway at DCs with the Anubis software.

- Provide software tools to support data conversion (e.g., RINEX V3 to RINEX V2; RINEX V3 filename creation) that both DCs and ACs can use.

  – Progress: In order to provide more data in RINEX V3 format in the main/non–campaign directories at the GDCs, the IC has requested that the DCs create files using the RINEX V3 file naming convention from multi–GNSS data in the old file-name format. The IC has had success with the gfzrnx tool, developed at GFZ; DCs are testing the software for this function.

2.2 Site Metadata Activities

Another area of interest for the IGS IC and DCWG involves metadata, particularly in the area of site logs. The IGS CB uses the Site Log Manager System for handling IGS site logs, which provides a basis for promoting the transmission of these logs in XML format. An XML/database management approach to site logs provides several advantages, such as rapid update of site log contents, utilization of consistent information across data centers, and availability of more accurate station metadata. The IGS CB and UNAVCO, in conjunction with the DCWG, held email discussions and telecons to allow participants in this effort to collaborate and plan for the way forward in design, development, and implementation of a shared geodesy XML schema, possibly utilizing the site log schema developed at SOPAC, for site information. During 2015, F. Boler continued coordination of this activity under the auspices of the IGS DCWG. Several telecons were held with various IGS data center, network, and infrastructure contacts; the collaborators have identified GeodesyML, an application schema of the Open Geospatial Consortium, for encoding the Site Log XML metadata elements.

DCWG members participated in a GGOS–sponsored technical interchange meeting on metadata in August 2015, hosted by UNAVCO, in order to develop a space geodesy metadata standard that can be used by the services and GGOS. The Site Log XML effort was a topic for discussion and attendees agreed that this effort within the IGS will prove useful to, and could be adopted and modified by, the other services.

2.3 Other Activities

DCWG members worked with contacts at the new GDC in Wuhan to begin their integration into the flow of IGS data and products. The chair also worked with ACs and coordinators on submission of repro2 products for their contributions to ITRF2014. Transmission of data from the NGA GPS monitoring sites resumed in 2015 and GDCs were notified of their availability for their archives.

3 Future Plans

The DCWG will continue to coordinate with the IC and MGEX activity to fully realize the integration of data in RINEX V3 format into the main, operational archives at the IGS GDCs. The integration of these files with "long"/RINEX V3 filenames into the operational archives is progressing for data in 2016. Data centers will continue to test software for creating files using this V3 filename format to support the integration task. Once these procedures are reviewed by the IC and tested, DCs will provide files following the V3 naming convention in the operational archives for MGEX data prior to 2016. Work on the site metadata activity will also continue. Additional topics the WG hopes to address follow.

- Support of the IGS Infrastructure Committee: A major focus of the DCWG will be to support the IC in its various activities to coordinate the resolution of issues related to the IGS components. These activities will address recommendations from the 2016 IGS Workshop as well as past workshops, including assessment and monitoring of station performance and data quality, generating metrics on these data.
- Data center harmonization: The working group will consider methodologies for ensuring key data sets are available at all GDCs.
- Compression: As per a recommendation from past IGS workshops, the DCWG will develop a plan for the introduction of a new compression scheme into the IGS infrastructure by evaluating tests of available tools, surveying the IGS infrastructure, making a recommendation on a new IGS compression scheme, and coordinating recommendations with the IC to develop implementation schedule. Ideally, the new compression scheme will be made part of the RINEX V3 file naming implementation.
- Next meeting: A meeting of the DCWG is planned for the next IGS workshop in 2016.

4 Membership

- Carey Noll (NASA GSFC/USA), Chair
- Yehuda Bock (SIO/USA)
- Fran Boler (UNAVCO)
- Ludwig Combrinck (HRAO/South Africa)
- Bruno Garayt (IGN/France)
- Kevin Choi (NOAA/USA), ex–officio
- Heinz Habrich (BKG/Germany)
- Michael Moore (GA/Australia)
- Ruth Neilan (JPL/USA), ex–officio
- Markus Ramatschi (GFZ/Germany)
- Nacho.Romero (ESA/Germany)
- Mike Schmidt (NRCan/Canada)
- Giovanni Sella (NOAA/USA)
- Grigory Steblov (RDAAC/Russia)
- Dave Stowers (JPL/USA)

Ionosphere Working Group Technical Report 2015

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10 UB–D.Electronics, Spain

1 Introduction

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 four IGS Ionosphere Associate Analysis Centers (IAACs): CODE (Center for Orbit Determination in Europe, Astronomical Institute, University of Berne, Switzerland), ESOC (European Space Operations Center of ESA, Darmstadt, Germany), JPL (Jet Propulsion Laboratory, Pasadena, California, U.S.A), and UPC (Tech-

*Chair of Ionosphere Working Group

nical University of Catalonia, Barcelona, Spain). Independent computation of rapid and final VTEC maps is used by the each analysis centers: Each IAACs compute the rapid and final TEC maps independently and with different approaches including the additional usage of GLONASS data in the case of CODE.

2 Membership

- Dieter Bilitza (GSFC/NASA)
- Ljiljana R. Cander (RAL)
- M. Codrescu (SEC)
- Anthea Coster (MIT)
- Patricia H. Doherty (BC)
- John Dow (ESA/ESOC)
- Joachim Feltens (ESA/ESOC)
- Mariusz Figurski (MUT)
- Alberto Garcia–Rigo (UPC)
- Manuel Hernandez–Pajares (UPC)
- Pierre Heroux (NRCAN)
- Norbert Jakowski (DLR)
- Attila Komjathy (JPL)
- Andrzej Krankowski (UWM)
- Richard B. Langley (UNB)
- Reinhard Leitinger (TU Graz)
- Maria Lorenzo (ESA/ESOC)
- A. Moore (JPL)
- Raul Orus (UPC)
- Michiel Otten (ESA/ESOC)
- Ola Ovstedal (UMB)
- Ignacio Romero (ESA/ESOC)
- Jaime Fernandez Sanchez (ESA/ESOC)
- Schaer Stefan (CODE)
- Javier Tegedor (ESA/ESOC)
- Rene Warnant (ROB)
- Robert Weber (TU Wien)
- Pawel Wielgosz (UWM)
- Brian Wilson (JPL)
- Michael Schmidt (DGFI)
- Mahdi Alizadeh (TU Vienna)
- Reza Ghoddousi–Fard (NRCan)

3 Products

a) final GIM (please note that GIMs also include GPS and GLONASS stations' and satellites' DCBs)

- combination of CODE, ESA, JPL and UPC iono products conducted by UWM
- temporal and spatial resolution – at 2 hours x 5 deg. x 2.5 deg (UTxLon.xLat.),
- availability with a latency of 11 days

b) rapid GIM

- combination of CODE, ESA, JPL and UPC iono products conducted by UWM
- temporal and spatial resolution – at 2 hours x 5 deg. x 2.5 deg (UTxLon.xLat.),
- availability with a latency of less than 24 hours

c) predicted GIM for 1 and 2 days ahead (pilot product)

- combination of ESA and UPC iono products conducted by ESA
- temporal and spatial resolution – at 2 hours x 5 deg. x 2.5 deg (UTxLon.xLat.),

4 Key accomplishments

a) IGS Global ionosphere predicted products for 1 and 2 days ahead (pilot product). This new IGS products are currently based on predicted ionosphere maps prepared by UPC and ESA.

b) IGS Global ionosphere maps with 1 hour time resolution. This new IGS products are currently based on ionosphere maps prepared by UPC, ESA and CODE.

c) IGS Global Ionosphere Maps (GIMs) now include differential code biases (DCBs) for GLONASS satellites.

d) The pilot phase of the new IGS ionospheric product – TEC fluctuations maps

5 Recommendations after IGS Workshop 2016, Sydney, Australia

a) To accept CAS–IGG, NRCan and WHU as new Ionospheric Analysis Centers, contributing to the IGS combined VTEC GIMs,.

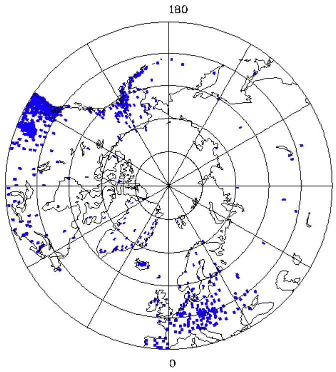

Figure 1: The locations of the stations around the North Geomagnetic Pole.

