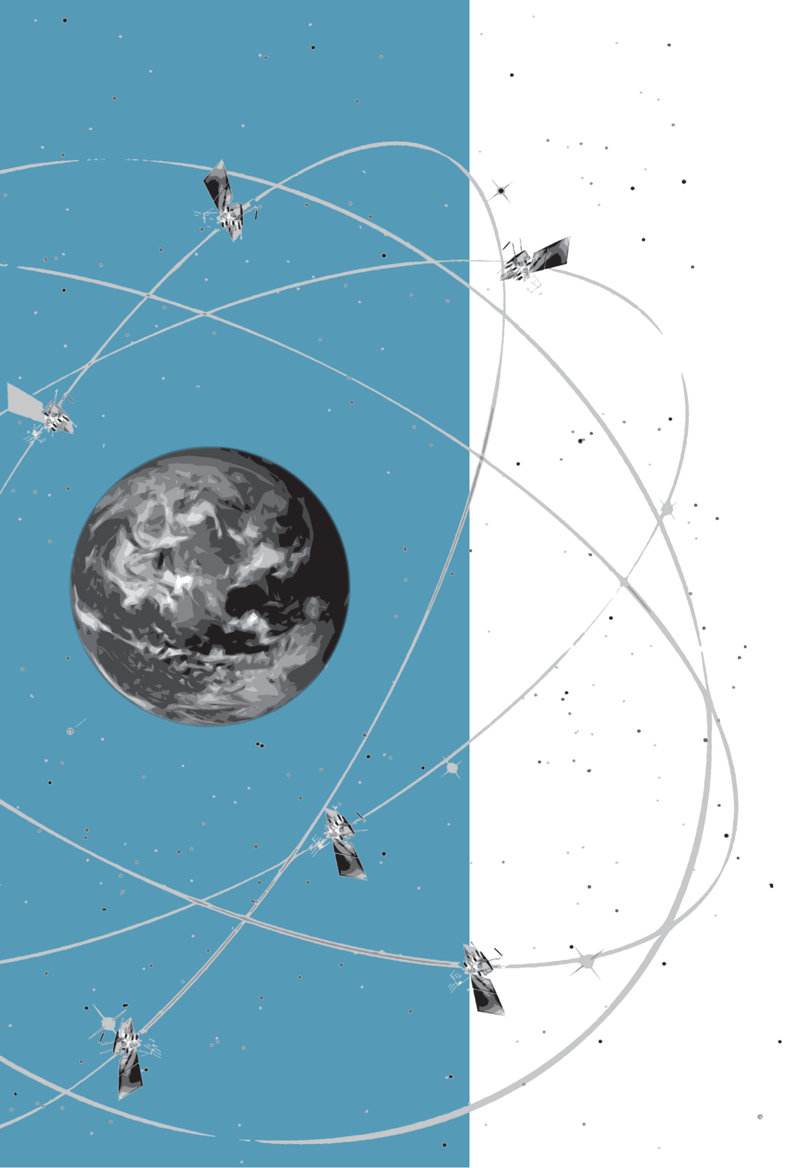
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2014



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IGS INTERNATIONAL GNSS SERVICE

Technical Report 2014

IGS Central Bureau

http://www.igs.org

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Abstract

Applications of the Global Navigation Satellite Systems (GNSS) to Earth Sciences are numerous. The International GNSS Service (IGS), a federation of government agencies, universities and research institutions, plays an increasingly critical role in support of GNSS–related research and engineering activities. This Technical Report 2014 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 2014.

This report is available online as PDF version at
ftp://igs.org/pub/resource/pubs/2014_techreport.pdf.

The IGS wants to thank all contributing institutions operating network stations, data centers or analysis centers or supporting the IGS in any other form. All contributions are welcome. They guarantee the success of the IGS also in future.

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Executive Groups

IGS Governing Board Technical Report 2014

The Development of the IGS in 2014 – *The Governing Board's Perspective*

Urs Hugentobler

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1 Introduction

Since its founding twenty years ago the IGS developed rapidly as a service of the IAG. The IGS tracking network grew from some 30 stations to well over 400 today, with orbit quality improving from a level of several decimeters down to a few centimeters. Since its beginning the IGS provides, on an openly available basis, the highest quality GNSS data, products and services for a large variety of applications that benefit the scientific community and society. This impressive success and achievement of a collaborative effort were commemorated at the anniversary workshop "Celebrating 20 Years of Service" held in June 2014 in Pasadena, California. There were several other accomplishments in 2014, such as the launch of a new website, the extension of the MGEX network to more than 100 tracking sites worldwide, and the revision of the Terms of Reference. But the IGS also continues to face challenges, such as the difficulty to find a new Analysis Center Coordinator. This report describes some highlights, and challenges, in 2014 as well as related GB activities.

2 IGS Operational Activities

The 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. About 440 tracking stations are maintained and operated globally, by many institutions and station operators, making tracking data available at different time latencies, from daily RINEX files to real–time streams. The amount of IGS tracking data and products held by each of the four global Data Centers on permanently accessible servers increased over the last year by 2 TB to a total of 11 TB (135 million files) while significant additional storage capabilities are provided by regional Data Centers. Twelve Analysis Centers and a number of Associate Analysis Centers utilize tracking data from 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. About 700 IGS final, rapid, ultra–rapid and GLONASS–only product files, and 126 ionosphere files are made available per week as well as daily troposphere files for more than 300 stations. A total of 640 million tracking data files (60 TB) and 110 million product files (15 TB) were downloaded in 2014 from CDDIS, one of the four global Data Centers, by more than 10,000 unique hosts – demonstrating the intense interest of users in IGS data and products. The Central Bureau has the responsibility 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 day–by–day basis, with high redundancy and reliability – an impressive effort which is only possible by a strong engagement of many individuals and the support of more than 240 institutions worldwide.

3 IGS Highlights in 2014

The highlight of 2014 was without question the 20th Anniversary IGS Workshop. It demonstrated that with constructive collaboration, the IGS has accomplished over the past twenty years what no single entity could do alone and provided the forum to discuss the future developments of our service. On August 28 the launch of the new and extensively reorganized IGS website at www.igs.org, which was developed with strong support from UNAVCO, could be announced. Our Real–Time Service is running smoothly and with an availability exceeding 99% under the auspice of our Real–Time Analysis Coordinator. At the end of 2014, about 500 users from 66 countries worldwide were registered at the CB, most of them from academia, from engineering services and from GNSS equipment and software manufacturers. The MGEX network has grown to some 120 multi–GNSS tracking stations. Six Analysis Centers compute orbits for three new satellite systems. A RINEX3 transition plan, developed under the guidance of the Infrastructure Committee, was endorsed by the Governing Board; the plan defines the steps required for a transition to long filenames for RINEX3 files, a prerequisite for the transition of the multi–GNSS IGS activities into routine operations. The reprocessing activities are almost completed with the contribution to ITRF2014 being finalized. The 2014 highlights were accompanied by several major challenges, the most important being the departure of Jake Griffiths as Analysis Center Coordinator.

4 IGS Workshop "Celebrating 20 Years of Service"

The highlight of 2014 was the IGS workshop held from June 23 to 27 in Pasadena, California, USA, where 189 attendees celebrated 20 years of service. It was a forum to look back to the impressive achievements of the IGS in the last twenty years, to determine the status of the IGS today, and to discuss the steps for the next twenty years in fruitful technical, organizational and strategic discussions.

Rolf Dach, as the chair of the Scientific Organizing Committee, together with Shailen Desai and Andrzej Krankowski, put together an excellent scientific program, while the Local Organizing Committee, led by Ruth Neilan and Steve Fisher, strongly supported by Allison Craddock, made sure that we could work in an excellent environment taking advantage of the facilities of the CalTech Campus. The workshop format allowed enough time for discussions and splinter meetings. The program included an ice breaker party, a conference dinner and an Anniversary Colloquium, and was complemented by thrilling matches transmitted from the Soccer World Championships in Brazil. During the breaks we were served excellent coffee, and the whole week was favored by the best Californian weather.

The scientific program included plenary and poster sessions focusing on the Real–Time Service and its applications, the progress and developments in the MGEX project, the IGS infrastructure, antenna calibrations, format issues, the reference frame and the reprocessing effort, orbit modeling effects in IGS products, ionosphere and troposphere modeling, and diverse applications of IGS products. The workshop presentations, posters, and recommendations, including videos recorded from the presentations, can be found at http://igs.org/presents. The Workshop compendium is available at http://kb.igs.org/hc/en-us/articles/204895687.

5 Revision of Terms of Reference

After a first discussion of modifications of the Terms of Reference (ToR) at the December 2013 GB meeting the proposed changes prepared by the CB and Executive Committee were extensively discussed at the June 2014 GB meeting and approved by email vote on October 15, 2014. The new ToR include three important changes:

1. The mission statement of the IGS was updated, now explicitly mentioning the open availability of data and products as a basic principle of the IGS.
2. In order to underline the importance of the IGS Real–Time Service the Real–Time Analysis Coordinator was designated a voting member of the GB. The number of voting members thus was increased up to 19 and Loukis Agrotis, the IGS Real–Time AC was welcomed as a new member of the GB.

3. The position of a Chair–elect as non–voting member was installed in order to allow for a smoother transition from one GB chair to the next with an overlap period of at least one year.

Finally, the definition of the different product types was cleaned up throughout the text.

6 Governing Board Meetings in 2014

The GB discusses the activities of the various components, sets policies and monitors the progress with respect to the agreed strategic plan using newly developed tools. The Board met three times in 2014. A GB business meeting took place on April 27 associated with the EGU General Assembly in Vienna, the 43rd GB meeting took place on June 22 with a wrap–up meeting on June 27. The 44th GB meeting, the regular end–of–year meeting, took place on December 15 during the AGU Fall Meeting in San Francisco. The IGS Executive Committee – consisting of Urs Hugentobler, Chuck Meertens, Ruth Neilan, Chris Rizos, Tim Springer and with regular participation of Steve Fisher, Allison Craddock, and of WG Chairs as required – has met five times in 2014 by teleconference. Topics covered at the different meetings included the preparations for the IGS Workshop in June, the update of the Terms of Reference, the progress of the Multi–GNSS Experiment, Real–Time Service and RINEX3, the launch of the new IGS website, and the search for a new ACC.

A summary of the GB meeting in December 2014 may be found in IGS Mail 7024 and in the IAG Newsletter of January 2015. Tab. 1 lists the important events in 2014.

Table 1: IGS events in 2014

Date	Event
Apr. 27	GB Business Meeting in Vienna (EGU)
Jun. 22	43rd GB Meeting in Pasadena with wrap–up meeting on June 27
	– Reappointment of Chuck Meertens for a further term of four years
	– Extension of MGEX project until end of 2015
Jun. 23–27	IGS Workshop “Celebrating 20 Years of Service” in Pasadena, USA
Oct. 15	Updated Terms of Reference approved by the GB
	– Loukis Agrotis new voting member of the GB
Dec. 15	44th GB Meeting in San Francisco (AGU)
	– Gary Johnston elected as new Chair of the GB
	– Rolf Dach elected as Analysis Center Representative
	– Carine Bruyninx re–elected as Network Representative

7 Governing Board Membership

A number of changes in the GB membership took place in 2014. As the term of Urs Hugentobler as Chair of the GB ended 2014, a Search Committee consisting of Urs Hugentobler (Chair), Chris Rizos and John Dow sought candidates for the position. Marek Ziebart (University College London) and Gary Johnston (Geoscience Australia) were ready to stand for election by the GB and gave very strong and visionary statements on their ideas for the future development of the IGS. Both received strong support by the voting members of the GB. However Gary Johnston was elected as the new Chair of the IGS for 2015–2018.

Two positions were up for elections, namely an Analysis Center Representative and a Network Representative, as the terms of Urs Hugentobler and Carine Bruyninx ended at the end of 2014. Six candidates agreed to stand in the elections, which were organized by a Nominating Committee consisting of Chuck Meertens (Chair), Carey Noll, and Ralf Schmid. The candidates were Rolf Dach, Mathias Fritsche and Tom Herring as Analysis Center Representatives, and Carine Bruyninx, Ludwig Combrinck and Yuki Hatanaka as Network Representatives. All candidates received strong support from the Associate Members. As a result of the election Rolf Dach (University of Bern, Switzerland) was elected as Analysis Center Representative and Carine Bruyninx (Royal Observatory of Belgium, Brussels) was re–elected as Network Representative.

With the update of the Terms of Reference the Real–Time AC became a voting member of the GB. Loukis Agrotis (ESA/ESOC) was welcomed as a new voting member of the GB in October 2014. Unfortunately Jake Griffiths decided to leave NGS and ended his position as Analysis Center Coordinator on May 18. Jake's departure was a severe loss to the IGS; his position was taken over by Kevin Choi who demonstrated excellent competences as coordinator of the IGS analysis activities.

All WG chairs whose terms concluded at the end of 2014 were unanimously extended by the GB until 2016 based on their contributions as demonstrated at the IGS Workshop: Andrzej Krankowski as Chair of the Ionosphere WG, Oliver Montenbruck as Chair of the Multi–GNSS WG, Stefan Schaer as Chair of the Bias and Calibration WG, Ralf Schmid as Chair of the Antenna WG, Tilo Schöne as Chair of the TIGA WG, and Marek Ziebart as Chair of the Space Vehicle Orbit Dynamics WG. Tab. 2 lists the members of the IGS Governing Board for 2014.

8 Outreach

The IGS is well represented on the GGOS Coordinating Board. It plays a leadership role in the International Committee on GNSS (ICG), co–chairing Working Group D on Reference Frames, Timing and Applications, and facilitating a resolution for use of ITRS by all GNSS providers, and the International GNSS Monitoring and Assessment (IGMA) Subgroup within ICG Working Group A. In these roles the IGS participated in the ICG–9 meeting in November 2014 in Prague, Czech Republic. 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.

IGS has been involved with many outreach activities in 2014. The following list provides a selection of presentations at international meetings and articles in geospatial magazines. As in previous years the IGS was also given visibility as session organizers of, or presenters in, IGS–related sessions at conferences such as those of the EGU in Vienna and AGU in San Francisco.

Selection of presentations at international meetings:

- Munich Satellite Navigation Summit 2014, Munich, Germany, March 26, Panel Discussion with Georg Weber in session "Precise Point Positioning" on IGS Real–Time Service.
- Munich Satellite Navigation Summit 2014, Munich, Germany, March 27, Munich, Panel Discussion with Chris Rizos and Urs Hugentobler in session "Monitoring of the System Earth and Disaster Monitoring" on IGS products.
- Chinese Satellite Navigation Conference 2014, Nanjing, China, May 12–15, Montenbruck, Hugentobler, Steigenberger: "Recent Progress of IGS Multi–GNSS Experiment".
- Wuhan University, Wuhan, China, May 26, Montenbruck, Hugentobler, Steigenberger: "The IGS Multi–GNSS Experiment (MGEX)".
- Hong Kong Polytechnic University, HK, May 28, Rizos: "The International GNSS Service (IGS) in a Multi–Constellation GNSS World".
- FIG Congress, Kuala Lumpur, Malaysia, June 19, Rizos: "The IGS in a Multi–GNSS World".
- 6th Asia–Oceania Regional Workshop on GNSS, Phuket, Thailand, October 9–11, Rizos: "IGS Activities in Multi–GNSS and Real–Time Service".
- 9th Meeting of the ICG, Prague, Czech Republic, November 9–14, Rizos, Neilan: "The IGS in its 20th Anniversary Year: New GNSS Activities Related to MGEX and the Real–Time Service".