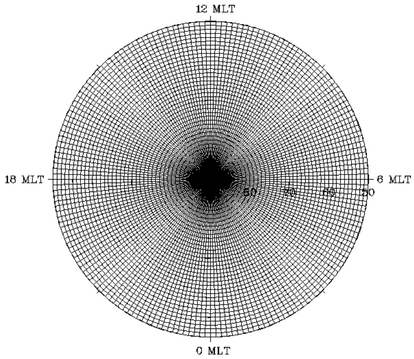

Figure 2: The grid of ROTI maps in polar coordinates with grid 2 degree (magnetic local time) and 2 degree (geomagnetic latitude).

b) The IONEX format shall be updated in order to accommodate contributions from multiple constellation and adequately describe the associated differential code biases.

c) Cooperation with IRI COSPAR group for potential improvement of both IRI and IGS TEC.

d) Cooperation with International LOFAR Telescope (ILT) for potential synergies

6 The pilot phase of the new IGS ionospheric product

– TEC fluctuations maps; Space Radio–Diagnostics Research Centre, University of Warmia and Mazury in Olsztyn, Poland (SRRC/UWM)

According to the resolution of the IGS Ionosphere Working Group, which has been passed during the IGS Workshop 2014 in Pasadena, the new product – the ionospheric fluctuations maps – was established as a pilot project of the IGS service. Taking into account that the Earth ionosphere is formed by superimposing of Earth magnetic field and Solar irradiance level for the geomagnetic field the TEC fluctuations are calculated as a function of a spherical geomagnetic latitude and magnetic local time.

In the updated version, more than 700 permanent stations (available both from UNAVCO and EUREF databases) have been involved into analysis of the ionosphere fluctuation service. In order to describe the TEC variability in the ionosphere, the Rate of TEC (ROT) and its deviation – Rate of TEC Index (ROTI) are used. The ROT is calculated as the difference of two geometry–free observations for consecutive epochs. The ROTI

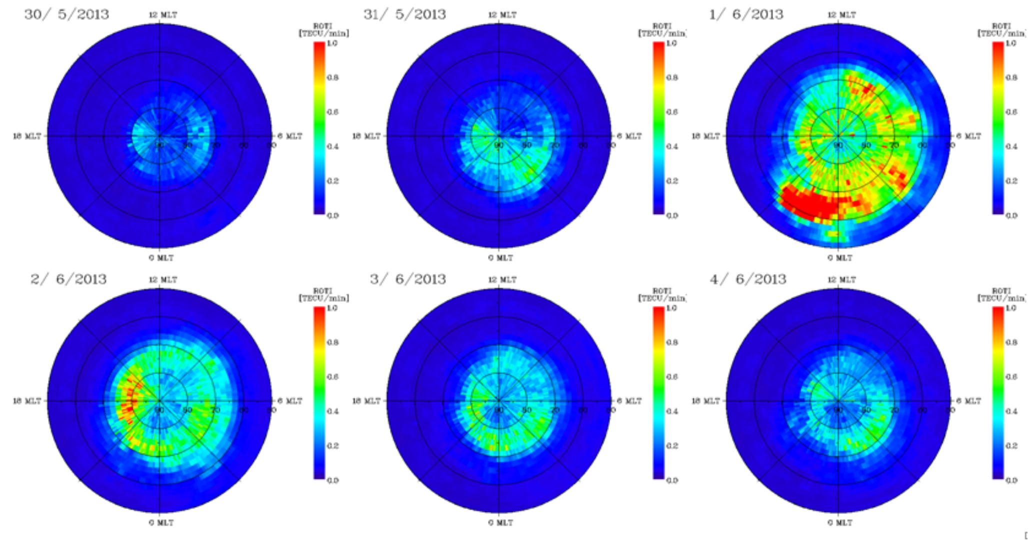

Figure 3: Evolutions of the daily ROTI maps for 30 May – 4 June 2013.

	89	87	85	83	81	79	77	75	73	71	69	67	65	63	61	59	57	55	53	51
1	0.2959	0.4422	0.465	0.311	0.3678	0.4486	0.3578	0.3835	0.4148	0.3314	0.3425	0.126	0.0913	0.032	0.0351	0.0331	0.036	0.0372	0.0382	0.0336
3	0.2927	0.4224	0.3924	0.3731	0.4034	0.4608	0.3389	0.4352	0.4048	0.2986	0.248	0.1268	0.1171	0.0378	0.0352	0.0335	0.0346	0.0343	0.0396	0.0335
5	0.2792	0.394	0.3942	0.4697	0.3284	0.4379	0.3944	0.465	0.3843	0.2807	0.2481	0.1496	0.1099	0.0438	0.0323	0.0327	0.0355	0.0367	0.0374	0.0336
7	0.2609	0.4365	0.3266	0.3829	0.4267	0.5317	0.4661	0.4689	0.3635	0.3103	0.2117	0.1402	0.0725	0.0444	0.0335	0.0344	0.0363	0.0382	0.0357	0.034
9	0.4455	0.4226	0.3477	0.4237	0.4313	0.5694	0.5135	0.3641	0.4155	0.2923	0.2217	0.1319	0.0794	0.0449	0.0369	0.0335	0.0385	0.0396	0.0383	0.0358
11	0.5008	0.4245	0.4262	0.3578	0.3814	0.5214	0.5073	0.3896	0.3925	0.3136	0.2374	0.1492	0.08	0.0393	0.0322	0.033	0.0367	0.0411	0.0384	0.0389
13	0.3294	0.3593	0.4965	0.3778	0.4072	0.7487	0.5215	0.3219	0.3607	0.3442	0.2959	0.1609	0.0808	0.0463	0.0344	0.0292	0.0343	0.0422	0.0377	0.038
15	0.3004	0.3847	0.4443	0.3325	0.3606	0.6081	0.3513	0.3715	0.368	0.307	0.2705	0.1739	0.068	0.0364	0.0365	0.0293	0.0342	0.0416	0.0397	0.0401
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
345	0.3648	0.6725	0.3646	0.4227	0.4633	0.4701	0.568	0.433	0.3694	0.3681	0.2091	0.1214	0.0726	0.0373	0.0385	0.0391	0.0347	0.0342	0.0352	0.0336
347	0.3667	0.4735	0.3784	0.3845	0.5204	0.5891	0.5423	0.434	0.4858	0.3508	0.2132	0.1101	0.0882	0.0437	0.0373	0.0412	0.0361	0.0345	0.0343	0.0345
349	0.3688	0.5449	0.4021	0.3499	0.5294	0.6081	0.578	0.4124	0.4193	0.3378	0.2235	0.1295	0.0939	0.0418	0.0367	0.0369	0.0379	0.0346	0.0334	0.036
351	0.4049	0.5729	0.4159	0.3901	0.4119	0.5135	0.4602	0.4285	0.4767	0.3112	0.2217	0.1312	0.0837	0.0399	0.0355	0.034	0.0536	0.035	0.0328	0.0325
353	0.3524	0.389	0.4495	0.3115	0.5101	0.5135	0.4072	0.4766	0.5348	0.282	0.2186	0.1162	0.0782	0.0412	0.0342	0.0314	0.0545	0.0372	0.0326	0.0339
355	0.297	0.3992	0.3368	0.3606	0.5323	0.4776	0.367	0.4452	0.5001	0.336	0.282	0.1088	0.0834	0.0404	0.0327	0.0321	0.0391	0.0441	0.0323	0.0352
357	0.2614	0.4348	0.31	0.4465	0.3972	0.4235	0.3796	0.3958	0.44	0.3829	0.3155	0.1115	0.0709	0.0361	0.033	0.0318	0.0408	0.0397	0.0382	0.0367
359	0.2838	0.3851	0.3392	0.4338	0.4432	0.3893	0.323	0.3949	0.4581	0.3688	0.3274	0.147	0.0744	0.0332	0.0331	0.0338	0.0365	0.0378	0.0377	0.0364

Figure 4: The sample of ROTI–ex format body.

represents the ROT deviation over 5 minute periods with one minute resolution. This ionospheric fluctuations service allows to estimate the levels of TEC fluctuations for spatial range from 50 degree of the north geomagnetic latitude to the North Geomagnetic Pole. The results have visualization as daily ROTI maps in polar coordinates with grid 2 degree (magnetic local time) and 2 degree (geomagnetic latitude). The every grid cell represents the average weighted value of ROTI values included in this cell.

The final TEC fluctuations maps are written in the modified IONEX format. For ROTI data storing it is proposed simple ASCII format based on grid 2 x 2 degree – geomagnetic latitude from 89o to 51o with step 2 and corresponded to magnetic local time (00–24 MLT) polar coordinates from 0 to 360 .

7 Comparing performances of seven different global VTEC ionospheric models in the IGS context

In this section two independent techniques to assess global Vertical Total Electron Content (VTEC) ionospheric models computed from GNSS data (GIMs) are applied in the context of the International GNSS Service (IGS): to the GIMs of CODE, ESA, JPL and UPC (analysis centers contributing since 1998.5), NRCAN (resuming its contribution), and, Chinese Academy of Sciences (CAS) and Wuhan University (WHU) as new contributors.

Two important and complementing aspects of the ionospheric models are assessed: On one hand the VTEC accuracy, by comparing with direct measurements of VTEC up to the orbital height of dual–frequency altimeters (around 1200–1300 km, containing the most part of electro content affecting GNSS signals), providing them over the seas (i.e. typically far from existing receivers, assessing mostly interpolation), and with almost no interruption since the beginning of the IGS ionospheric service (missions TOPEX, JASON–1 and JASON–2). And, on the other hand, the Slant Total Electron Content (STEC) provided by the GIMs, typically not far from the receivers used in their computation, is assessed versus very precise direct STEC observations taken by GNSS receivers in different regions of the world, not used in the GIMs computation.

The first VTEC assessment results obtained during the recent period of days 117 to 317, 2015, show a very good behavior of the new GIMs (EMR, CAS & WHU) in terms of VTEC bias regarding to JASON2 direct measurements, compared with the existing GIMs, contributing since 1998.5 (CODE, ESA, JPL & UPC). From the point of view of the corresponding Standard Deviations, the new GIMs present, in general, similar, or either better precision than the existing IGS GIMs and their combinations. The extended VTEC assessment will be completed with the STEC one.

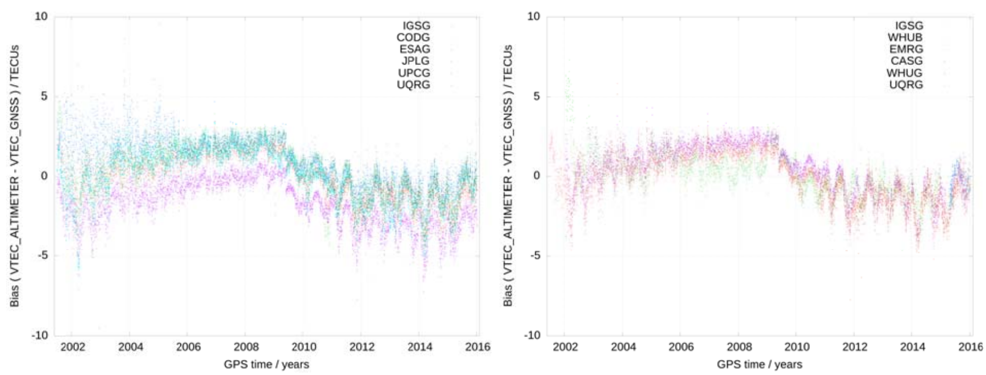

Figure 5: VTEC GIMS Bias regarding JASON* VTEC (daily values, since days 2001.6 to 2016.0).

Finally the convenience of maintaining the good practice of a right assessment of ionospheric models, by using external measurements, absolutely independent from any of the compared models, will be emphasized.

It is remarkable as well the general agreement of the bias, at 1 to few TECUs level, regarding the altimeter VTEC for the most part of analysis centers. This happens among different mapping functions used (related with the general leveling) and the topside electron content climatology between the altimeter and GPS orbit (seen as variations interpreted as "inverse climatology", <VTEC_alt – VTEC_GPS>, in the time series, appearing clearly the Solar Cycle and seasonal cycles, among others.

Multi–GNSS Working Group Technical Report 2015

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1 Introduction

As its primary task, the Multi–GNSS Working Group (MGWG) steers the performance of the Multi–GNSS Experiment (MGEX), which promotes and prepares the use of new signals and constellations within the IGS. As of Dec. 2015, the MGWG has a total of 16 members. These include representatives of selected analysis and data centers (BKG, CODE, CNES/CLS, DLR, ESA, GFZ, JAXA, WU) as well as various individuals contributing to the overall goals of this project. No changes of membership occurred during the reporting period, but the position of M. Uhlemann as representative of GFZ was taken over by M. Fritsche starting January 1, 2016.

2 GNSS Evolution

Within 2015, a total of three GPS Block IIF satellites were launched thus increasing their total number to 11. By the end of that year only one Block IIA satellite remained active in the constellation. With 18 L2C-capable satellites (IIR–M and IIF) and 11 L5–capable satellites, the GPS makes substantial progress towards provision of a dual–frequency service for civil users. Along with this goal, CNAV navigation messages are issued with a more frequent (once–per–day) upload cycle since the beginning of 2015, which yields a user performance compatible with that of the legacy LNAV message (Steigenberger et al. 2015d). In extension of prior policy, the US government announced in its new Federal Aviation Plan to ensure availability of P(Y) code transmission for a minimum of two years after availability of a 24 satellites L5 constellation. This is presently foreseen for 2024.

No GLONASS launches took place in 2015, but some of the satellites in spare slots started to identify themselves with slot numbers in the range of 24–27. This enables tracking of these satellites by various types of receivers and first RINEX observation data could be collected. Among others this has enabled first analyses of the new Rubidium clock operated on the GLONASS K1–2 satellite (A. Hauschild, private communication).

China initiated the build–up of their global navigation satellite system with the launch of four 3rd–generation BeiDou satellites. This includes two spacecraft in inclined geosynchronous orbit (IGSO) and two spacecraft in medium altitude Earth orbit (MEO). The new satellites have started to transmit diverse types of next–generation signals overlaying (and planned to be compatible/interoperable with GPS and Galileo) in the B1 (L1/E1) and B2 (L5/E5a/E5b) bands as well as B3 (E6). Legacy signals (identifying the four satellites as PRN C31–C34) are transmitted on the legacy B1 frequency at 1561 MHz. This has so far enabled single–frequency tracking by existing BeiDou capable receivers. In the absence of a consolidated and publicly documented new signal structure as well as various changes of the test signals transmitted so far, tracking of the new satellites is not yet properly supported by the existing networks. Following the loss of one MEO satellite (C13) in Oct. 2014, the regional (second generation) BeiDou system comprised a total of 13 active spacecraft.

Galileo launched a total of six new Full Operational Constellation (FOC) satellites in 2015 and is now on a rapid pace to build up an initial service. The first pair of FOC satellites, which had been launched into a wrong orbit and were later raised into a somewhat eccentric orbit with a semi–major axis of 28,000 km, transmit high–grade signals and are already incorporated into the IGS/MGEX tracking and product generation.

IRNSS, finally, launched its fourth satellite (IRNSS 1D) in spring 2015, which enabled first standalone position solutions with this system.

3 Network

The number of stations contributing multi–GNSS observations for the MGEX project continued to increase moderately and amounted to almost 130 near the end of 2015 (Fig. 1). About 50% of these stations provide real–time data streams hosted by BKG's MGEX caster (http://mgex.igs-ip.net/). While the majority of streams is delivered in vendor–specific data formats and converted to the RTCM–3 MSM format by BKG, an increasing number of receivers is already able to output observation data directly in this new standard format.

In accord with the currently offered capabilities of commercial GNSS receivers, the current network supports tracking of Galileo (E1, E5a/b), BeiDou (B1, B2, B3) and QZSS (L1, L2, E6, L5) signals next to GPS and GLONASS. So far, neither IRNSS nor the new BeiDou–3 signals can be tracked with the current infrastructure. Diversity of equipment (receivers, MGEX Offline Network (4 Oct 2015, 129 Stations)

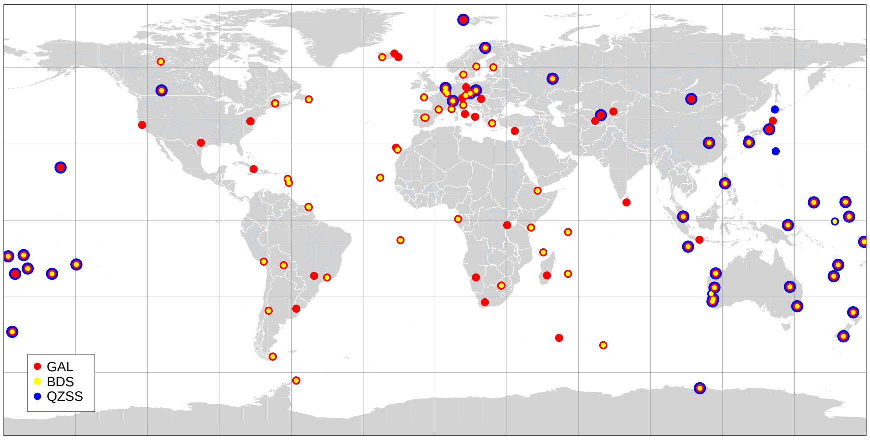

Figure 1: Distribution of MGEX stations supporting tracking of QZSS (blue), Galileo (red), and BeiDou (yellow) as of Oct. 2015.

antennas) in the multi–GNSS network is generally considered an asset for the IGS, but also poses notable challenges and concerns for high–end processing. Equipment characterization (including, e.g. antenna phase pattern and receiver–specific biases) remains a continued task for the MGWG in coordination with other IGS working groups.