Reports, Brochures, Flyers:

- Technical Report 2013
- IGS Network Fact Sheet
- Contribution to IERS Annual Report 2012

9 Outlook

The year 2015 poses a number of challenges. The transition to RINEX3 was approved and has to be implemented in the course of 2015. The Multi–GNSS Experiment is progressing towards a Pilot Service, the network is further extended, new satellites are launched, and the tracking data will be integrated into the standard IGS directory trees. It is the task of the Governing Board to define the criteria triggering the end of the experiment phase based on a concept note that will be drafted during 2015. A new ionosphere scintillation product is under preparation. The Real–Time Service is moving towards Full Operational Capability. To define the next steps forward the RT WG Chair plays a pivotal role and the vacant position should again be filled.

Most critical is the transition to a new Analysis Center Coordinator by the end of 2015, a task of the highest priority. The challenge to find the next ACC also indicates that after 20 years the existence of the IGS cannot be taken for granted. The permanent operation of the IGS requires an every–day effort by the engaged institutions and many enthusiastic individuals. Continuous effort is required to increase the sustainability of the Service, which is today indispensable for numerous applications.

As outgoing Chair I would like to thank the Governing Board members for the cooperation and support they have given over the past four years, as well as all those associated with the IGS for their continuing effort and support for advancing our Service. The IGS remains an impressive organization, with a large number of individuals from many institutions from all over the world devoting their expertise and investing their time to the IGS in an exemplary spirit of cooperation. I wish our new GB Chair all the best and much success in leading the IGS into an exciting future.

Table 2: IGS Governing Board Members 2014 (*: voting members, §: Executive Committee)

Member	Affiliation	Country	Function
Urs Hugentobler*§	TU München	Germany	Board Chair Analysis Center Representative
Loukis Agrotis*	ESA/ESOC	Germany	Real–Time Analysis Coordinator (since Oct. 2014)
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 Géographique et Forestière	France	IERS Representative
Carine Bruyninx*	Royal Observatory of Belgium	Belgium	Network Representative
Mark Caissy	Natural Resources Canada	Canada	former Real–Time WG Chair
Michael Coleman*	Naval Research Laboratory	USA	Clock Product Coordinator
Yamin Dang*	Chinese Academy 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	Reference Frame Coordinator, IGS Representative to IAG Sub–commission 1.2
Jake Griffiths*	NOAA, NGS	USA	Analysis Center Coordinator (replaced by Kevin Choi in May 2014)
Christine Hackman	USNO	USA	Troposphere WG Chair
Gary Johnston*	Geoscience Australia	Australia	Appointed
Satoshi Kogure*	JAXA	Japan	Appointed
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
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	President of IAG since July 2011 (before: appointed)
Ignacio Romero	ESA/ESOC	Germany	Infrastructure Committee Chair
Laura Sanchez*	DGFI	Germany	Network Representative
Stefan Schaer	Swisstopo	Switzerland	Bias and Calibration WG Chair
Ralf Schmid	DGFI	Germany	Antenna WG Chair
Tilo Schöne	GFZ Potsdam	Germany	TIGA WG Chair
Tim Springer*§	ESA/ESOC	Germany	Analysis Center Representative IGS Representative to IERS Chair of Associate Members Committee
Marek Ziebart	University College London	UK	Space Vehicle Orbit Dynamics WG Chair

IGS Central Bureau Technical Report 2014

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1. NASA/Jet Propulsion Laboratory, Caltech, Pasadena, California
2. Raytheon, Inc., Pasadena, California
3. UNAVCO, Inc., Boulder, Colorado
4. SBAR, Inc., Pasadena, California

1 Introduction

The Central Bureau supports IGS focusing on two principal functions: 1) executive management of the service, including international coordination and outreach, and 2) coordination of IGS infrastructure, including the IGS tracking network and the CB information system (CBIS) where the IGS web, ftp and mail services are hosted. Specific responsibilities of the Central Bureau are outlined in the IGS Terms of Reference (see `www.IGS.org`).

The CB is hosted at the California Institute of Technology/Jet Propulsion Laboratory and is funded by NASA. It contributes significant staff, resources and coordination to advance the IGS mission.

In 2014, the CB staff included part time contributions by the individuals listed in Tab. 1 together with their corresponding roles within the CB. Regrettably, funding limitations have resulted in an approximate 1.5 fte reduction in the CB staff since October 1 that is anticipated to continue through at least the NASA fiscal year ending in September 2015.

2 Board Participation

R. Neilan and S. Fisher continued to fulfill designated GB responsibilities on behalf of the CB in 2014. The entire CB staff helps to facilitate the GB meetings and interaction, and

Table 1: Central Bureau staff members 2014

Name	Role
Ruth Neilan	Director
Steve Fisher	Operations Manager
Gaurav Walia	Development Manager
Robert Khachikyan	Information Systems Manager
	Co–Network Coordinator (through September)
David Maggert	Co–Network Coordinator
Gary Mize	Database/web Developer
Juan Ceva	Management Support
Allison Craddock	Outreach and Communications Specialist

acts on behalf of the GB to implement decisions and defined action items. Three meetings of the Governing Board were coordinated in 2014 (Vienna/April, Pasadena/June, and San Francisco/December), as well as 5 tele–conference meetings of the Executive Committee through the year. Minutes of these meetings are available by request from the CB. The CB also continued participating on other IAG and services Boards in 2014: R. Neilan participates on the GGOS Coordinating Board and Executive Committee and S. Fisher fulfills one of the two IERS Directing Board positions allocated to IGS (though NASA support for this activity was temporarily suspended due to budgetary constraints as of October 1).

3 Associate Members and GB Elections

The CB helped the IGS Associate Member Committee review and renew the IGS Associate List, which is done routinely every other year, and supporting the Governing Board and Chair elections by operating the online polling system. The current Associate Member and GB Member lists are available online at http://igs.org/about/organization.

4 Terms of Reference Review

A review of the IGS Terms of Reference was facilitated by the CB and approved during the December GB meeting. The updated version has been published online at http://kb.igs.org/hc/en-us/articles/204189428.

5 IGS 20th Anniversary Workshop Organization

All of the local preparations, registrations and coordination with program committee were conducted by the CB. Approximately 190 people attended the 5 day long workshop, which included plenary presentations, Working Group splinter meetings, posters and social events. Information about the Workshop, including the key recommendations that were developed, are published online at http://kb.igs.org/hc/en-us/sections/200369263.

6 Strategic Plan/ Progress

The year of 2014 marked the second full year of formal monitoring of progress on Strategic Plan objectives. The 2014 update of the IGS Dashboard of performance metrics tracked by the CB is published online at http://kb.igs.org/hc/en-us/sections/200623533. The 2015 Strategic Implementation Plan which defines the principal IGS activities through the year was compiled by the CB with input from the Component leads and approved by the GB during the December meeting. It is published online at http://kb.igs.org/hc/en-us/sections/200287408.

7 Website Development

The updated IGS website was released in beta in May for broad review by IGS participants and users. The first production release in October marked the official switchover to the new site, though the old website remnants active for legacy purposes. With this release, the phase I development goals were completed that resulted in the following improvements in 2014:

- New navigation and graphics were introduced.
- All content was re written or otherwise updated.
- A consistent template for WG content was introduced and working with WGs to improving information content.
- Most key processes have been migrated to globally available external servers.
- Knowledge Base functionality was implemented and populated with all relevant information from the old IGS website.
- Workflows for backup and disaster recover across all CB servers were reviewed and documented.

- The Site Log Manager database application was released for production use by the IGS station operators
  - Completed testing phase, now in production with approximately 45 registered users representing all of the largest station operators and a majority of stations.
  - The database has been populated with all categories of IGS stations – full IGS, MGEX, RTS, proposed, dormant, etc.
  - The external user interface is via the website network page.
  - Information is updated by the Station Operators either within the database or by text or XML log exchange.
  - Supporting XML metadata exchange, scripts schema implemented, have identified improvements to this that we are coordinating through the data center WG.
  - Database is used to generate the main IGS SINEX file, working on a single unified SINEX file that includes additional select MGEX and RTS stations to be fully integrated within IGS.
  - Participated in 2014 IGS Workshop with poster and breakout demonstration of the Site Log Manager.
  - Videos and user documentation are in the KB at `http://kb.igs.org/hc/en-us/sections/200562873`.

8 Network/station management

There are 453 official stations within the IGS network at the end of 2014. Eighteen new stations were added in the past year (Tab. 2) that required significant coordination with station operators in processing the applications, and verifying station meta data and data files. Five stations that had been decommissioned in 2014 were deleted from the active network list. Additional site data and meta data were processed and verified for 17 new MGEX (now totaling 115) stations, and processing and verification of metadata for 18 NGA stations whose historical data was provided to IGS was completed. Thirty–nine new equipment models were added to the `rcvr_ant.tab` and available sketches with their ARP definitions were added to the `antenna.gra`.

Table 2: New IGS stations in 2014

Station	Location
ARUC	Aruch–Yerevan, Armenia
DAKR	Dakar, Senegal
GODN	Greenbelt, MD, USA
GODS	Greenbelt, MD, USA
GRAC	Caussols, France
JFNG	Jiufeng, China
KIRI	Betio, Kiribati
KRGG	Kerguelen Islands
MELI	Melilla, Spain
METG	Metsahovi, Finland
NAUR	Nauru, Nauru
POHN	Pohnpei, Micronesia
SEYG	Pointe Larue, Seychelles
TONG	Naku'alofa, Tonga
TUVA	Funafuti, Tuvalu
SEJN	Sejong, Korea
LCK3	Lucknow, India
LKC4	Lucknow, India

9 Project Support, Committee and Working Group Participation

The CB has continued to broadly support the IGS Working Groups and Projects. Progress in 2014 has included:

- Regular coordination with IC on broad range of network and other matters, participating in RINEX3 transition planning.
- Operate RTS website, caster, user registrations, user support. Maintain redundant station streams from 75 priority stations. Participate in RT WG activities to develop the IGS/RTS network.
- Coordinating with COSMIC to participate within IGS, helping to define COSMIC/LEO ground subnetwork and shared stations.
- Supporting MGEX website, integrated MGEX station meta data within SLM.
- Participate on Antenna WG and maintain antenna and equipment files on IGS website.
- Interface with all other WGs as necessary on a variety of topics.

Table 3: External meetings where the CB participated in 2014

Month	Location
January	Geneva, Switzerland (IAG/GGOS Plenary Session)
February	Greenbelt, MD (IGS/SGP Meetings at Goddard)
March/April	Paris, France (10^{th} Meeting of WDS Science Committee)
April	Vienna, Austria (SGP Programmatic Meetings)
May	Boulder, CO (IGG10 location scouting/planning with State Department and UN–OOSA)
July	New York, NY and Washington, DC (UN GGIM, GGOS Forum, plus SGP meetings at Headquarters)
August	Boulder, CO (Programmatic meetings with UNAVCO and UCAR)
October/November	New Delhi, India (SciDataCon 2014)
November	Prague, Czech Republic (ICG–9)
December	Washington, DC (PNT Advisory Board Meeting, Programmatic meetings NASA HQ)
December	San Francisco, CA (IGS and GGOS Board and related meetings)

10 IGS User Support

The CB provides the first level of technical and other support on behalf of IGS to anyone who inquires through the IGS website and CB mail (support@ and cb@). In 2014 just over 2900 emails were sent through these addresses, which is consistent with the last several years that this has been monitored by the CB. The Knowledge Base support system that was implemented this year includes trouble ticketing functionality which we have integrated with the current e–mail based support system to help provide better response and efficient tracking of support issues.

11 Outreach/External Participation

The CB has continued to aggressively reach out to external stakeholders on behalf of the IGS by broadly participating in external meetings that relate to the IGS interests (Tab. 3), participating in policy interactions with various groups (Tab. 4), and by promoting standards for the open exchange GNSS data, products and information with the appropriate standards organizations (Tab. 5).

Table 4: Policy interactions where the CB participated in 2014

	Organization	CB's role/activities
UN	International Committee on GNSS	CB co–chairs the WG–A activities and is supporting planning for the 10^{th} Anniversary ICG Meeting
UN	GGIM Global Geodetic Reference Frame WG	CB participates on the WG on behalf of IGS
ICSU	World Data System	CB represents IGS membership in WDS
IAG	Global Geodetic Observing System	CB Director is a Coordinating Board and EC member
NASA		CB routinely interacts within NASA on GNSS and related policy matters within the US government and scientific organizations

Table 5: Standards for open GNSS data and exchange supported by the CB in 2014

Group	Activities
IGS Infrastructure Committee	GNSS site and networks standards
IGS Antenna Working Group	Maintenance of the IGS equipment files
RTCM/RINEX WG	Participate RINEX3 activities
RTCM/Real–time GNSS	Participate RTCM SC–104 activities
IGS Data Center WG	Participating in XML definition for exchange of site metadata, extending upon scripts definition
UN–ICG	Participate in interchangeability/interoperability monitoring standards definition

12 Funding Development

Although the CB extended considerable programmatic effort to sustain its funding, now through the NASA/Space Geodetic Program, CB funding was reduced significantly from 2013 levels.

13 IGS Institute (IGSI)

IGSI is now an essential, integral part of the CB. In 2014, the IGSI:

- Business plan was updated (available by request).
- Supported registrations and vendor contracts for the Pasadena Workshop.
- Supported website/IT, branding and marketing activities.
- Is developing capacity/programs to accept contributions to support IGS activities to be pursued in 2015.

14 Publications

- 2014 IGS Performance Dashboard
- IGS 2013 Technical Report section
- 2012 IERS Annual Report – IGS section
- 2014 Workshop Compendium
- SGP/ICO project plan and activity report
- Updated RTS and Network brochures, solicited other WG's to provide one page summary brochures for IGS portfolio.
- Reviewed quality of service table and found that no updates are needed

Part II

Analysis Centers

CODE Analysis Center Technical Report 2014

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1 The CODE consortium

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

- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland
- Federal Office of Topography swisstopo, Wabern, Switzerland
- Federal Agency of Cartography and Geodesy (BKG), Frankfurt a. M., Germany
- 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 usually carried out at IAPG, TUM. All solutions and products are generated with the latest development version of the Bernese GNSS Software (Dach et al. 2007).

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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

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 clock product related to the final rapid orbit, clock RINEX format
CODwwwwd.CLK_R	CODE early rapid clock product, 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

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

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

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

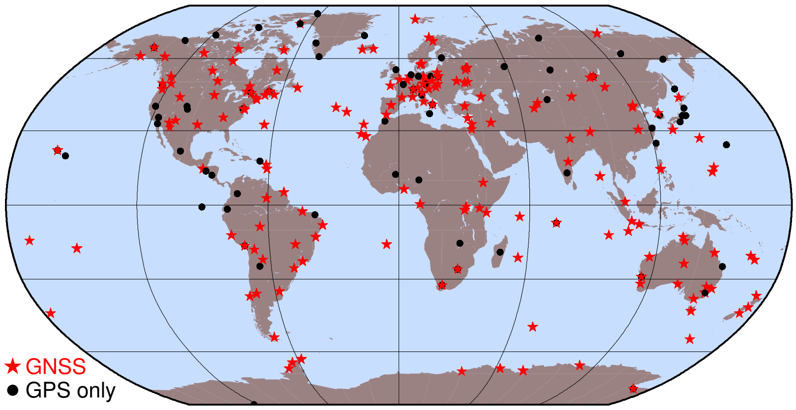


Figure 1: Network used for the GNSS final processing at CODE by the end of 2014.

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).

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. 2014.

In Sect. 3.1 we give an overview of important development steps in the year 2014. Section 3.2 describes the new generation of the CODE rapid products and Section 3.3 provides details on the extended empirical orbit model used at CODE.

3.1 Overview of changes in the processing scheme in 2014

Table 3 gives an overview of the major changes implemented during year 2014. Details on the analysis strategy can be found in the IGS analysis questionnaire at the IGS Central Bureau (ftp://ftp.igs.org/pub/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 2014

Date	DoY/Year	Description
16-Mar-2014	075/2014	Vienna non–tidal atmospheric pressure loading model switched from version 2 to 4 (no effect on the products because it is deactivated with scaling factors, see Dach et al. 2013)
04-Jun-2014	155/2014	Major revision of the ultra–rapid and rapid product generation: • Separated product generation and NEQ manipulation to significantly speed up the processing • Automatic datum definition verification • *New:* SINEX from ultra-rapid solution, currently with daily resolution of the Earth rotation parameters • Setup of Z (and X/Y) satellite antenna offsets (Z included in SNX) • A new product line extracted from the middle day of a rapid and ultra-rapid solution is implemented
10-Jun-2014	158/2014	Start to produce bias-SINEX (BIA) result files from ionosphere processing
10-Jun-2014	160/2014	Start to submit middle-day solutions for the IGS rapid combination from a subsequent ultra-rapid solution
12-Jun-2014	162/2014	Start to post the middle-day submissions to the IGS separately with the label _M files to ftp server
22-Sep-2014	264/2014	Increase the number of stations in the clock final solution (new limit is 150)
23-Sep-2014	265/2014	Increase the number of stations in the clock rapid solution (new limit is 120)
24-Sep-2014	266/2014	Clock rapid: backsubstitution of epoch parameters using only phase measurements (as done in final clock estimation)
14-Nov-2014	292/2014	Global ionosphere map estimation completely redesigned, temporal resolution increased from 2 hours to 1 hour
03-Dec-2014	337/2014	Activate a completely revised RINEX data download system: • Efficient download with a multi–threading Perl tool • Construct an XML database on the content of each RINEX file • Evaluation of the XML database instead of the original RINEX files for observation statistic generation
16-Dec-2014	347/2014	Improvement in the program for Helmert Transformation to be used for the automated datum definition verification

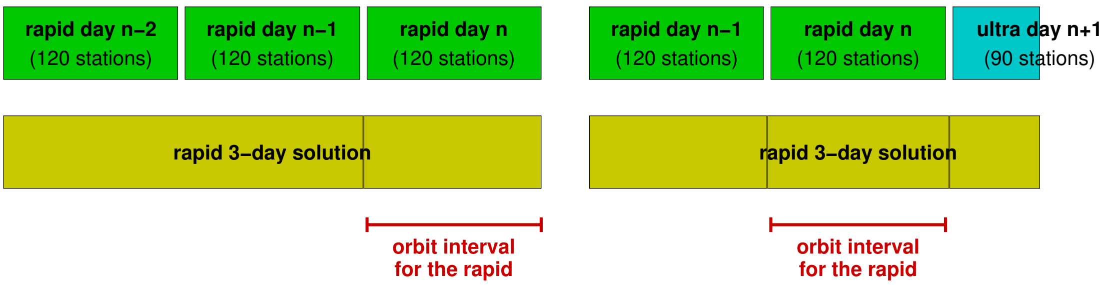
3.2 Enhancing the CODE rapid product generation

The procedure to compute ultra-rapid solutions at CODE was deeply revised in 2013 (reported in Lutz et al. 2014). The processing of the observations results in normal equation (NEQ) files from which different ultra-rapid solutions can be derived. Each ultra-rapid update may produce in the same way also a solution taylored for the IGS rapid solution with a set of Earth rotation parameters (offset and drift) referring to noon and an estimated orbit arc from midnight to midnight for the day before the ultra-rapid solution itself.

Starting with day 155 of year 2014 (04–June–2014) the traditional rapid solution from CODE is submitted as the "early rapid solution" in the morning. In that case the orbit is extracted from the end of a three day solution (see Figure 2(a)). By construction this orbit is extracted from the most uncertain part of the arc.

The quality of the orbit can significantly be improved if the orbit arc is continued what is, e.g., done with the subsequent ultra-rapid runs as illustrated in Figure 2(b). The submission schedule for the IGS rapid allows to update the rapid solution extended by the normal equation from the ultra-rapid computation for 12:00 UTC. This new so-called "final rapid solution" is used to replace the previously submitted CODE rapid solution for the combination.

Even if the extension of the orbit is only based on an ultra-rapid solution considering for instance a lower number of tracking stations, the quality of the GNSS orbits in the "final rapid solution" is already close to those in the CODE final orbits. For applications that are not so critical in time, these orbits may be interesting. For that reason they are specifically indicated with _M on the AIUB's FTP server (see Table 1). This allows to use the availability of these files to trigger a certain processing based on these new "final rapid solution".



(a) Early rapid solution

(b) Final rapid solution

Figure 2: Principle to extract the early and final rapid products from the rapid and subsequent ultra–rapid solutions.

3.3 Studies for Updating the 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

$$\vec{e}_D \doteq \frac{\vec{r}_\mathrm{s} - \vec{r}}{|\vec{r}_\mathrm{s} - \vec{r}|}\,,\ \vec{e}_Y \doteq -\frac{\vec{e}_r \times \vec{e}_D}{|\vec{e}_r \times \vec{e}_D|}\,,\ \vec{e}_B \doteq \vec{e}_D \times \vec{e}_Y\,, \tag{1}$$

where $\vec{r}_\mathrm{s}$ and $\vec{r}$ are the geocentric vectors of the Sun and the satellite, respectively, and $\vec{e}_r$ is the unit vector associated with $\vec{r}$. The vector $\vec{e}_D$ is the unit vector in the direction satellite-Sun, $\vec{e}_Y$ points along the satellite's solar panel axis, and $\vec{e}_B$ completes the orthogonal system. The total acceleration of a satellite due to solar radiation pressure can then be written as

$$\vec{a} = \vec{a}_0 + D(u)\vec{e}_D + Y(u)\vec{e}_Y + B(u)\vec{e}_B\,, \tag{2}$$

where $\vec{a}_0$ is a selectable a priori model, and where u is the satellite's argument of latitude. 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. Springer et al. 1999 proposed the so-called reduced ECOM,

$$\begin{aligned} D(u) &= D_0 \\ Y(u) &= Y_0 \\ B(u) &= B_0 + B_\mathrm{c}\cos u + B_\mathrm{s}\sin u\,, \end{aligned} \tag{3}$$

which was used for the IGS contributions of CODE until 5 January 2015. Up to 2005 the reduced ECOM was set up on top of the ROCK-T models, then on top of an a priori model derived from the parameters of the ECOM (Springer et al. 1999; Dach et al. 2009). From July 2013 to January 2015 the reduced ECOM was used at CODE without any a priori model $\vec{a}_0$, after having implemented albedo modeling.

When applied to GLONASS satellites, the ECOM reveals shortcomings, which map into spurious signals in time series of geophysically interesting parameters, like geocenter coordinates or Earth rotation parameters (ERPs). These problems grew creepingly with the increasing influence of the GLONASS in recent years (Meindl 2011; Meindl et al. 2013). Rodriguez-Solano et al. 2014 documented a significant reduction of the spurious signals by replacing the reduced 5-parameter ECOM for GPS and GLONASS by an adjustable box-wing model.

The mentioned problems asked for a thorough review of the ECOM. Arnold et al. 2015 showed that the largest deficit of the ECOM, when applied to GLONASS satellites (which are of an elongated shape), is the lack of periodic terms in the $\vec{e}_\mathrm{D}$-direction. Guided by

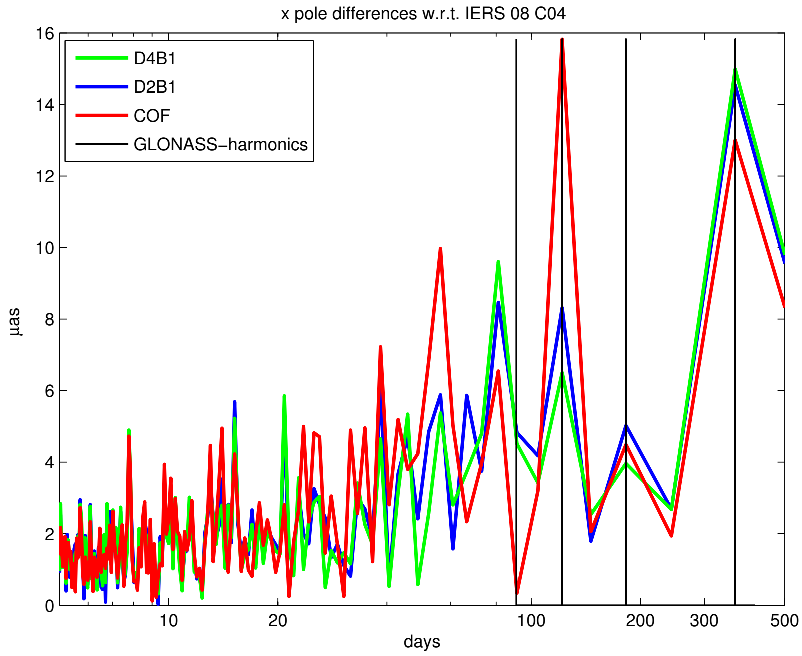


Figure 3: Amplitude spectra of differences of the polar motion coordinate x w. r. t. IERS 08 C04 for solutions obtained using the old ECOM (COF) and the extended ECOM with periodic D-terms up to 2pr (D2B1) and 4pr (D4B1). The spurious amplitude at 120 days is significantly reduced by the new ECOM.

theoretical considerations and the spectral analysis of accelerations predicted by a priori models, the authors proposed the following extended ECOM:

$$\begin{aligned} D(u) &= D_0 + \sum_{i=1}^{n_D} \{D_{2i,\mathrm{c}} \cos 2i\Delta u + D_{2i,\mathrm{s}} \sin 2i\Delta u\} \\ Y(u) &= Y_0 \\ B(u) &= B_0 + \sum_{i=1}^{n_B} \{B_{2i-1,\mathrm{c}} \cos(2i-1)\Delta u + B_{2i-1,\mathrm{s}} \sin(2i-1)\Delta u\} \ , \end{aligned} \tag{4}$$

where $\Delta u \doteq u - u_\mathrm{s}$, 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. The introduction of these terms significantly reduced the spurious signals in time series of geocenter coordinates and ERPs (see Fig. 3), slightly decreased the orbit misclosures at the day boundaries and considerably reduced spurious patterns in residuals obtained within an SLR validation of the GNSS satellite orbits.

As a result of the review of the ECOM performed in Arnold et al. 2015, the CODE IGS contributions are based on the extended ECOM (4) with $n_\mathrm{D} = 2$ and $n_\mathrm{B} = 1$ (i. e., including up to 4pr terms in D and 1pr terms in B) since 4 January 2015 (GPS week 1826).

4 CODE contribution to the IGS–MGEX campaign

Since 2012 CODE contributes to the IGS Multi-GNSS EXperiment (MGEX) aiming at the integration of new GNSS into existing processing chains. In 2014 CODE's focus was on removing bottlenecks in the Bernese GNSS Software that so far prevented the processing of more than three GNSS (GPS, GLONASS, Galileo) together. Besides the software also the MGEX orbit and clock processing chains have been updated to BeiDou and QZSS processing capability. Satellite clock estimates and related inter-frequency biases (IFB) are now also provided for GLONASS. This means that CODE is now able to provide orbits and satellite clock corrections (plus related biases) for the GNSS GPS, GLONASS, Galileo, BeiDou (MEO and IGSO), and QZSS in a fully integrated solution.

This capability has been demonstrated on MGEX data of the whole year 2014. The increasing number of tracking stations providing RINEX3 data (via MGEX and non-MGEX sources), the different characteristics of the involved GNSS (regional vs. global navigation systems), and the fact that not all MGEX stations track all GNSS, made it necessary to pay more attention to the station selection. From the RINEX pool station subsets optimized for only one GNSS at the same time are selected paying attention to a good station distribution for the GNSS in question, respectively. The sub-networks are merged. When forming baselines for the double-difference processing weakly observed GNSS (QZSS, BeiDou) are preferred. Thanks to the station selection and the constantly improving MGEX network satellite clock corrections could be provided at a rate of almost 100 percent for most involved satellites at the end of 2014. The overall number of selected stations is limited to 130.

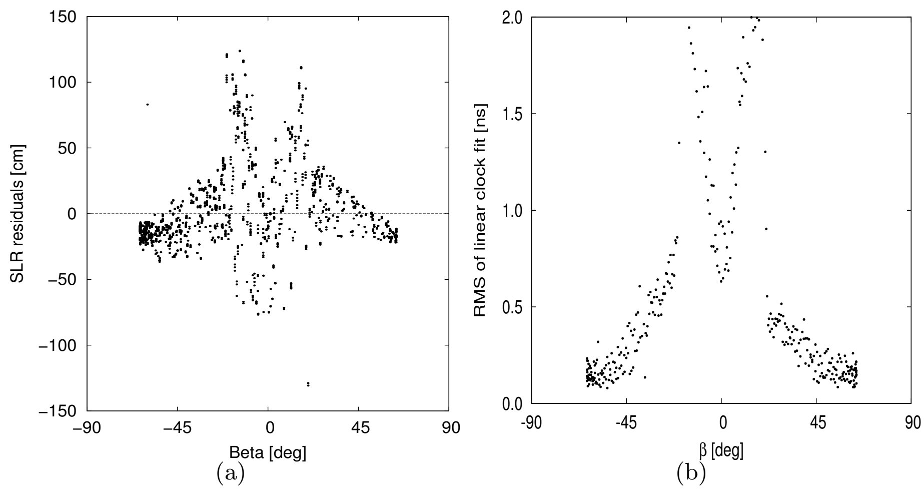


Figure 4: SLR residuals (a) and RMS of daily linear fit through estimated epoch-wise satellite clocks (b) of QZS-1 as a function of the elevation angle of the Sun over the satellite's orbital plane (beta). The impact on orbit and clock estimates from ignoring the switch of QZSS's attitude steering mode at beta angles of ±20 degrees (Inaba et al. 2009) is clearly visible.