In accord with the RINEX transition plan, released by the IGS Governing Board (GB) in Dec. 2014, efforts have started to migrate to the more flexible, long RINEX–3 file names and to integrate the MGEX data into the standard IGS data repository. For a full harmonization, the vast majority of MGEX stations was included into the IGS network after verification of their compatibility with the IGS site standards by the Infrastructure Committee (IC). Users are now offered a unified network with a strong multi–GNSS component rather than two independent networks. In particular, sitelog holdings, station information pages and network maps are now fully integrated and cover both legacy and multi–GNSS IGS stations (see http://www.igs.org/network). Selected MGEX stations not meeting the IGS site standards are still available at the MGEX data centers and labeled as “MGEX Experimental” in the IGS site database.

4 Products

Data from the IGS multi–GNSS network are routinely used by various MGEX analysis centers (ACs) to generate various forms of products. Most importantly, these include precise orbit and clock solutions as well as differential code biases. Other types of auxiliary

Table 1: Multi–GNSS orbit and clock products provided by the MGEX analysis centers (Status 12/2015). ACs with clock sampling in brackets do not provide dedicated RINEX clock files

Agency	ID	GNSS	Sampling (Orbit/Clock)
CNES/CLS	grm	GRE	15 min/30 s
CODE	com	GRECJ	15 min/5 min
GFZ	gbm	GRECJ	5 min/30 s
JAXA	qzf	GJ	5min/(5 min)
TUM	tum	EJ	5 min/(5 min)
WU	wum	GRECJ	15 min/5 min

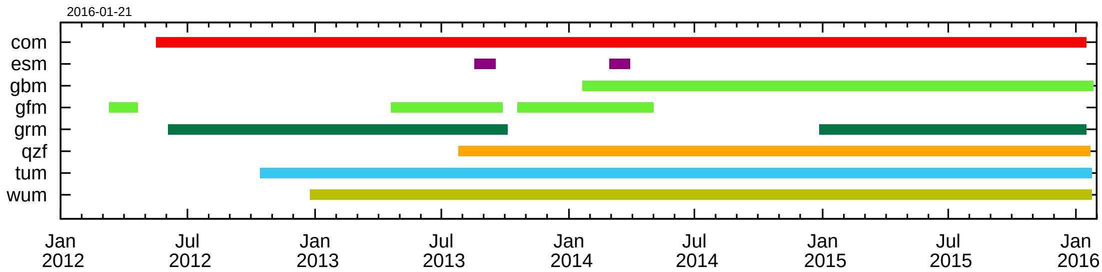

Figure 2: Overall availability of multi–GNSS orbit and clock product contributions from individual MGEX analysis centers. Note that the set of supported constellations has gradually been increased over time by some ACs.

products include cumulative broadcast orbits (available in offline and real–time formats), station coordinates, and intersystem biases

Within 2015, a total of six analysis centers generated multi–GNSS obit and clock products for MGEX on a routine basis (Tab. 1). Three of these are full five–constellation products including GPS, GLONASS, Galileo, BeiDou–2, and QZSS in a common reference frame and time. A bar chart indicating the overall product availability is shown in Fig. 2.

The availability of orbit and clock products from multiple ACs enables a basic assessment of the product quality for each constellation based on the consistency of the individual solutions. In addition, satellites of all new GNSSs are equipped with laser retroreflector arrays, that enable satellite laser ranging for validation of the orbit accuracy.

As summarized in Tab. 2, a precision of a few decimeters is typically achieved for MEO and IGSO satellites, with best results obtained for Galileo as a result of the large number of worldwide tracking stations. Worst results are obtained for geostationary BeiDou–2 satellites, where the orbit determination suffers from the quasi–static and thus nearly degenerate viewing geometry. Further studies will be required to investigate the potential

Table 2: Representative precision of orbit for new constellations as provided by the MGEX analysis centers in the 2013–2015 time frame

GNSS	Consistency(3D RMS)	SLR	Notes
Galileo	$10 - 20\,\text{cm}$	$10\,\text{cm}$	
BeiDou	$20 - 40\,\text{cm}$	$10\,\text{cm}$	MEO/IGSO
	few m	$0.5\,\text{m}$	GEO
QZSS	$20 - 40\,\text{cm}$	$0.2\,\text{m}$	

benefit of a combined processing of GNSS and laser ranging observations for this class of satellites.

Compared to GPS and GLONASS, the orbit determination accuracy achieved for the new constellations is still substantially lower, which presently limits the use of these products for high–grade geodetic applications. The inferior performance can in part be attributed to the specific choice of orbits, the regional visibility of IGSO and GEO satellites, and the moderate overall number of satellites deployed within each constellation, which impacts the ambiguity success rate. More notably, however, uncertainties in the observation modeling limit the capability to accurately propagate and adjust the orbits for the new constellations. These problems refer to the description of

- the spacecraft attitude (which affects the modeling of the antenna phase center location and carrier phase wind–up, but also solar radiation pressure),
- the antenna phase center offset and variation (preferably for individual frequencies),
- the solar (and Earth) radiation pressure, and
- the orbital maneuvers.

As part of the development of relevant models and standards, a harmonized convention of spacecraft body systems and nominal attitude control laws has been established in close cooperation of the antenna working group and the MGWG for all constellations and satellite types (Montenbruck et al. 2015a). So far, conventional values of the phase center offsets (PCOs) are recommended for use with the new constellations along with dummy (zero) phase center variation (PCV) values. Even though initial estimates for PCOs (and in part PCVs) have been obtained for BeiDou (ESA, WU) and Galileo (DLR, GFZ), the results are not consolidated, yet. Further comparisons and performance assessments will probably be required prior to their introduction into the IGS antenna model.

With respect to radiation pressure modeling, the introduction of the new ECOM2 model (Arnold et al. 2015) into the MGEX processing at CODE has shown particularly beneficial results for Galileo. Similar to the box a priori model proposed earlier by DLR, use of ECOM2 effectively removes systematic radial errors in the precise orbit products. Despite a better performance of this model (e.g. in terms of SLR residuals) the benefit does not show up, yet, in the inter–agency comparison, since other MGEX ACs do not presently use ECOM2 or a suitable a priori box(–wing) model.

To facilitate a precise orbit modeling and the generation of high–grade products, further effort will need to be made to obtain relevant information on the satellites from the manufacturer or operator. Information deemed necessary for this purpose include geometric data (surface dimensions, antenna locations), optical/thermal radiation properties, ground based phase center calibrations and documentation of non–standard attitude (noon/midnight turns, mode transitions).

Aside from orbit and clock products, the multi–GNSS DCB product constitutes a major contribution of the MGEX analysis centers for the GNSS community. In 2015 the quarter–annual product provided by DLR since 2014 has been complemented by a new product contributed by the Institute of Geodesy and Geophysics (IGG) of the Chinese Academy of Sciences (CAS) in Wuhan. This new product is generated on a daily basis to minimize latency for the user. For performance studies two years of backwards data have also been provided by IGG.

5 Acronyms and Abbreviations

BKG	Bundesamt für Kartographie und Geodäsie
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
GFZ	Deutsches GeoForschungsZentrum
JAXA	Japan Aerospace Exploration Agency
RTCM	Radio Technical Commission for Maritime Services
TUM	Technische Universität München
WU	Wuhan University

The following list provides an overview of MGEX–related publications issued in 2015 by the members of the multi–GNSS working group. It does not reflect the much wider list of publications using MGEX data and providing MGEX–related results that has been made by the scientific community in this period.

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Reference Frame Working Group Technical Report 2015

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1 Introduction

Besides a continuous quality monitoring of the operational IGS SINEX combination products (Sect. 1), the main activity of the Reference Frame Working Group in 2015 was the finalization of the IGS contribution to ITRF2014, which consists of daily combinations of the AC SINEX solutions from the IGS 2nd reprocessing campaign (Sect. 3).

2 Operational SINEX combinations

Figure 1 shows the RMS of the AC station position residuals from the daily IGS SINEX combinations of year 2015, i.e. the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed. Unlike in 2014, where successive updates of the AC's analysis strategies translated into a progressive improvement of the inter–AC agreement (Rebischung et al. 2015), the RMS of the AC station position residuals have remained at nearly constant levels in 2015.

Figures 2 and 3 show the AC Earth Orientation Parameter (EOP) residuals from the IGS SINEX combinations of year 2015. The inter–AC agreement on EOPs has not shown any major evolution either in 2015. Simply note that SIO's pole rate estimates have been included back with weight in the daily IGS SINEX combinations since week 1832.