The analysis of the long time series of CODE MGEX products clearly shows that certain models (e.g., the ECOM SRP model (Springer et al. 1999)) and assumptions (e.g., yaw-attitude mode is nominal) working fine for GPS and GLONASS must be re-considered or improved if new GNSS are involved. On the other hand the MGEX results confirm that the clocks of some new GNSS spacecraft (i.e., Galileo, QZSS, GPS IIF) are so stable that their estimated clock corrections are suitable for orbit validation purposes (see, e.g., Fig. 4). These results suggest that our focus in 2015 should be on qualitative aspects, such as the introduction of the updated ECOM RPR model (Arnold et al. 2015), attitude modeling, and satellite antenna phase center modeling for the new GNSS. Furthermore it is planned to deliver the CODE-MGEX ("com") products (available at ftp://cddis.gsfc.nasa.gov/gnss/products/mgex) with a shorter delay in the future.

5 CODE contribution to IGS repro2

Detailed information on the CODE contribution to the IGS repro2 effort were already provided in Dach et al. 2014 .

In April 2014, the results are posted to the CDDIS server (ftp://cddis.gsfc.nasa.gov/gnss/products/repro2/). Table 4 provides the list of files. The long-arc series (COD) have been published on the CODE's FTP server (ftp://ftp.unibe.ch/aiub/

Table 4: CODE repro2 products available in weekly subdirectories at ftp://cddis.gsfc.nasa.gov/gnss/products/repro2/.

Files generated from three–day long–arc solutions:

`co2wwwwd.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
`co2wwwwd.snx.Z`	GNSS daily coordinates/ERP/GCC/satellite antenna offsets from the long–arc solution in SINEX format
`co2wwwwd.tro.Z`	GNSS 2–hour troposphere delay estimates obtained from the long–arc solution in troposphere SINEX format
`co2wwww7.erp.z`	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily CO2–ERP solutions of the week in IGS IERS ERP format
`co2wwww7.sum.Z`	Analysis summary for 1 week

Files generated from pure one–day solutions:

`cf2wwwwd.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
`cf2wwwwd.snx.Z`	GNSS daily coordinates/ERP/GCC/satellite antenna offsets from the pure one–day solution in SINEX format
`cf2wwwwd.tro.Z`	GNSS 2–hour troposphere delay estimates obtained from the pure one–day solution in troposphere SINEX format
`cf2wwww7.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.Z`	Analysis summary for 1 week

REPRO_2013/). The publication of the reprocessing series includes the file ftp://ftp.unibe.ch/aiub/REPRO_2013/CODE_REPRO_2013.ACN containing a detailed description of the models used.

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NRCan Analysis Center Technical Report 2014

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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 2014 (products labelled 'em*'). Additionally, changes to the IGS stations operated by NRCan are briefly described. Readers are referred to the Analysis Coordinator website (http://acc.igs.org) for historical combination statistics of the NRCan–AC products.

2 NRCan Core Products

There were no major changes for NRCan–AC Ultra–Rapid, Rapid and Final (GLONASS) core products in 2014. The *Bernese GNSS Software* supporting these will be updated to version 5.2 during 2015. There were no major changes to the NRCan–AC Real–Time GPS correction stream.

During 2014 the NRCan–AC re–estimated its core GPS products for the years 1994 to 2014. This contribution to the 2nd IGS reprocessing campaign (repro2) was carried out using JPL's *GIPSY–OASIS Software* v6.3 running on Linux servers. The NRCan repro2 products (em2) were estimated following the latest set of IGS recommended models. Also during 2014 the NRCan–AC Final GPS products were upgraded using *GIPSY–OASIS* v6.3 with the latest recommended IGS models starting with 2014–03–30. For details on the NRCan–AC Final GPS (emr) and repro2 (em2) strategies please refer to the IGS central bureau summary. (ftp://igs.org/pub/center/analysis/emr.acn)

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

3 Ionosphere and DCB monitoring

Daily and near–real–time ionosphere products and DCB estimates continue to be generated internally. Following a recommendation made at the 2014 IGS workshop, hourly TEC maps are being included in NRCan's daily files since 2014–07–29. Contribution of daily TEC maps to Final IGS combined global ionosphere products are awaiting evaluation by IGS ionosphere working group chair.

4 NRCan stations contributing to the IGS network

In addition to routinely generating all core IGS products, NRCan is also providing public access to GPS/GNSS data for more than 60 stations. This includes 38 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 22 GNSS + 16 GPS only stations. In addition, several of the most important sites have multiple monuments in order to monitor the stability of the monument and the quality of the GNSS observations. These NRCan core sites with multiple monuments are listed in Tab. 2. Several upgrades to the CGS–CACS were completed in 2014 and these are listed in Tab. 3. Figure 1 shows a map of the NRCan GPS/GNSS network as of January 2015. Further details about NRCan stations and access to NRCan public GPS/GNSS data and site logs can be found at http://geod.nrcan.gc.ca or from the following anonymous ftp site: ftp://rtopsdata1.geod.nrcan.gc.ca/gps

Table 1: NRCan–AC Products

Product	**Description**
Repro2	
em2wwwwd.sp3 em2wwwwd.clk em2wwwwd.snx em2wwww7.erp	GPS only • Time Span 1994–11–02 to 2014–03–29 • Use of JPL's *GIPSY–OASIS II* v6.3 • Daily orbits, ERP and SINEX • 5–min clocks • Submission for IGS repro2 combination
Final (weekly)	
emrwwwwd.sp3 emrwwwwd.clk emrwwwwd.snx emrwwww7.erp emrwwww7.sum	GPS only • Since 1994 and ongoing • Use of JPL's *GIPSY–OASIS II* v6.3 • Daily orbits, ERP and SINEX • 30–sec clocks • Weekly submission for IGS Final combination
	GPS+GLONASS • Since 2011-Sep-11 and ongoing • Use of *Bernese Software* 5.0 • Daily orbits and ERP • 30–sec clocks • Weekly submission for IGLOS Final combination • Station XYZ are constrained, similar to our Rapid solutions
Rapid (daily)	
emrwwwwd.sp3 emrwwwwd.clk emrwwwwd.erp	GPS only • From July 1996 to 2011-05-21 • Use of JPL's *GIPSY-OASIS* (various versions) • Orbits, 5-min clocks and ERP (30–sec clocks from 2006-Aug-27) • Daily submission for IGR combination
Ultra–Rapid (hourly)	
emuwwwwd_hh.sp3 emuwwwwd_hh.clk emuwwwwd_hh.erp	GPS only • From early 2000 to 2013–09–13, hour 06 • Use of *Bernese Software* v5.0 • 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 Software* v5.0

	• Orbits and ERP (hourly) • 30–sec GNSS clocks (every 3 hours) • 30–sec GPS-only clocks (every other hours) • Submission for IGUIGV combination (4 times daily)
Real–Time	
	GPS only • Since 2011–11–10 • Custom software (HPGPS.C) • RTCM messages: – orbits & clocks:1060 (at Antenna Reference Point) – pseudorange biases: 1059 • Interval: 5 sec

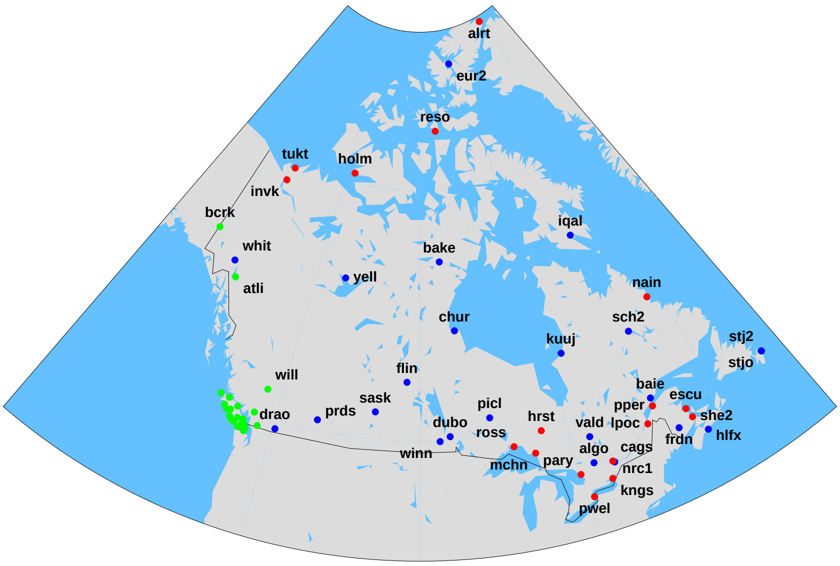

Figure 1: NRCan Public GPS/GNSS Stations (CGS–CACS in blue, CGS–RACS in red and GSC–WCDA in green).

Table 2: NRCan Multiple Monument GNSS Sites

Site	Stations	Remarks
ALGO	algo, alg2, alg3	Secondary stations installed 2006–01–06
		No alg2 data from 2012–12–21 to 2014–11–27
CHUR	chur, chu2	Secondary station installed 2010–08–02
DRAO	drao, dra3, dra4	Secondary stations installed 2013–10–29
NRC1	nrc1, nr23	Secondary stations installed 2008–12–23
		nr23 data is private
PRDS	prds, prd2, prd3	Secondary stations installed 2014–07–09
STJO	stjo, stj2, stj3	Secondary stations installed 2009–07–02
		stj3 jointly operated with CNES since 2013–07–10
		(now part of REGINA network)
YELL	yell, yel2, yel3	Secondary stations installed 2008–11–14
		yel2 jointly operated with CNES since 2013–07–10
		(now part of REGINA network)

Table 3: NRCan Station Upgrades in 2014

Station	Date	Remarks
frdn	2014–01–31	TPS NETG3 to NET–G3A upgrade
vald	2014–01–31	TPS NETG3 to NET–G3A upgrade
chu2	2014–02–18	TPS NETG3 to NET–G3A upgrade
flin	2014–02–24	TPS NETG3 to NET–G3A upgrade
dubo	2014–02–26	TPS NETG3 to NET–G3A upgrade
prd2	2014–07–09	New station installed at PRDS site
prd3	2014–07–09	New station installed atPRDS site
eur2	2014–08–10	Station upgraded from GPS–only to GNSS
alg2	2014–11–27	Station repaired and brought back on–line after an extended outage.

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ESA/ESOC Analysis Center Technical Report 2014

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1 Introduction

The IGS Analysis Center of the European Space Agency (ESA) is located at the European Space Operations Center (ESOC) in Darmstadt, Germany. The ESA/ESOC Analysis Center 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 2014.

2 Overview 2014

2.1 Routine Products

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

- Reprocessed Final GPS products (repro2)
  - Provided from 1995 to 2014 day 140, from there on our normal Final products.
  - Based on 24–hour solutions using 150 stations GPS–only, until 2008
  - Based on 24–hour 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 24–hour 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 24–hour 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 Center 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 centers we are also responsible for the analysis center coordination. Also our efforts in the scope of MGEX, the antenna calibrations 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 2014 were the following:

- Upgrade of the ESA/ESOC GNSS Sensor Station network
- Using a box–wing model for the GNSS satellites to a priori model the Solar and Earth Albedo radiation pressure

2.3 Product Highlights

The main highlight of the ESA/ESOC Analysis Center products is that they are one of the best products available from the individual IGS analysis centers. Furthermore, the ESA products are one of the most complete GNSS products. In fact ESA/ESOC was the first IGS analysis center 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. Another 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.

The largest change, or rather improvement, we made in our processing in 2014 was that we started using 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 et al. 2014). As significant improvements were observed for most, if not all, estimated parameters it was decided to use the a priori box–wing modeling for our IGS reprocessing efforts. After completing the reprocessing the box–wing model usage was activated for the generation of all our routine IGS products in April 2014. For our IGS final products this started with the products of GPS week 1789. As a consequence our agreement with the combined IGS orbit shows a significantly degradation. Despite the fact that the quality of all our products, including our orbits, improved, our orbits now deviate more from the combined IGS orbit product then they did before. This may be explained by the fact that most of the IGS analysis centers do not model the radiation pressure on the satellite adequately. The box–wing model gives rise to very significant radial and cross-track orbital differences, see Fig. 1, which can not be absorbed by the orbital parameters that are commonly estimated by the different IGS ACs. The improvement of all our estimated parameters does clearly indicate that these radial– and cross–track orbital differences are real and have to be taken into account. For 2015 we are planning to invest significantly more time into this topic to further improve our understanding and modeling capabilities regarding the different radiation pressures acting on the GNSS satellites. With future GNSS satellites having a much higher area to mass ratio the accurate modeling of the radiation pressure is becoming *much* more important.

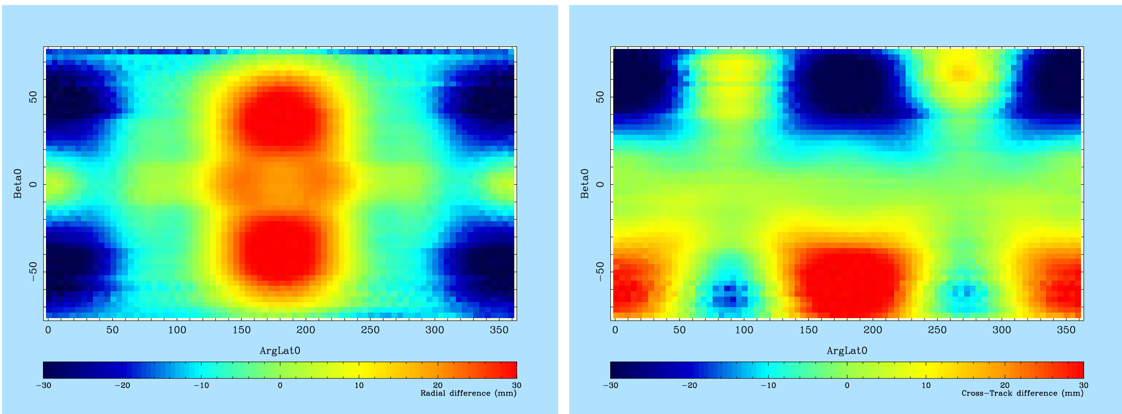

Figure 1: Radial (left) and Cross–track (right) differences between the original ESA final orbits and the ES2 reprocessed orbits using the box–wing model.

2.4 Multi–GNSS (MGEX)

We periodically analyze the data from the IGS Multi–GNSS Experiment (MGEX). At the current stage we prefer the detailed analysis of the MGEX data over routine analysis. The orbit and clock products from two 16 day periods we analyzed in detail were made available to the general public on the MGEX servers. The second 16 day period period we analyzed, centralized GPS weeks 1783 and 1784 in March 2014, included *all* the active GNSS satellites from *all* the GNSS constellations: GPS, GLONASS, GALILEO, BEIDOU, and QZSS. This gives rise to solutions including a maximum of 74 actively transmitting GNSS satellites in that period. We provided our orbit and clock products for these two weeks which should enable multi–GNSS precise point positioning. The main interesting features and challenges we have found so far in our MGEX analysis activities were presented at the IGS workshop in June 2014 (Garcia-Serrano et al. 2014) 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

2.4.1 Estimation of Satellite Antenna Phase Center Corrections for BEIDOU

In support of the IGS Multi–GNSS Experiment (MGEX), ESA/ESOC has put in significant effort to derive initial phase center corrections for the L–Band transmitter antenna arrays aboard the Inclined Geosynchronous (IGSO) and Medium Earth Orbiting (MEO) BEIDOU spacecraft (Dilssner et al. 2014). Almost one and one–half year of BEIDOU triple–frequency (B1, B2, B3) measurement data – gathered between February 2013 and May 2014 by 39 ground stations of the MGEX tracking network – was used to derive the satellites′ antenna phase center offsets (PCOs) and variations (PCVs) for the ionosphere–free linear combinations B1–B2 and B1–B3, respectively. Processing was carried out in daily batches using the most recent version of ESOC′s multi–GNSS analysis software, the Navigation Package for Earth Observing Satellites (NAPEOS version 3.8). The parameterization of the PCVs was done in the conventional IGS–style, that is, using piece–wise linear functions of the satellite nadir angle with 13 (MEO) and 9 (IGSO), respectively, linear segments (Fig. 2). The estimates were found to agree to within 0.1–1 millimeter (PCVs) and 1–2 decimeter (z–PCOs) with independently–computed values from Wuhan University′s GNSS Research Center (J. Guo).

Applying these initial PCO/PCV corrections to the BEIDOU observables gives an improved performance compared to the currently recommended standard offset values (x =

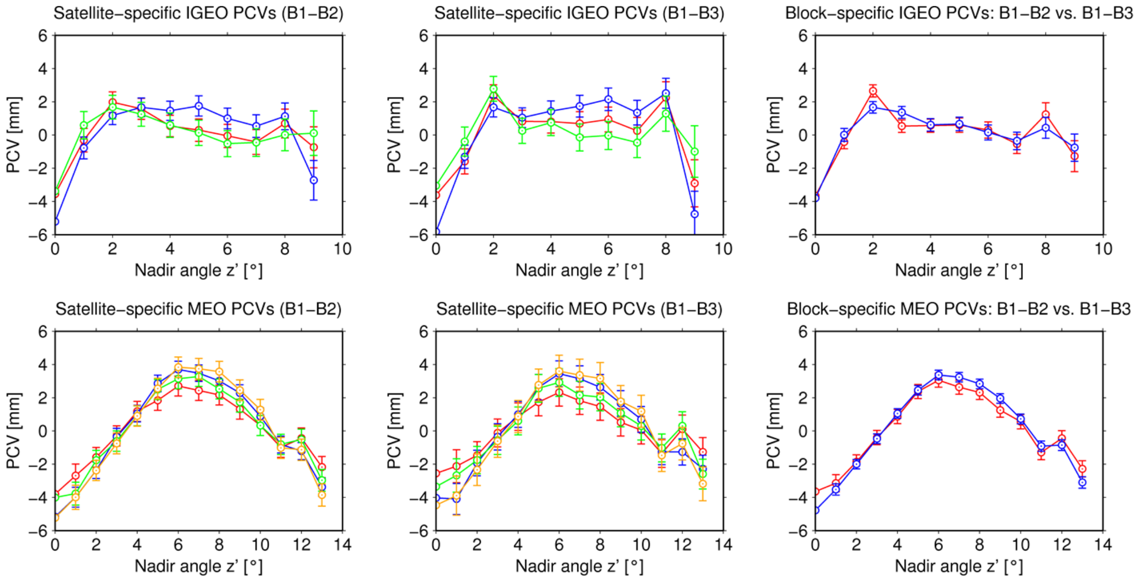

Figure 2: Satellite– and block–specific IGSO (top) and MEO (bottom) PCV estimates together with error bars representing the formal errors from the variance–covariance matrix. Results for IGSO–4/5 are not shown for reasons of clarity.

0.6 m, y =0.0 m, z =1.1 m). Initial comparisons of overlapping orbit solutions suggest that the orbit accuracy (3D–RMS) of the MEO spacecraft is substantially improved by more than a third. The orbital component that benefits most from the improved phase center modeling is the MEOs along–track component (see Fig. 3). Similar improvements against the standard offset parameters were reported to us by GFZ (Z. Deng).

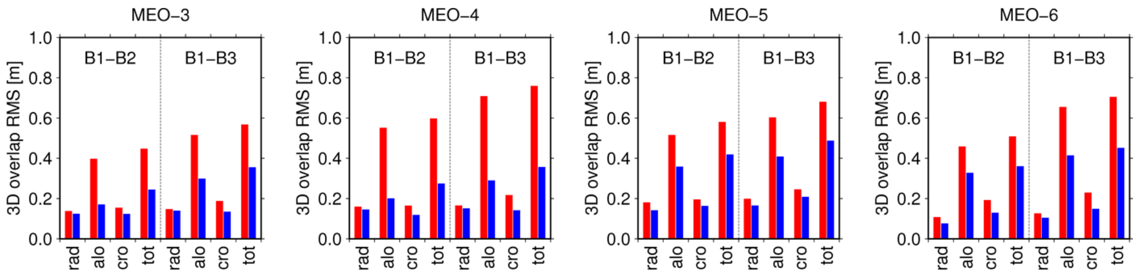

Figure 3: Day-to-day orbit overlap differences (RMS) computed for each MEO spacecraft over a five–month processing period. The standard PCO–only solution is shown in red, the advanced PCV–based solution in blue

3 Reprocessing Activities

ESA/ESOC has participated in the first IGS reprocessing efforts (repro1) for the IGS contribution to the realization of the International Terrestrial Reference Frame 2008 (ITRF 2008) and will also participate in the reprocessing for the ITRF2014. For this reprocessing effort ESA will process all historic GNSS data of the IGS from 1994 to 2014. In this reprocessing the years 1994 to 2008 are reprocessed using only GPS observations, but from 2009 onwards the reprocessing fully includes the GLONASS observations and thus provides true GNSS solutions.

The products from the first ESA official reprocessing efforts, based on the ITRF2005 reference frame, are available from the official IGS data centers (label "es1"). The most recent ESA reprocessing products, currently based on the ITRF2008, are 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 do 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.

4 GNSS Sensor Station Upgrade

ESA/ESOC contributes to the IGS the data of its GNSS station network, see Fig. 4, which currently comprises 10 stations at ESA ESTRACK core/cooperation locations; Kourou (KOUR), Redu (REDU), Maspalomas (MAS1), Cebreros (CEBR), Villafranca (VILL), Kiruna (KIRU), Malargue (MGUE), New Norcia (NNOR), Malindi (MAL2), as well 1 station installed in Tahiti (FAA1) in close cooperation with Meteo France. ESOC is providing worldwide data from those 10 stations for all GNSS constellations as a result of having completed the upgrade of the equipment at all the current installations over the last few years. ESA/ESOC is as well focusing on the establishment of collaborations with third parties to install new stations at various new locations around the world such as the recently complete Santa Maria Island in the Azores and Awarua in New Zealand, and soon to come Japan, Malaysia and Dubai, as shown in the map above. 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, now the entire ESA GNSS network now operates these Septentrio receiver/antenna combinations, with the exception of MGUE, MAL2, MAS1 and FAA1 where the Leica antennas are used. The Polar Rx4 Septentrio receivers installed provide all observations for the GNSS constellations as available: GPS, GLONASS, GALILEO, QZSS, BEIDOU, SBAS, EGNOS, etc. As of mid–2013, ESOC has been contributing with daily, hourly and high rate multi–GNSS RINEX 3 data to the

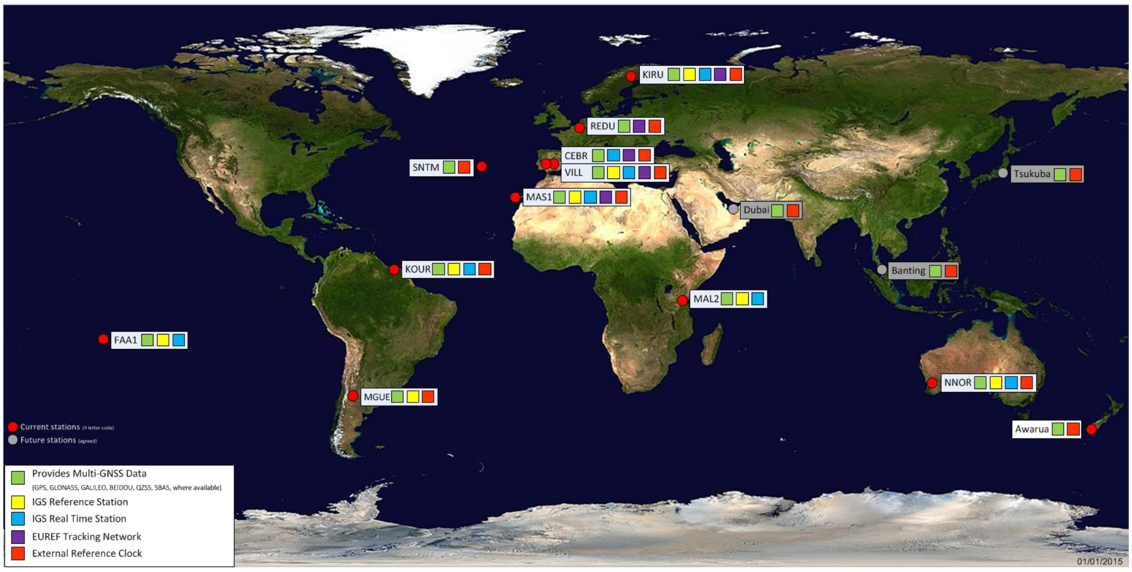

Figure 4: ESA/ESOC GNSS Station Network.

MGEX effort. Also, since the beginning of 2013, ESOC has been providing NBS (NavBits) data from this same set of stations to Eumetsat to support LEO satellite occultation processing. The ESOC station network also supports the new RINEX 3 file naming as promoted within the IGS for the mainstream adoption of the RINEX 3 format, as well as retaining the distribution of the legacy GPS+Glonass RINEX 2.11 files.

5 Ionosphere Modeling Activities

ESA/ESOC contributes with IONEX products to the IGS Ionosphere Working Group since its inception in 1998, initially with daily global ionospheric TEC maps in final mode (11 days latency). ESA/ESOC′s activities for the ionosphere in the frame of the IGS since 2004 can briefly be summarized as follows:

- Spring 2004: Start routine delivery of daily global ionospheric TEC maps in rapid mode (1 day latency)
- December 2005: Start routine delivery of TEC maps in 2–hour time resolution, i.e. since then each ESA IONEX file provides 13 TEC and RMS maps per day
- September 2009: Commence submission of IONEX files containing 1 and 2 days ahead predicted TEC maps in 2–hour time resolution
- February 2009 – January 2010: ESA Study: GNSS Contribution to Next Generation Global Ionospheric Monitoring (Feltens et al. 2009 and Feltens et al. 2010)

- July 2010: Commence combination of predicted Ionosphere Associate Analysis Centers (IAACs) TEC maps and submission of combined predicted IGS IONEX files in 2 hour time resolution
- February 2011: Commence submission of ESA IONEX files with 1–hour time resolution
- January 2013: The IONMON became an integral part of ESOC′s *NAPEOS software* allowing for GPS+GLONASS based ionosphere estimation
- Summer 2014: : Mathematical algorithms of a new 3D TEC and electron densities assimilation approach worked out and coded as new NAPEOS component.

ESOC employs the Ionosphere Monitoring Facility (IONMON) for its ionosphere processing. IONMON algorithms were initially devoted to single layer approaches. Since 1999, investigations were undertaken into the direction of 3D ionosphere modelling. Starting with an extended Chapman profile approach, in the subsequent years the concept of a multilayer modelling was developed, combining empirical surface functions to describe the horizontal structures of the ionosphere with vertical profile functions, which should, to some limited extent, also allow for a physical interpretation of results. It was foreseen that this new modelling should process TEC data from GNSS combined with observed electron density profiles from different sources, namely CHAMP, F3/COSMIC and ionosonde in least squares fits. In relation to these IONMON developments, from March 2009 to January 2010 the ESA Study *"GNSS Contribution to Next Generation Global Ionospheric Monitoring"* was conducted, Feltens et al. 2009 and Feltens et al. 2010, working out recommendations for a new ionosphere monitoring system.

In summer 2013, the IONMON became an integral part of ESOC′s *NAPEOS software*. ESOC′s actual ionosphere model development efforts are clearly directed to 3D modelling, where the concept had to be changed from the least squares fitting of TEC and electron density data into a model comprising a combination of vertical and horizontal functions, to an approach in which TEC and electron density observables from different sources will be assimilated into a background model. It turned out that, in spite of including F3/COSMIC and CHAMP electron densities in addition to GNSS TEC observables, the data coverage was not yet dense enough to perform reliable and stable least squares fits. This was also one of the results from the Iono Study conducted in 2009–10. The mathematical algorithms for this new 3D assimilation approach were worked out and coded as new component of NAPEOS in 2014. From its design, the assimilation scheme shall also enable NRT & RT processing and upgrade time resolutions down to several minutes, i.e. simple, fast and robust algorithms are required.

5.1 Actual / Future Activities

The 3D assimilation model code within NAPEOS has still to be tested. Once the new assimilation approach in NAPEOS will be operational, ESOC′s ionosphere processing will be switched over from the current single layer modelling to this new 3D modelling technique. This will then also concern ESOC′s ionosphere products delivered to the IGS, including new aspects such as 3D IONEX.

A follow-up study to the Iono Study of 2009–10 is currently under planning.

The implementation of a more sophisticated Iono prediction scheme at ESOC will be an important future topic too.

In parallel to the tasks described above, other ionosphere-related activities are ongoing at ESOC:

- Establishment of a new model for the plasmasphere in a cooperative effort with the German Aerospace Center (DLR) in Neustrelitz, Germany. This plasmasphere model will then complement the new 3D assimilation approach.
- Establishment of an ionospheric & tropospheric media calibration service to be operationally used by the ESOC Flight Dynamics Department.
- Routine contributions to ESA′s Space Situational Awareness (SSA) service – spaceweather part.

6 Summary

The European Space Operations Center (ESOC) of the European Space Agency (ESA) Analysis Center has continued to produce "best in class" products for the IGS in 2014. Practically 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 Center, ESA/ESOC is also an Analysis Center of the IDS and the ILRS.

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GFZ Analysis Center Technical Report 2014

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1 Summary

During 2014 the standard IGS product generation was continued with minor changes in the processing software *EPOS–8*. The GNSS observation modeling was adapted to conform to the GFZ *repro–2* (2nd IGS Reprocessing campaign) settings for IGS Final product generation.

End of 2014 the *repro–2* processing for IGS (GF2) and TIGA (GT2) was nearly finished. Newly re-runs for GF2 and GT2 became necessary, because a preliminary SINEX combination of *repro–2* submissions revealed systematic problems for GFZ SINEX submissions related to station network scale and length of day (LOD) estimates.

A routine multi–GNSS processing including GPS, GLONASS, BeiDou and Galileo has been set up similar to the IGS Rapid processing scheme.

At the end of February 2014, Dr. Gerd Gend retired from GFZ and such also resigned as head of the IGS analysis center. We would like to take the opportunity to express our sincere appreciation and gratitude to him for his longstanding efforts within the IGS community but also for his collegial spirit over many years.