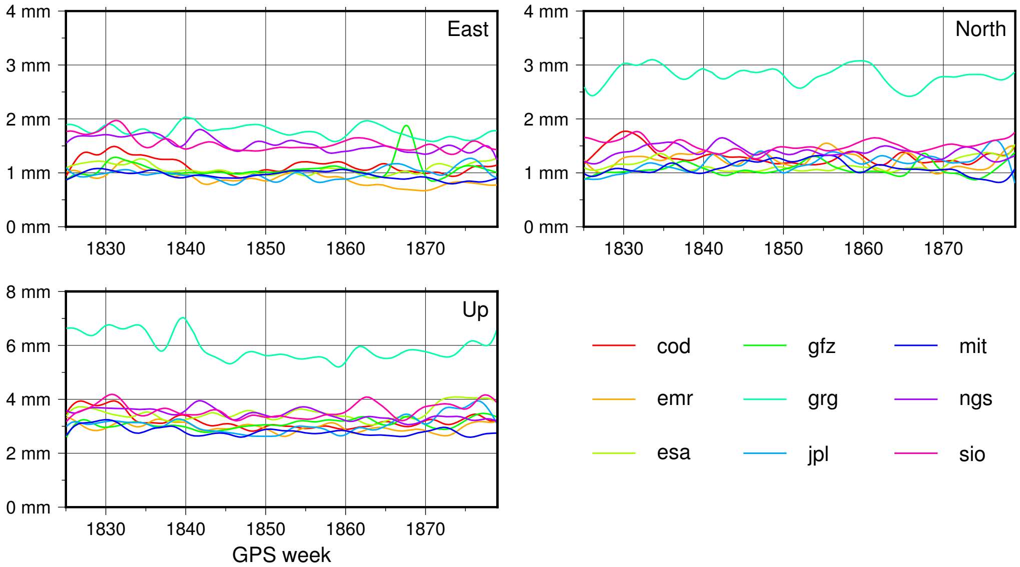

Figure 1: RMS of AC station position residuals from the 2015 daily IGS SINEX combinations. All time series were low–pass filtered with a 10 cycles per year cut–off frequency.

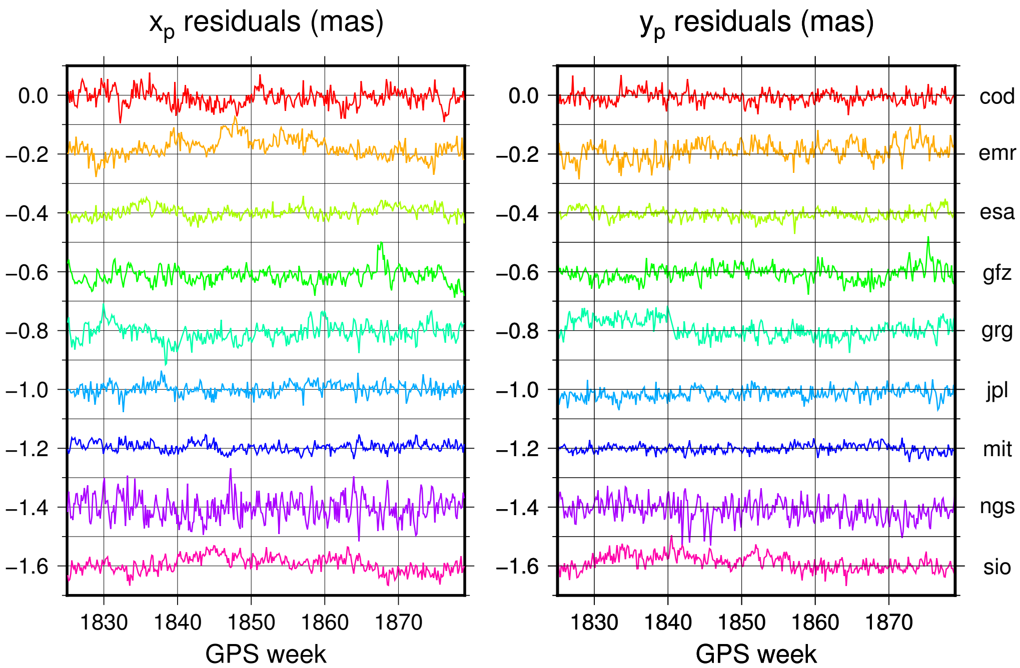

Figure 2: AC pole coordinate residuals from the 2015 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 0.2 mas for clarity.

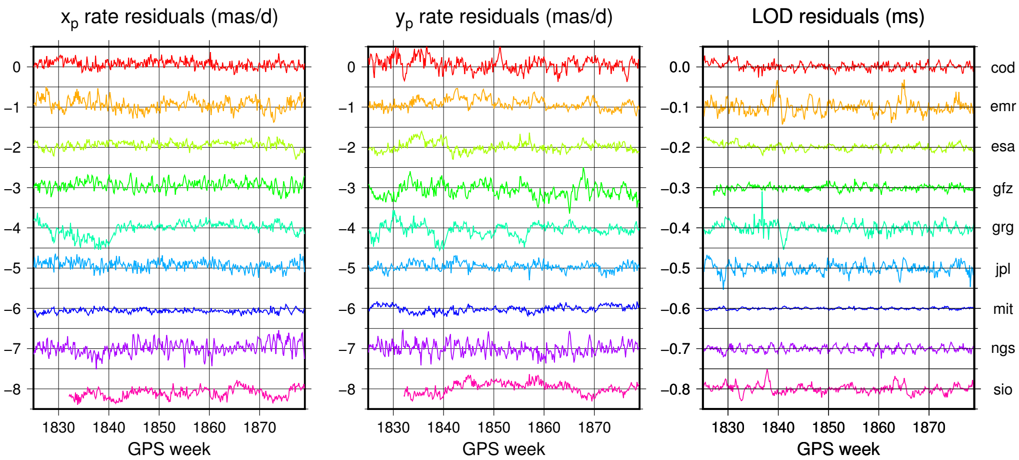

Figure 3: AC pole rate and LOD residuals from the 2015 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 1 mas/d and 0.1 ms for clarity.

3 The IGS contribution to ITRF2014

The IGS contribution to ITRF2014 is based on the products from the second IGS reprocessing campaign (`repro2`). A complete list of the models and conventions used in the `repro2` data analyses can be found at `http://acc.igs.org/reprocess2.html`. A total of 9 ACs contributed to the `repro2` campaign and provided daily terrestrial frame (SINEX) solutions among other products. The AC `repro2` SINEX time series were extended with consistent operational products up to GPS week 1831, when available, and daily combinations of the AC `repro2`+operational SINEX solutions were performed over the period 1994–01–02 to 2015–02–14 (GPS weeks 730 to 1831). The resulting daily combined SINEX solutions, named `ig2`, were made available on February 27, 2015 (IGSMAIL–7055) and can be retrieved from the IGS global data centers. They constitute the IGS contribution to ITRF2014.

From WRMS values of the residuals of the daily `repro2` combinations, the overall inter–AC level of agreement is assessed to be 1.5 mm for the horizontal components and 4 mm for the vertical component of station positions, 25–40 μas for pole coordinates, 140–200 μas/d for pole rates, 8–20 μs/d for calibrated LOD estimates, 4 mm for the X and Y components of geocenter motion, 8 mm for its Z component and 0.5 mm for the terrestrial scale. On the long term, the origins (resp. scales) of the AC terrestrial frames show relative offsets and rates within $\pm$3 mm and $\pm$0.3 mm/yr (resp. $\pm$0.5 mm and $\pm$0.05 mm/yr). The combination residuals also present AC–specific features, some of which are explained by known analysis specifics, while others remain under investigation.

See Rebischung et al. 2016 for a complete description of the `repro2` SINEX combination methodology and results.

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Real–Time Service Technical Report 2015

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1 Introduction

The International GNSS Service (IGS) Real-time Service is a GNSS orbit and clock correction service that enables precise point positioning (PPP) at worldwide scales. The RTS products enable applications such as scientific testing, geophysical monitoring, hazard detection and warning, weather forecasting, time synchronization, GNSS constellation monitoring, imagery control and many other public-benefit applications.

The RTS is made possible through partnerships with Natural Resources Canada (NRCan), the German Federal Agency for Cartography and Geodesy (BKG), and the European Space Agency's Space Operations Centre in Darmstadt, Germany (ESA/ESOC). Support is provided by 160 station operators, multiple data centres, and 10 analysis centres around the world. The service has been available since April 2013, after transitioning from a highly successful Pilot Project which allowed the development, prototyping and testing of the different elements of the Real Time infrastructure.

The International GNSS Service (IGS) has ensured open access, high–quality GNSS data products since 1994. These products enable access to the definitive global reference frame for scientific, educational, and commercial applications – a tremendous benefit to the public. Through the Real-time Service (RTS), the IGS extends its capability to support applications requiring real-time access to IGS products.