2 Products

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

3 Operational data processing and latest changes

The *EPOS–8* processing software is following the IERS Conventions 2010 (Petit and Luzum 2010). The station network used in the processing is shown in Fig. 1. For the IGS Final, Rapid and Ultra Rapid about 200, 110, and 95 sites are used, respectively. The sites providing GLONASS observation data is steadily increasing. Some processing related information is given in Tab. 2.

Recent changes in the processing strategy are listed in Tab. 3. Major changes in the strategy for observation modeling have been applied in order to have identical strategies for *repro–2* and operational products. From the IGS Final combination it was noticed, that due to switching to the *repro–2* modeling standards a significant bias was introduced in length of day (LOD) estimates (see Fig. 2). The root cause of this LOD bias was identified to be a misused C_{20}–term in the gravity field model. Instead of applying the C_{20}–term delivered along with the *EGM2008* gravity model, the corresponding value listed in Tab. 6.2 of the IERS Conventions 2010 was introduced. Figure 3 shows LOD differences with respect to the IGS Final LOD time series when applying different gravity field models. The jump of about 0.6 ms/d which is also obvious from the IGS Final combination results in Fig. 2 can clearly be attributed to the application of the inconsistent C_{20}–term.

Table 1: List of products provided by GFZ AC

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
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
Ultra	(every 3 hours; provided to IGS every 6 hours; GLONASS since week 1603)
gfuWWWWD.sp3	Adjusted and predicted orbits for GPS/GLONASS satellites
gfzWWWWD.erp	Earth rotation parameters

Table 2: Recent Processing changes

IGS Product	# Sites	# Sites with with GLONASS	Duration [h]
Ultra	95	65	≈ 1
Rapid	110	80	≈ 2
Final	200	115	≈ 4

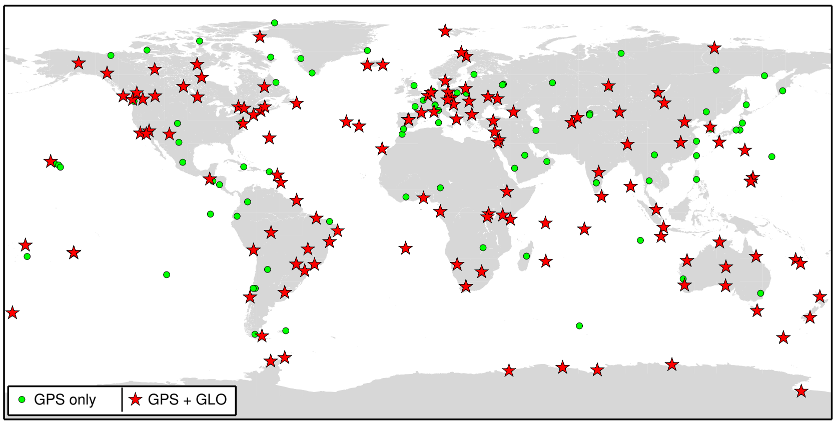

Figure 1: Used IGS stations for combined GPS+GLONASS data processing.

Table 3: Recent Processing changes

Date	IGS	IGR/IGU	Change
2014-06-05	w1795	w1795.4	Meta data retrieval from SEMISYS
2014-09-03	w1807	—	2nd order ionosphere correction applied
			Troposphere modeling based on VMF–1 mapping function
2014-10-15	w1812	w1814.4	Switch to gravity model EGM2008 and ocean tide model FES2004
2014-12-02	w1820	w1821.3	Bug fix C_{20} term in gravity model EGM2008
For the reprocessing GF2/GT2 submissions following changes were implemented:			
			Bug fix C_{20}–term in gravity model EGM2008
			Bug fix 2nd-order ionospheric correction calculation

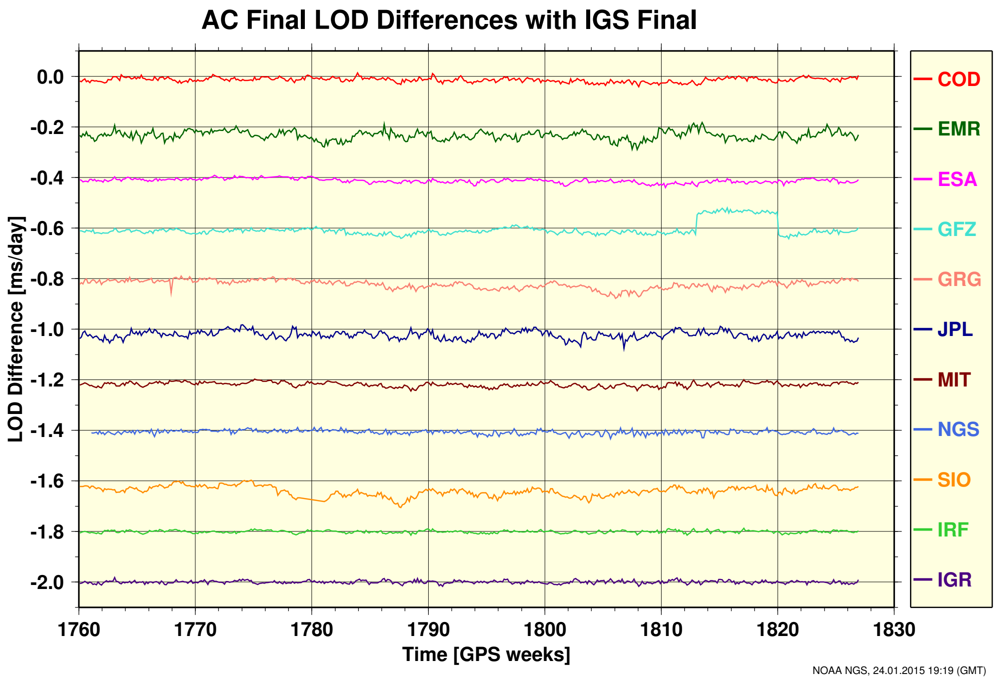

Figure 2: Differences in length of day (LOD) of Analysis Center submissions with respect to IGS Final combined LOD product. Note the jumps for GFZ solution at GPS weeks 1812 and 1820.

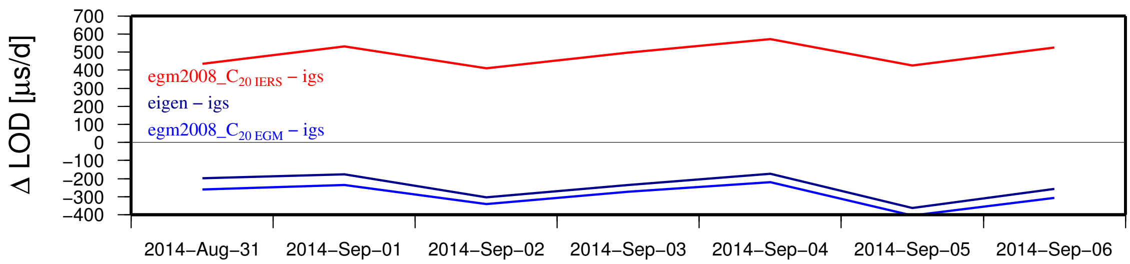

Figure 3: Differences in length of day (LOD) estimates with respect to IGS Final combined LOD product (igs) based on different internal GFZ solutions. eigen: *EIGEN_GL04C* gravity model, egm2008_$C_{20\,\mathrm{IERS}}$: *EGM2008* gravity model but with supplemented IERS2010 C_{20}-term (from Tab. 6.2 in Petit and Luzum 2010); egm2008_$C_{20\,\mathrm{EGM}}$: *EGM2008* gravity model.

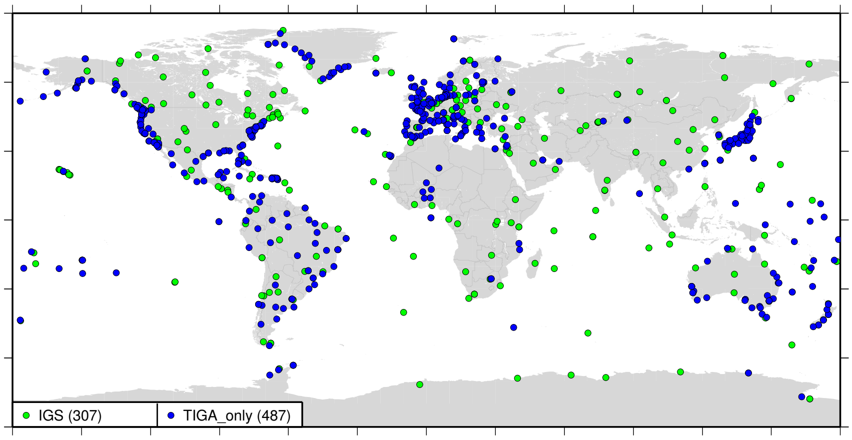

Figure 4: Global distribution of the reprocessed GPS stations for IGS (GF2) and TIGA-only (GT2) solutions.

4 Reprocessing activities

GFZ is contributing to the 2nd IGS and TIGA Reprocessing Campaigns. For the IGS/TIGA reprocessing the GPS data from a globally tracking network of 307/794 stations has been included (Deng et al. 2014a, b). The GF2 time series extend to end of 2014 (GPS week 1824) whereas GT2 time series are provided until end of 2012 (GPS week 1720). The distribution of the GPS stations involved in GF2/GT2 is shown in Fig. 4.

Initial GF2 and GT2 reprocessing solutions were also affected by using an improper C_{20}–term in the *EGM2008* gravity model as described in section 3. Accordingly, both solutions have been re-generated and re-submitted in January 2015.

5 Metadata Management Tool SEMISYS

For the precise analysis of GNSS observation data a variety of metadata from different sources is required. In particular, validated integrity of station and satellite related metadata information is required in order to deliver consistent products. Station and satellite meta information is usually distributed and maintained by ASCII based files. To ease the handling of metadata and to improve the trackability of changes to meta information, the Operational Data Center (ODC) group of the GFZ developed a Sensor Meta Information System (SEMISYS) for the central, format independent and validated storage of station and satellite metadata based upon a relational database (Bradke et al. 2014). Figure 5 provides a schematic overview on the basic system design of SEMISYS and relations according to the data flow.

Following processing related meta information is currently stored in SEMISYS:

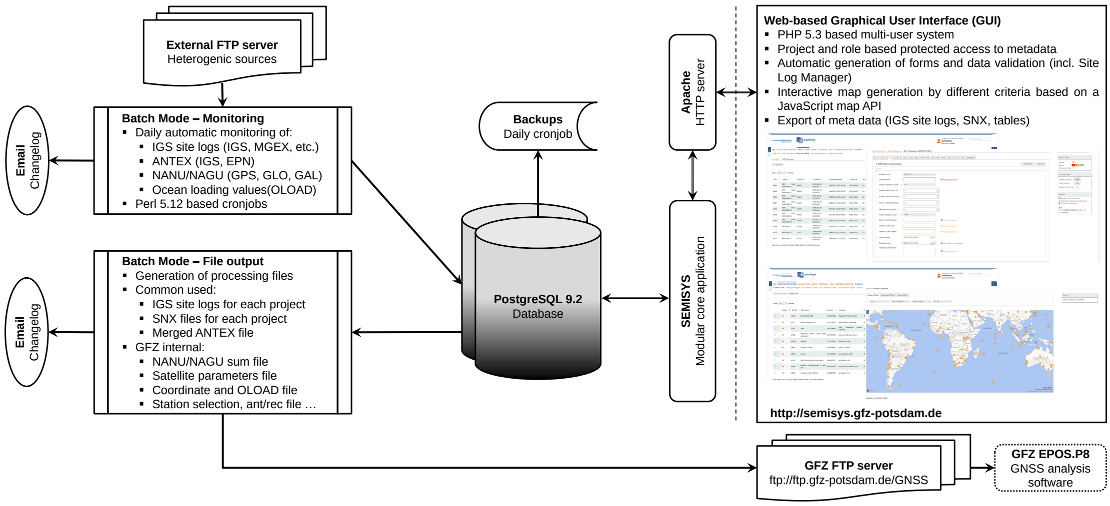

Figure 5: Basic system design of the *Sensor Meta Information System* (SEMISYS), data flow and client/server communication.

- station meta information extracted from IGS site logs
- hardware meta information (receiver, antenna, radome)
- satellite parameter for GPS, GLONASS, Galileo, BeiDou, QZSS and SBAS
- notice advisories from GPS, GLONASS, and Galileo (NANU, NAGU)
- antenna phase center model (ANTEX) from different sources (GFZ, IGS, EPN)
- initial station coordinates
- ocean loading displacements (retrieved from http://holt.oso.chalmers.se/loading)

GFZ has started to use SEMISYS in order to regularly generate up–to–date metadata related processing files required to run the *EPOS–8* software environment. In principle, also metadata files in different file formats used by other processing software packages could be generated and provided to external users.

6 Multi-GNSS data processing

Since end of 2012 with a total of 14 operational satellites, BeiDou constitutes the third satellite navigation system next to GPS and GLONASS that offers a fully operational navigation service for China and surrounding regions. Tracking of the BeiDou satellites is supported by a subset of stations from the MGEX network. Based on that continuous observation data of satellites in geostationary orbit (GEO) and inclined geosynchronous orbit (IGSO) can be provides as well as partial tracking of the four satellites in medium Earth orbit (MEO) is enabled.

At GFZ an upgraded version of *EPOS.P8* software is used for processing dual-frequency GPS+BDS data. Ambiguity–fixing was also set up for BeiDou IGSO and MEO type satellites. The ionosphere–free linear combination of B1 (1561.098 MHz) and B2 (1207.140 MHz) frequencies is applied for estimation of satellite orbits, clocks, and other relevant parameters. The a priori BeiDou orbits are taken from the broadcast navigation message files, which are available from the MGEX network. More details are described in Deng et al. 2014c, d.

Since 28th January, 2014 GFZ generates IGR-like GPS+BeiDou orbits and 5 min clock products routinely. For the analysis, GPS and BeiDou data of the MGEX and IGS networks is used. Starting with 8th July, 2014 (doy 200) besides GPS and BeiDou, also GLONASS and GALILEO are included in the analysis. Table 4 gives an overview on the number satellites included per system and the frequencies used for product generation. Associated final products are provided as GBM products (`ftp://ftp.gfz-potsdam.de/pub/GNSS/products/mgex`).

In order to check the quality of the GBM orbits the median daily RMS of orbit differences with respect to GFZ rapid orbit GFR are computed (doy 200 to 250 in 2014, Deng et al. 2014e). Statistical results are shown in Fig. 6. Looking at GPS, the RMS values for most of the satellites are on a level of about 1.5 cm. The RMS for GLONASS satellites is on the order of 3 cm. Since the GFR orbit has an accuracy of approximately 2.5 cm, 3.0 cm for GPS and GLONASS, respectively, the accuracy of the GBM GPS and GLONASS orbits are assumed to be on a similar order of magnitude.

Besides the orbit differences with respect to GFR, the RMS of the differences from overlapping orbit positions (4 hours interval) has been evaluated. Figure 7 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 vary between 10 and 20 cm for GLONASS. For GALILEO satellites, we find an RMS of about 10 cm. For BeiDou, there are three different types of orbits: GEO, IGSO and MEO. Because of the weak observation geometry and the lack of orbit change with respect to the ground tracking station network, GEO satellites reveal the largest RMS value of 1 to 2 meter. The IGSO and MEO satellites have RMS values of 40 cm and 12 cm, respectively.

Fortunately, all BeiDou and Galileo satellites are equipped with laser reflectors. An independent validation of the microwave-based satellite orbits can be performed via SLR measurements (mainly the radial component). Figure 8 shows the resulting mean bias and standard deviation for different satellite types which indicate the achieved orbit accuracies for that satellites (Uhlemann et al. 2014) currently observed by the International Laser Ranging Service.

Table 4: Used observation types and number of satellites in the multi-GNSS data processing

Satellite System	# of Satellites	Observation Types
GPS	31	L1/L2
GLONASS	24	L1/L2
BeiDou	14	B1/B2
Galileo	3	E1/E5a

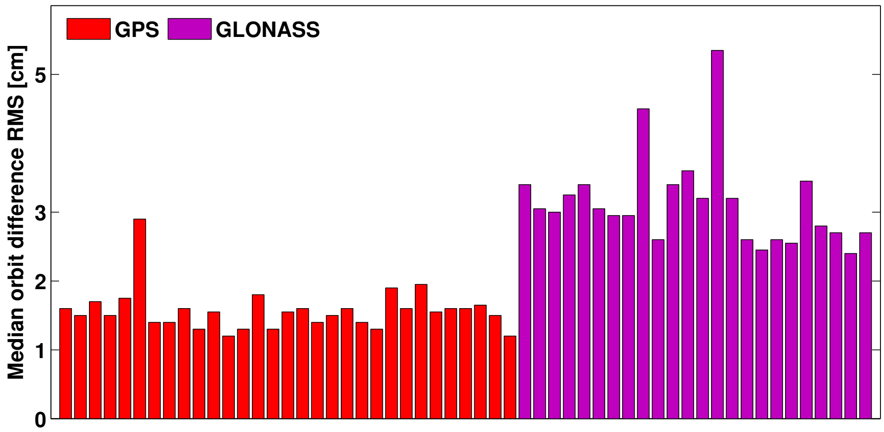

Figure 6: Daily median RMS [cm] of orbit differences between GBM (GPS+GLONASS+BeiDou+Galileo) and GFR (GFZ IGS Rapid) solution.

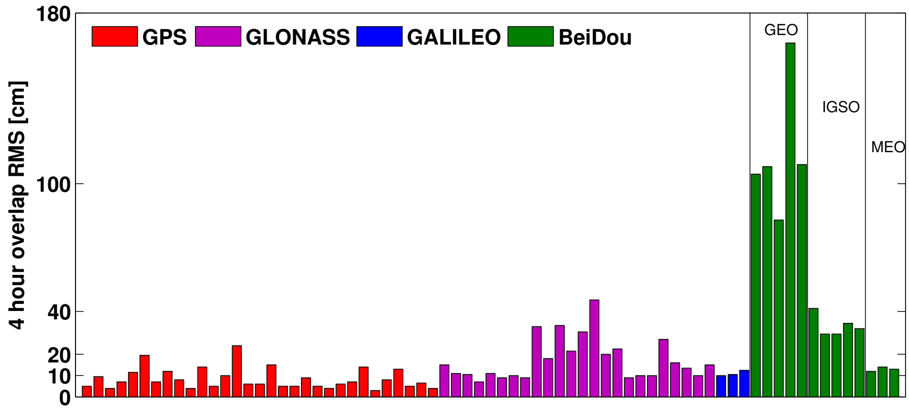

Figure 7: Daily median RMS [cm] of the differences from overlapping orbit positions (4 hours interval).

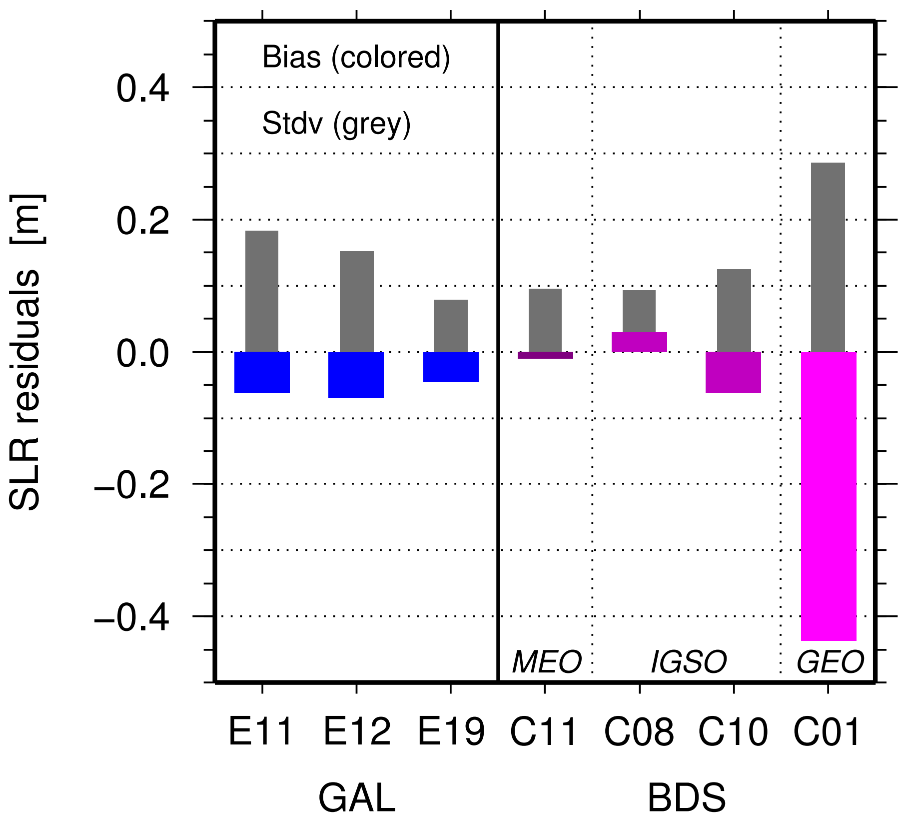

Figure 8: SLR residual statistics. The bias (colored) and STDV (grey) are given for individual Galileo and BeiDou satellites.

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CNES–CLS Analysis Center Technical Report 2014

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1 Introduction

The *GINS CNES/GRGS software* (Marty et al. 2011) is routinely operated in order to deliver to IGS, final GPS and GLONASS products. We process zero–difference GNSS observations and the details of our strategy are described in Loyer et al. 2012. More information on our AC activity can also be found at: www.igsac-cnes.cls.fr.

In 2014, the activities were dominated by our contribution to REPRO2 campaign.

2 Operational products delivery

Since GPS week 1786 the GRG satellite clock solution is aligned using a combination of the best stations clocks. This significantly improves the Allan variance of each daily GRG clock solution. There is no specific processing to achieve a correct behavior of their reference between successive days. This improves significantly the RMS of GRG clocks relatively to the combined solution as shown on Fig. 1.

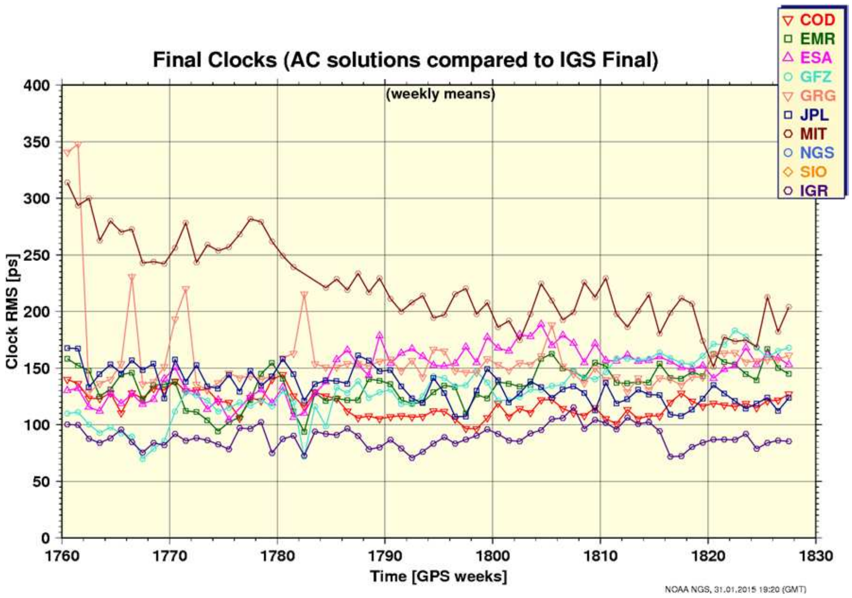

Figure 1: GRG GPS satellites clock solutions RMS improvement after week 1786 (from IGS Analysis Center Coordinator).

3 Participation to REPRO2 campaign

As we became an Analysis Center in 05/2010, REPRO2 was in fact our first experience in a massive reprocessing campaign and has proven to be a heavy but instructive experience for our group. In March 2014, we delivered 18348 files including GPS products starting 01/01/1998 and GLONASS products starting 01/01/2009.

3.1 Standards and models

Most of the standards we used followed the recommendations of the Analysis Center Coordinator. The main specificities of our processing were the use of the Eigen6S2 Time Variable Gravity (TVG) field model (up to degree and order 12), ocean tide loading displacement derived from FESS2012 model, second order ionospheric corrections and GPT2/VMF1 tropospheric model.

Dedicated tests have been realized in order to quantify the impact of TVG model on IGS products (Loyer et al. 2014). Results are summarized in Tab. 1.

The main conclusion was that the impact of TVG on IGS products is sufficiently high to consider today these effects (especially on the EOP), but small enough that our solution could be combined to other ACs's.

Table 1: Impact of gravity field variations on GNSS products

Product	Impact	Detail
Residuals	<0.1 mm on phase un–differenced observations	Not significant
Orbit	RMS 3D $\sim$ 4 mm SSA $\sim$ 0.3 mm	Below todays ACs differences
Orbit frame translations	$\pm$4 mm	Dominated by seasonal variations
EOP	Few tens of uas in xp/yp	Order of magnitude of IGS ACs discrepancies LOD differences linked to C20 differences
Stations Coordinates	East/North: <1 mm RMS Up : $2.5 - 3$ mm RMS	Dominated by seasonal variations

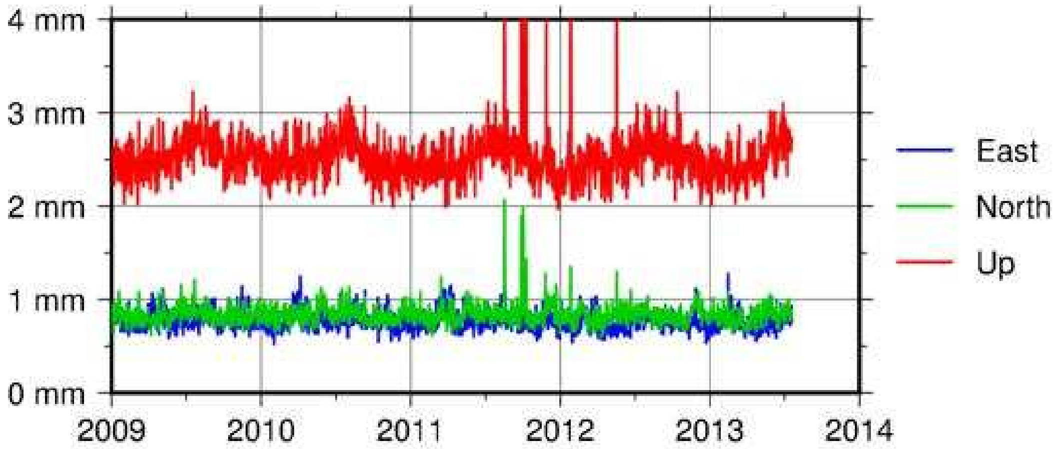

Figure 2: WRMS of station coordinates differences between static and TVG field model solutions (from P. Rebischung, IGN).

In addition, in the framework of the ITRF14 realization, a comparison of GR2 station coordinate series with a preliminary combination from all contributing ACs have been kindly provided by IERS. A spectral analysis of the coordinate differences clearly shows an annual signal of $2-6$ mm affecting the Up and North component which was questioning our participation to the combined coordinate solution. After intensive investigations we discovered that we used a bad parameterization of the GPT2/VMF1 tropospheric model. We hope that an a posteriori correction of the series will be possible.

3.2 Zero difference ambiguity fixing

Fixing zero–difference ambiguity before 2004 has proven to be an unexpected challenge. This corresponds to the times when cross–correlated receivers were dominating the IGS network. After intensive investigations, we came to the conclusion that P1–C1 biases provided by the IGS were not compatible with our processing strategy in the case of ROGUE8000 and Trimble receivers. Mercier et al. 2014 has demonstrated that a set of biases per receiver "family" can be identified and would help in fixing ambiguities.

3.3 P1–C1 DCB

Discrepancies in the GPS P1–C1 DCB have been observed according to the receiver make and manufacturer. In particular, receivers that produces both the P1 and C1 observable have a similar behavior, while other type of receiver and in particular Trimble receiver have a different P1–C1 DCB. The difference is satellite dependent and can reach up to 40 cm (see Fig. 3), and therefore the traditional approach in geodetic processing to separate biases into a purely receiver dependent and a purely satellite dependent part is not accurate and we are working on an improved model that will take into account this observation.

Moreover, high gain antenna measurements of a few GPS satellites have been made at CNES in experiments made as preparatory work for the future GNSS signal observatory (DCT/RF/SR). These measurements have revealed signal distortion specific to each satellite that closely explains the observed difference between receiver types. Making the link between the biases determined from the high gain antenna measurements and the observed geodetic receiver bias would allow to better monitor and correct the signal biases. This can improve the accuracy of PPP and the success rate of i–PPP positioning.

We are currently working on a new modeling of GNSS signal biases that could include measurements made with high gain antenna

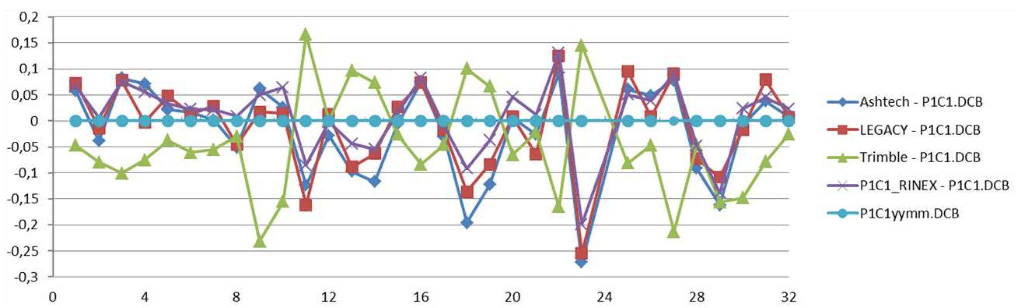

Figure 3: P1–C1 difference with IGS P1C1 DCB files according to receiver make.