2 WG membership

Loukis Agrotis (ESA)
Axel Rülke (BKG)

Steve Fisher (JPL)
Allison Cradock (JPL)
Mark Caissy (NRCan)
Georg Weber (BKG)
Guillermo Tobías González (GMV)
Manuel Hernandez–Pajares (UPC)
Andre Hauschild (DLR)
Denis Laurichesse (CNES)
Martin Schmitz (GEO++)
Gerhard Wubbena (GEO++)
Ken Macleod (NRCan)
Lou Estey (UNAVCO)
Erik Vigen (Fugro)
Carey Noll (CDDIS)
Mathias Fritsche (GFZ)
John Braun (UCAR)
Fabian Hinterberger (TUW)

IGS Working Group Chairs
IGS Analysis Center Representatives
ex officio: R. Neilan (JPL), Kevin Choi (NGS)

3 Summary of Activities in 2015

- GPS–only combinations from ESOC and BKG were continuously available without significant performance issues.
  - Two outages of IGS01 and IGC01 were encountered over two weekends. The cause was due to issues with the RTCM ephemeris streams that are used for stream encoding/decoding.
  - There was an issue with encoding/decoding of G03 on 7 December, which resulted in a corruption of the results for that satellite.
  - Occasional performance degradation is still observed when Block IIA satellites are in eclipse.
  - Orbit performance degradation of the Block IIF satellites was observed in several instances. The suspected cause is uncertainty in the radiation pressure modeling, probably related to non–nominal spacecraft attitude.
- Focus on GLONASS products to promote AC improvements
  - Four AC streams and the GPS+GLONASS combination stream IGS03 are

monitored by the ACC.

  - One stream, from DLR, is currently unavailable, leaving 3 available AC solutions.
  - Daily clock comparisons against the ESA rapid products are made available by email.
  - PPP monitoring is performed continuously by BKG.
  - There are still encoding/decoding issues with GLONASS, but steps are in place to update software in order to eliminate them.

- Members of the WG participated in RTCM meetings in the US. Concerns on competition with commercial services and magnitude of implementation effort are still holding back acceptance of the SSR format extensions for ambiguity resolution and support for additional constellations (Galileo, QZSS and Beidou). Adoption of the RTCM MSM format for multi–GNSS observation streaming in receiver firmware is finally starting to appear. The standards for Beidou and Galileo I/NAV ephemeris messages have not yet been approved, so the MGEX streams are using draft formats for these. However, these messages cannot yet be streamed directly from receiver firmware.
- The latest statistics for registrations to the IGSCB caster: (unavailable at time of preparation. Update will be provided ASAP.
- A presentation on the RTS status was given at the IUGG (Axel Ruelke).

4 Plan in 2016

- Encourage additional RTAC's to contribute GLONASS solutions
- Improve the reliability of the broadcast ephemeris streams used by RTAC's.
- Encourage processing of MGEX streams. One key objective is that all RTACs become able to use MSM streams in their routine RTS processes.
- Participation in SSR interoperability testing – for example ambiguity fixing and ionosphere
- Contact station operators and encourage the delivery, when possible, of a minimum of two streams to separate independent real–time data centers/casters.
- Optimization of real time observation data infrastructure in order
  - to reduce the total latency
  - avoid bandwidth problems at specific data centers

  - improve reliability

- Discussion on objectives of the IGS RTS (possible product limitations, broadcasting methods, competition with commercial providers etc.)
- Participation of some members in a newly formed IAG Real Time Ionosphere working group, starting work in 2016

RINEX/RTCM Working Group Technical Report 2015

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1 Highlights in 2015

- RINEX Version 3.03 released in July, 2015. Most significant updates include:
  - Addition of the Indian Regional Navigation Satellite System (IRNSS) Constellation
  - Updates to support BeiDou
  - Numerous message clarifications
  - Additional App. **??** RINEX 3.0x support is strong within both the IGS and RTCM–SC104.
  - Application support for RINEX 3.0x is growing.
- Formation of the RTCM–SC104/IGS GNSS Receiver Calibration Working Group:
  - This effort involves the cooperation of RTCM–SC104 members, the IGS Bias Working Group and NRCan. The calibration site is located in Ottawa, Canada and operated by Natural Resources Canada. The site hardware and infrastructure is at the initial operation stage.
- RTCM–SC104 Activities:
  - RTCM–Multiple Signal Messages (RTCM–MSM) now support all constellations (with the exception of SBAS (patent issue)). However, approval is still pending for ephemeris messages for Galileo I/NAV and Beidou. RTCM State Space Representation (RTCM–SSR) messages are used by the IGS Real–Time Service.

Currently there are several draft messages being defined (at the interoperability testing stage) they include: GPS and GLONASS phase bias, Vertical TEC (VTEC) and Galileo and QZSS orbit and clock correction messages. At the last meeting (September, 2015) the committee voted to proceed with: the VTEC and Galileo and QZSS Stage 1 messages. However, the GPS and GLONASS phase bias messages were not recommended as the committee determined that there was insufficient interoperability testing. Geo++ are leading this effort and are reassessing their options and deciding how to proceed. At this time IGS partners are using draft experimental message formats (testing and development) and the delay in message approval is not significant. However, if the messages are delayed for too long it could become a problem.

2 Plans in 2016

- Continue to update the RINEX 3.0x documentation to meet the needs of the GNSS community.
- Work with RTCM–SC104 to define a new navigation message to support the contents of the GPS CNAV messages.
- Work with the RINEX WG to define a RINEX CNAV message.
- Release a draft CNAV format in 2016.
- Update RINEX 3.0x to a new version number when there is a significant change (once a year at the most)
- Work with the IGS and RTCM Bias Working group to define the standard operating procedure of the working group. This includes:
  - Equipment and data sharing and observing procedures
  - Work towards having the calibration site in initial operations in the first half of 2016
  - Enter into production in the second half of 2016
  - Data from receivers running released firmware will be freely available. If receiver, beta firmware is being tested access to the data may be restricted (non–disclosure agreement required).
- Attend RTCM–SC104 North American meetings (Loukis Agrotis attends European meetings; Ken MacLeod attends North American meetings).
  - Ensure that RTCM–SC104 messages meet the needs of the IGS and high precision GNSS community.

– Communicate and coordinate IGS partner's needs to the RTCM. Prepare meeting reports for the IGS Governing Board.

3 RINEX WG Membership List

Table 1: RINEX WG Membership

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Tide Gauge Benchmark Monitoring Working Group Technical Report 2015

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1 Introduction

The Tide Gauge Benchmark Monitoring Working Group (TIGA) of the IGS continues its support for climate and sea level related studies and organizations concerned herewith. TIGA provides vertical geocentric positions, vertical motion and displacements of GNSS stations at or near a global network of tide gauges. To a large extend the TIGA Working Group uses the infrastructure and expertise of the IGS.

The main aims of the TIGA Working Group are:

- Maintain a global virtual continuous GNSS Tide Gauge network
- Compute precise coordinates and velocities of GNSS stations at or near tide gauges with a significant delay to allow as many as possible stations to participate. Provide a combined solution as the TIGA official product.
- Study the impacts of corrections and new models on the GNSS processing of the vertical coordinate. Encourage other groups to establish complementary sensors to improve the GNSS results, e.g., absolute gravity sites.
- Provide advice to new applications and installations.

2 Main Progress in 2015

- TIGA Working Group members primarily continued with the reprocessing of the TIGA network. Nearly 800 GNSSTG stations and IGS08b core sites are processed by the TIGA Analysis Centers.
- Two of the TIGA centers significantly contributed to the IGS repro2.
- Members participated in the GLOSS-GE14 in Goa (India); http://ioc-unesco.org/index.php?option=com_oe&task=viewEventRecord&eventID=1534; reports have been given by the TIGA-WG and the SONEL data center
- Participation/reporting in/at the IUGG 2015 (Prague) meeting.
- TIGA Network operator works with Tide Gauge and GNSS station operators to make existing stations available to TIGA
- The TIGA-WG carried forward the GLOSS-Task "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges. Report to Global Sea Level Observing System (GLOSS)" by King, M.A. (2014) for the densification and extension of the TIGA Observing Network to GGOS.

Table 1: TIGA Working Group Members in 2015

Name	Entity	Host Institution	Country
Guy Wöppelmann	TAC, TNC, TDC	University La Rochelle	France
Laura Sánchez	TAC	DGFI Munich	Germany
Heinz Habrich	TAC	BGK, Frankfurt	Germany
Minghai Jia		GeoScience Australia	Australia
Paul Tregoning		ANU	Australia
Zhiguo Deng	TAC	GFZ Potsdam	Germany
Daniela Thaller	Combination	BGK, Frankfurt	Switzerland
Norman Teferle	TAC/Combination	University of Luxembourg	Luxembourg
Richard Bingley	TAC	University of Nottingham	UK
Ruth Neilan	IGS Central Bureau	ex officio	USA
	IGS AC coordinator	ex officio	
Carey Noll	TDC	CDDIS, NASA	USA
Tilo Schöne	Chair TIGA–WG	GFZ Potsdam	Germany
Simon Williams	PSMSL	PSMSL, NOC Liverpool	UK
Gary Mitchum	GLOSS GE (current chair).	University of SouthFlorida	USA
Mark Merrifield	GLOSS GE (past chair)	UHSLC, Hawaii	USA
Matt King		University of Tasmania	Australia

Troposphere Working Group Technical Report 2015

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1 Introduction

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

Dr. Christine Hackman chaired the IGS TWG through December 2015. Dr. Sharyl Byram has chaired it since then and also oversees production of the IGS FTEs. IGS FTEs are produced within the USNO Earth Orientation Department GPS Analysis Division, which also hosts the USNO IGS Analysis Center.

The IGS TWG is comprised of approximately 50 members (cf. Appendix A). A revised charter approved by the IGS Governing Board at the close of 2011 is shown in Appendix B.

2 IGS Final Troposphere Product Generation/Usage 2015

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.

IGS Final Troposphere estimates are generated via Bernese GPS Software 5.0 (Dach et al. 2007) using precise point positioning (PPP; Zumberge et al. 1997) and the GMF mapping function (Boehm et al. 2006) with IGS Final satellite orbits/clocks and earth orientation parameters (EOPs) as input. Each site–day's results are completed approximately three weeks after measurement collection as the requisite IGS Final orbit products become available. Further processing details can be obtained from Byram and Hackman 2012.

Figure 1 shows the number of receivers for which USNO computed IGS FTEs 2011–5. The average number of quality–checked station result files submitted per day in 2015 was 323, slightly lower than the 2014 average value of 326 due to an aging of the station–identification file used to download observations for processing. This station–identification file was updated in December 2015; since then, the average number of station files submitted per day has risen to nearly 350. The result files can be downloaded from `ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd`. 20.9 million files were downloaded in 2015 by users from approximately 1900 distinct hosts (Noll 2016), a marked increase in usage over the 10.3 million files downloaded in 2014.

USNO will use Bernese GNSS Software 5.2 (`www.bernese.unibe.ch/features`) to compute troposphere estimates for the IGS Reprocessing 2 effort (`http://acc.igs.org/reprocess2.html`).

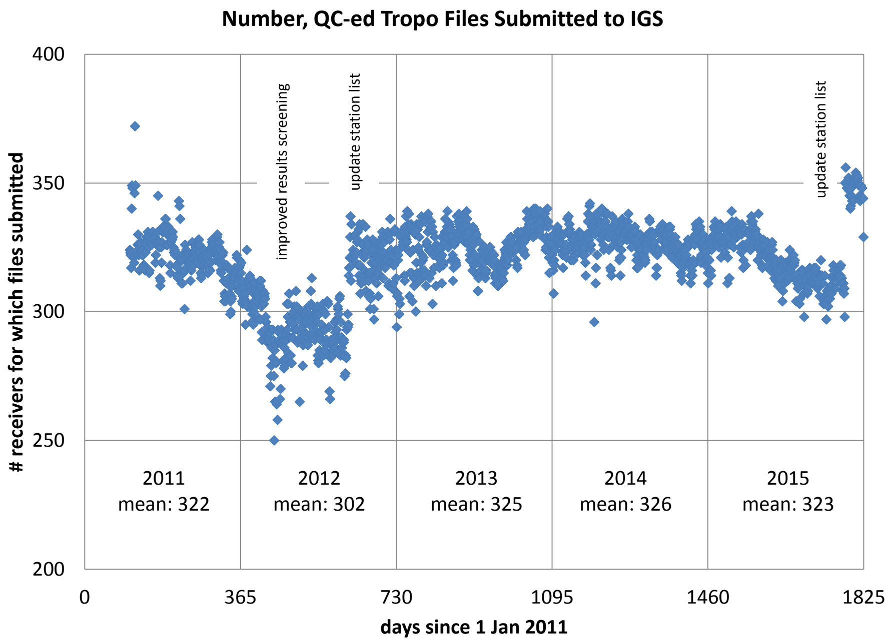

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011-5. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011.)

3 IGS Troposphere Working Group Activities 2015

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 biennial IGS Analysis Workshop.

The group meets twice per year: once in the fall in conjunction with the American Geophysical Union (AGU) Fall Meeting (San Francisco, CA, USA; December), and once in the spring/summer, either in conjunction with the European Geosciences Union (EGU) General Assembly (Vienna, Austria; April) or at the IGS Workshop (location varies; dates typically June/July).

Meetings are simulcast online so that members unable to attend in person can participate. Members can also communicate using the IGS TWG email list.

3.1 Working group meetings

The working group met twice in 2015: on 15 April 2015 at the Technical University of Vienna (in conjunction with EGU) and on 15 December 2015 in San Francisco, CA (in conjunction with AGU).

The April 2015 meeting featured presentations by:

- WG chair C. Hackman on
  - the quality and production of IGS Final Troposphere Estimates
  - the status of current working–group projects
- Dr. Rosa Pacione (e–geos, ASI/CGS[1]; Italy) on
  - the status of `tropo_sinex` standardization efforts (see "Working Group Projects," below)

The December 2015 meeting featured a status report by outgoing–chair C. Hackman on

- quality/production of IGS Final Troposphere Estimates
- current working group projects
- the leadership transition to incoming chair Dr. Sharyl Byram

Presentations from both meetings were distributed via the IGS TWG email list (message IGS–TWG–137) and can be obtained by contacting this report's first author.

[1] Agenzia Spaziale Italiana/Centre for Space Geodesy

3.2 Working group projects

- **Automating comparisons of troposphere estimates obtained using different measurement or analysis techniques**

  One way to assess the accuracy of GNSS–derived troposphere estimates is to compare them to those obtained for the same time/location using an independent measurement technique, e.g., VLBI[2], DORIS[3], radiosondes, or from a numerical weather model. Comparisons of GNSS–derived troposphere estimates computed by different analysis centers or using different models can also serve this purpose.

  The IGS TWG has therefore since 2012 been coordinating the creation of a database /website to automatically and continuously perform such comparisons.

  Dr. Jan Douša, Geodetic Observatory Pecny (GOP; Czech Republic) has been spearheading the development of the database (Douša and Gyõri 2013; Gyõri and Douša 2016), with contributions from other scientists at GOP, GeoForschungsZentrum (GFZ; Germany) and USNO. This database is now beta–complete and open for testing. Interested users can contact Dr. Dousa at `jan.dousa@pecny.cz`. Development of the website by which users can directly view/access the values is underway.

  In 2014, a grant proposal, *Automated Intra– and Inter–technique Troposphere Estimate Comparisons*, made to the Kontakt II Czech–US research partnership by Dr. Douša with supporting documents authored by WG chair C. Hackman, was funded. This funding supports, in addition to other items, travel to the US for joint US–Czech work on the database/website. Dr. Douša thus worked with USNO scientists on further website/database development during a Kontakt II funded USNO site visit 3–13 November 2015.

  Completion of this project is expected in 2016. This system has received interest from climatologists/meteorologists, e.g., those associated with the GRUAN[4] and COST[5] Action 1206 (GNSS4SWEC) projects, as it will simplify quality–comparison and perhaps acquisition of data used as input to their studies.

- **Standardization of the `tropo_sinex` format**

  The IGS Troposphere Working group also supports a project to standardize the **`tropo_sinex format`** in which troposphere delay values are disseminated. At issue is the fact that different geodetic communities (e.g., VLBI, GNSS) have modified the format in slightly different ways since the format's introduction in 1997. For example, text strings STDEV and STDDEV are used to denote standard deviation

[2] Very Long Baseline Interferometry
[3] Doppler Orbitography and Radiopositioning Integrated by Satellite
[4] GCOS (Global Climate Observing System) Reference Upper Air Network: `http://www.gruan.org`
[5] European Cooperation in Science and Technology: `http://www.cost.eu`

in the GNSS and VLBI communities respectively. Such file–format inconsistencies hamper inter–technique comparisons.

This project, spearheaded by IGS Troposphere WG members Drs. Rosa Pacione and Jan Douša, is being conducted within the COST Action 1206 (GNSS4SWEC) Working Group 3. This COST WG consists of representatives from a variety of IAG[6] organizations and other communities; its work is further supported by the EUREF Technical Working Group[7] as well as E–GVAP[8] expert teams. The WG is currently defining in detail a format able to accommodate both troposphere values and the metadata (e.g., antenna height, local pressure values) required for further analysis/interpretation of the troposphere estimates, with progress made in 2015 on a proposed "SLANT/SOLUTION BLOCK". For more information, please contact Dr. Pacione at rosa.pacione@e-geos-it or Dr. Douša.

3.3 Presentation at *FIG Working Week 2015*; preparations for 2016 IGS Workshop

- A presentation highlighting the IGS and its troposphere–related activities, "International GNSS Service (IGS) Troposphere Products and Working Group Activities," authors C. Hackman, G. Guerova, S. Byram, J. Dousa and U. Hugentobler, was delivered by G Guerova 18 May 2015 at FIG[9] Working Week 2015, Sofia Bulgaria, with the corresponding article published in the conference proceedings.
- Incoming chair Dr. Sharyl Byram began organizing troposphere–related activities for the then–future 2016 IGS Workshop, soliciting presenters for the troposphere plenary and poster sessions, and planning the working–group meeting to be held there.

4 How to Obtain Further Information

IGS Final Troposphere Estimates can be downloaded from:
ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd

For technical questions regarding them, please contact
Dr. Sharyl Byram at sharyl.byram@usno.navy.mil

[6] International Association of Geodesy
[7] http://www.euref.eu/euref_twg.html
[8] EUMETNET EIG GNSS Water Vapour Programme; http://egvap.dmi.dk
[9] International Federation of Surveyors; http://www.fig.net

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

- contact Dr. Sharyl Byram at sharyl.byram@usno.navy.mil
- visit its website (under development): http://igs.org/projects-working-groups/twg, and/or
- subscribe to its email list: http://igscb.jpl.nasa.gov/mailman/listinfo/igs-twg

5 Acknowledgements

Development of the troposphere–comparison database/website is supported by KONTAKT II project number LH14089. The authors furthermore thank the Technical University of Vienna (especially J. Boehm, S. Linsmayer and G. Moeller) for hosting the April 2015 working group meeting, IGS/UNAVCO (especially A. Craddock) for providing a room for the December 2015 meeting, and the IGS Central Bureau for the use of its gotomeeting.com subscription.

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Appendix A. IGS Troposphere Working Group Members

Last Name	First Name	Institution	Country
Ahmed	Furqan	Universite du Luxembourg	Luxembourg
Amirkhani	Mohammad	Islamic Azad Univ. Tehran	Iran
Bar–Sever	Yoaz	JPL	USA
Bevis	Mike	OSU	USA
Bock	Olivier	IGN–LAREG	France
Boehm	Johannes	TU Wien	Austria
Bosser	Pierre	ENSG/DPTS	France
Bosy	Jaroslaw	Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences	Poland
Braun	John	UCAR	USA
Byram	Sharyl	USNO	USA
Byun	Sung	JPL	USA
Calori	Andrea	Univ. Roma, La Sapienza	Italy
Cao	Wei	Trimble Terrasat	Germany
Chen	Junping	Shanghai Astronomical Observatory	China
Colosimo	Gabriele	Univ. Roma, La Sapienza	Italy
Crespi	Mattia	Univ. Roma, La Sapienza	Italy
Deng	Zhiguo	GFZ	Germany
Dick	Galina	GFZ	Germany
Dousa	Jan	GOP	Poland
Drummond	Paul	Trimble	USA
Ghoddousi–Fard	Reza	Natural Resources Canada	Canada
Guerova	Guergana	Univ. Sofia	Bulgaria
Gutman	Seth	NOAA	USA
Hackman	Christine	USNO	USA
Heinkelmann	Robert	GFZ	Germany
Herring	Tom	MIT	USA
Hilla	Steve	NGS/NOAA	USA
Hobiger	Thomas	Onsala Space Observatory, Chalmers Univ. of Technology	Sweden
Januth	Timon	Univ. of Applied Sciences, Western Switzerland	Switzerland
Jones	Jonathan	Met Office UK	UK
Langley	Richard	Univ. New Brunswick	Canada
Leandro	Rodrigo	Hemisphere GNSS	USA
Leighton	Jon	3vGeomatics	Canada/UK
Liu	George	Hong Kong Polytechnic University	Hong Kong
Melachroinos	Stavros	Geoscience Australia	Australia
Moeller	Gregor	TU Wien	Austria
Moore	Angelyn	JPL	USA
Negusini	Monia	Inst. Radioastronomy (IRA), National Inst. Astrophysics (INAF)	Italy
Nikolaidou	Thaleia	Univ. New Brunswick	Canada
Nordman	Maaria	Finnish Geodetic Inst.	Finland
Pacione	Rosa	ASI/CGS	Italy
Palamartchouk	Kirill	Univ. Newcastle	UK
Penna	Nigel	Univ. Newcastle	UK

Perosanz	Felix	CNES	France
Pottiaux	Eric	Royal Obs Belgium	Belgium
Prikryl	Paul	Communications Research Centre, Canada	Canada
Realini	Eugenio	GReD – Geomatics Research & Development s.r.l.	Italy
Rocken	Chris	GPS Solutions	USA
Roggenbuck	Ole	BKG	Germany
Rohm	Witold	Univ. Wroclaw	Poland
Romero	Nacho	Canary Advanced Solutions	Spain
Santos	Marcelo	Univ. New Brunswick	Canada
Schaer	Stefan	AIUB	Switzerland
Schoen	Steffen	Inst. Erdmessung, Leibniz Uni Hannover	Germany
Selle	Christina	JPL	USA
Sguerso	Domenico	Lab. Geodesy, Geomatics, GIS; Univ. Genoa	Italy
Soudarin	Laurent	Collecte Localisation Satellites	France
Teferle	Norman	Universite du Luxembourg	Luxembourg
Tracey	Jeffrey	USNO	USA
van der Marel	Hans	TU Delft	Netherlands
Waithaka	Edward Hunja	Jomo Kenyatta U. of Agriculture and Technology	Kenya
Wang	Junhong	UCAR/NCAR	USA
Willis	Pascal	Inst. de Physique du Globe de Paris	France
Xu	Zong–qiu	Liaoning TU	China
Zhang	Shoujian	Wuhan Univ.	China

Appendix B. IGS TROPOSPHERE WORKING GROUP CHARTER

GNSS can make important contributions to meteorology, climatology and other environmental disciplines through its ability to estimate troposphere parameters. Along with the continued contributions made by the collection and analysis of ground-based receiver measurements, the past decade has also seen new contributions made by space-based GNSS receivers, e.g., those on the COSMIC/FORMOSAT mission [1]. The IGS therefore continues to sanction the existence of a Troposphere Working Group (TWG).

The primary goals of the IGS TWG are to:

- Assess/improve the accuracy/precision of IGS GNSS-based troposphere estimates.
- Improve the usability of IGS troposphere estimates.
  - Confer with outside agencies interested in the use of IGS products.
  - Assess which new estimates should be added as “official” IGS products, and which, if any, official troposphere product sets should be discontinued.
- Provide and maintain expertise in troposphere-estimate techniques, issues and applications.

Science background

The primary troposphere products generated from ground-based GNSS data are estimates of total zenith path delay and north/east troposphere gradient. Ancillary measurements of surface pressure and temperature allow the extraction of precipitable water vapor from the total zenith path delay.

Water vapor, a key element in the hydrological cycle, is an important atmosphere greenhouse gas. Monitoring long-term changes in its content and distribution is essential for studying climate change. The inhomogeneous and highly variable distribution of the atmospheric water vapor also makes it a key input to weather forecasting.

Water vapor distribution is incompletely observed by conventional systems such as radiosondes and remote sensing. However, ground- and space-based GNSS techniques provide complementary coverage of this quantity. Ground-based GNSS observations produce continuous estimates of vertically integrated water vapor content with high temporal resolution over a global distribution of land-based locations; coverage is limited over the oceans (where there is no land). Conversely, water vapor can be estimated from space-borne GNSS receivers using ray tracing techniques, in which case solutions with high vertical resolution (laterally integrated over few hundred kilometers) and good oceanic/land coverage are obtained; these solutions however are discontinuous in geographic location and time.

Be it resolved that the IGS troposphere WG will:

- Support those IGS analysis centers providing official IGS troposphere products.
- Increase awareness/usage of IGS troposphere products by members of the atmospheric, meteorology and climate-change communities. Solicit the input and involvement of such agencies.
- Create new IGS troposphere products as needed (as determined by consultation with the potential user community).
- Determine the uncertainty of IGS troposphere estimates through comparison of solutions with those obtained from independent techniques, or through other means as appropriate.
- Promote synergy between space-based and ground-based GNSS techniques through interaction with researchers in both fields.

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