4 Contribution to MGEX

Our main short time objective is to provide the IGS with fully hybridized GPS + GLONASS + Galileo final products. To reach this goal several software implementations have been realized and are routinely tested in parallel to our operational activities. The major improvements include the capabilities to:

- Mix RINEX2 and 3 files
- Choose and manage the frequencies used for the processing (and the pre–processing)
- Include automatically new MGEX stations and new satellites
- Consider PCO/PCV and attitude laws provided by MGEX working group

Preliminary results derived from a dual frequency simultaneous processing of respectively 31, 23 and 3, GPS, GLONASS and Galileo satellites are very encouraging.

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JPL Analysis Center Technical Report 2014

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1 Introduction

In 2014, the Jet Propulsion Laboratory (JPL) continued to serve as an Analysis Center (AC) for the International GNSS Service (IGS). We contributed operational and reprocessed 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 2014, including our contribution to the second IGS reprocessing campaign (Repro 2).

Table 1 summarizes our contributions to the IGS Rapid and Final products. All of our contributions are based upon daily solutions centered at noon and spanning 30–hour. Each of our daily solutions is determined independently from neighboring solutions, namely without applying any constraints between solutions. Of note, JPL began to operationally deliver high–rate (30–second) Final GPS clock products to the IGS starting October 26, 2014.

The JPL IGS AC also generates Ultra-Rapid orbit and clock products for the GPS constellation (Weiss et al. 2010). These products are generated with a latency of less than 2 hours and are updated hourly. Although not submitted to the IGS, our Ultra-Rapid

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

products are available in native *GIPSY* formats at: ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Ultra.

2 Processing Software and Standards

The JPL AC continues to utilize the *GIPSY/OASIS software* package to generate our contributions to the IGS. Starting GPS week 1816 (October 26, 2014), we transitioned our operational IGS contributions to use *GIPSY/OASIS* version 6.3 and our Repro 2 processing configuration. Prior to this date we used *GIPSY/OASIS* version 6.2 to generate our products. A complete description of our current operational processing approach, also used for Repro 2, can be found at: http://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).

Our Repro 2 processing approach includes the following most notable improvements:

- 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.

Each of the changes were incrementally tested using a 1–year test period before they were accepted into our processing configuration.

3 Contribution to IGS "Repro 2" Reprocessing Campaign

At JPL we used our Repro 2 processed configuration to generate Final products (see Tab. 1) for GPS week 658 (August 16, 1992) onward (Desai et al. 2014). Our Repro 2 submission to the IGS was completely delivered on November 7, 2014 and included products spanning GPS weeks 729–1773 (December 25, 1993 to October 25, 2014). Our Repro 2 products for the full period, GPS week 658 onward, are available at the ftp site indicated below. As mentioned above, we then transitioned our operational submissions to the same Repro 2 processing configuration for October 26, 2014 onward. The full set of reprocessed and operational products, with a consistent Repro 2 approach, are available at:

1. `ftp://sideshow.jpl.nasa.gov/pub/jpligsac` in IGS formats, and
2. `ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Final` in *GIPSY* formats.

High-rate (30–second) GPS clock products were delivered to the IGS for the period May 5, 2000 onward, and are also available in native *GIPSY* format for that period. Also of note, daily JPL SINEX files are now available for our complete reprocessing period, GPS week 658 onward. Furthermore, our reprocessed products include our so–called "wide-lane phase bias" (WLPB) file for the entire time span of the products. The WLPB files enable single-receiver phase ambiguity resolved positioning when used with the *GIPSY/OASIS software* (Bertiger et al. 2010) and our GPS orbit and clock products.

Figure 1 shows that the most significant improvements to the JPL orbit products from Repro 2 relative to our products from the first IGS reprocessing campaign (Repro 1) are for 2003 onward. Meanwhile, the most significant improvements to the clock products are prior to 2002. These clock precision improvements are a result of the significant efforts made towards identifying and using stable reference clock sites in these earlier years. For the recent years, 2003–2011, orbit and clock precision is improved by 10–30 percent.

4 Future Work

In 2015, JPL will continue to submit operational Rapid and Final GPS products to the IGS using our Repro 2 processing configuration.

5 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.

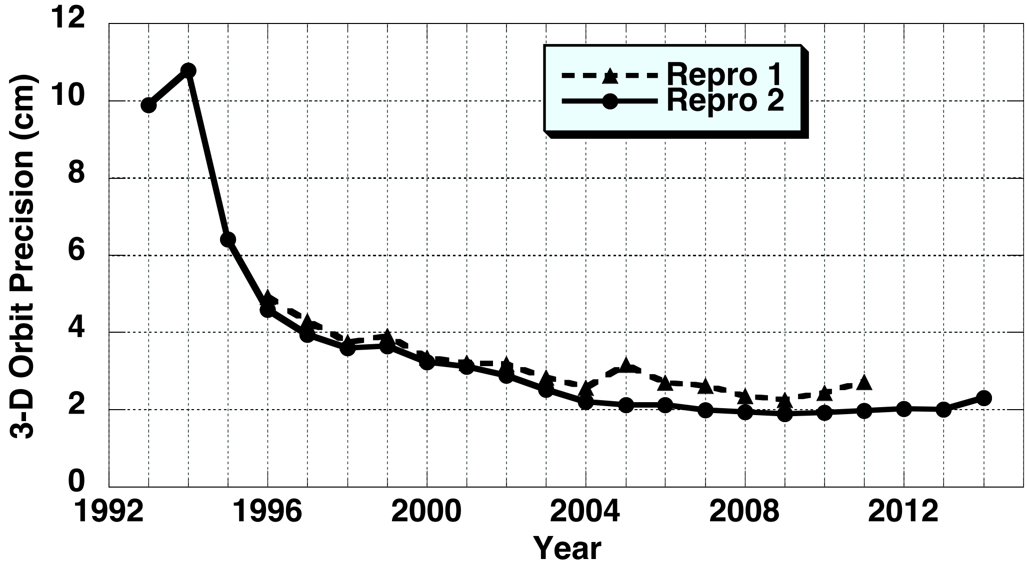

Figure 1: Precision of GPS orbit solutions from JPL's contributions to the IGS Repro 1 and 2 campaigns. Precision is measured using the annual median of daily RMS of differences during the middle 5 hours of the 6–hour overlapping period of adjacent–day solutions.

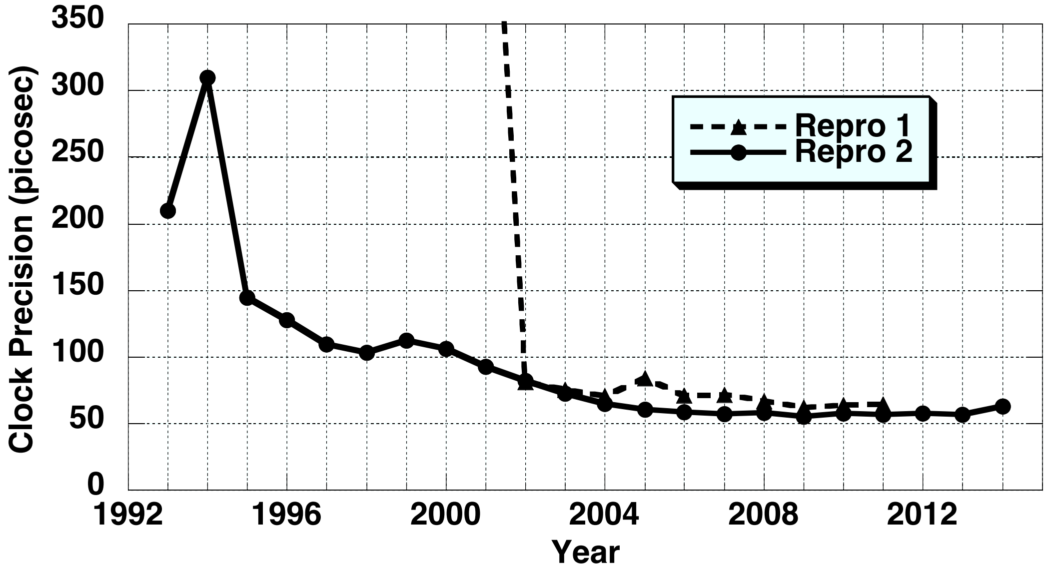

Figure 2: Precision of GPS clock solutions from JPL's contributions to the IGS Repro 1 and 2 campaigns. Precision is measured using the annual median of daily RMS of differences during the middle 5 hours of the 6–hour overlapping period of adjacent–day solutions. The Repro 1 clock precision for the periods 1996–2001 is 350–1200 picoseconds, and is therefore above the scale of the plot.

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USNO Analysis Center Technical Report 2014

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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). Dr. Christine Hackman directs AC activities, chairs the IGS TWG, and serves on the IGS Governing Board. Dr. Sharyl Byram oversees production of the IGS Final Troposphere Estimates. All GPSAD members, including Dr. Victor Slabinski, Mr. Jeffrey Tracey and contractor Mr. James R. Rohde, participate in AC work.

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

GPSAD also generates a UT1–UTC–like value, UTGPS, five times per day. UTGPS is a GPS–based extrapolator of VLBI–based UT1–UTC measurements. The IERS[2] Rapid Service/Prediction Center 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 in 2014

Figures 1–4 show the 2014 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 19 mm (24–h post–processed segment) and 38 mm (6–h predict) wrt the IGS rapid combined orbits. These values are largely the same as the 2013 values (16, 19 and 38 mm).

USNO rapid (post–processed) and ultra–rapid 6–h predicted clocks had median 162 ps and 1603 ps RMSs wrt IGS combined rapid clocks, compared to 146 and 1902 ps in 2013. Though by this measure the rapid clocks lost 11% precision, the ultra–rapid clocks gained 16 %.

USNO rapid polar motion estimates had (x, y) 186 and 108 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 by 105 and 110 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 338 and 278 micro arc sec. While the rapid and ultra–rapid post–processed estimate precision was slightly worse than the 2013 values (130, 99; 105, 60), the ultra–rapid prediction precision remained virtually the same as the 2013 value (338, 278).

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

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

[2] International Earth Rotation and Reference Systems Service

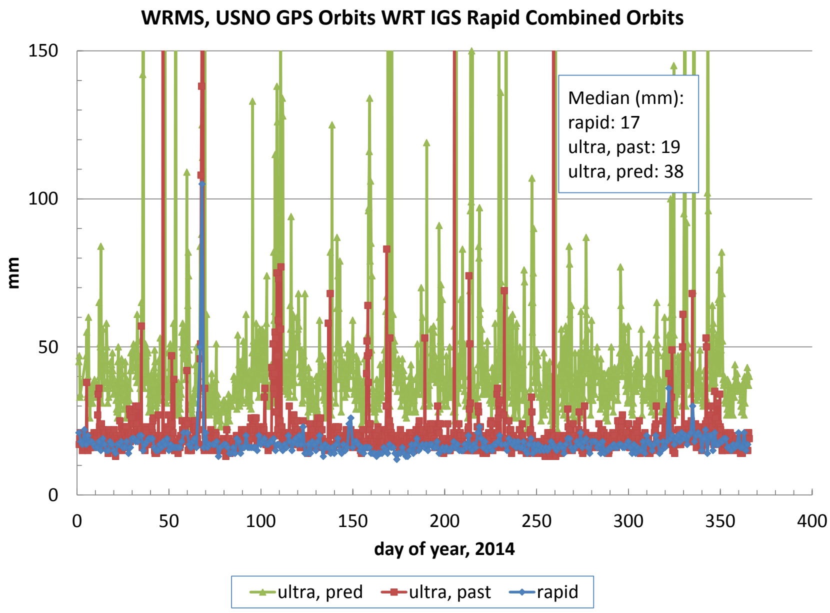

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2014. "Ultra, past" refers to 24–hour post–processed section of USNO ultra–rapid orbits. "Ultra, pred" refers to first six hours of ultra–rapid orbit prediction.

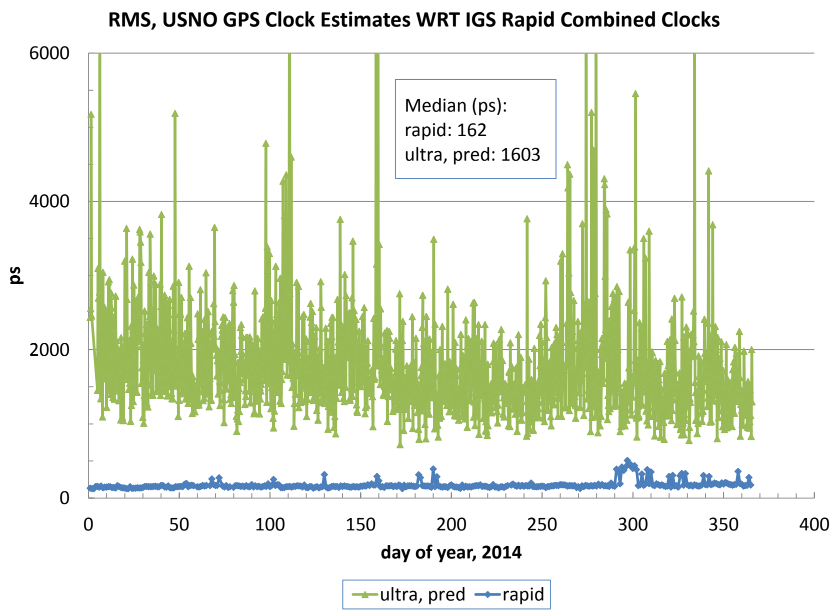

Figure 2: RMS of USNO GPS rapid clock estimates and ultra–rapid clock predictions with respect to IGS Rapid Combination, 2014.

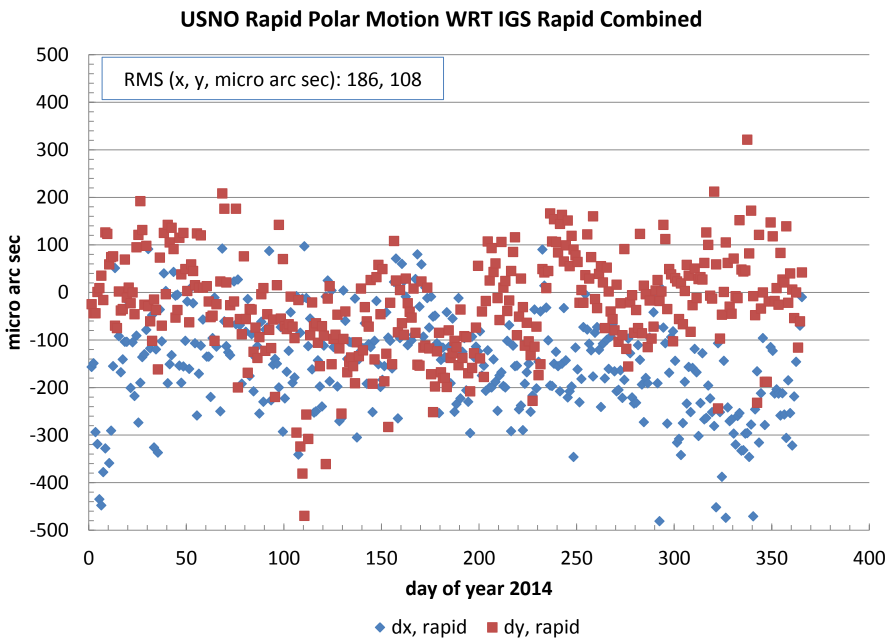

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2014.

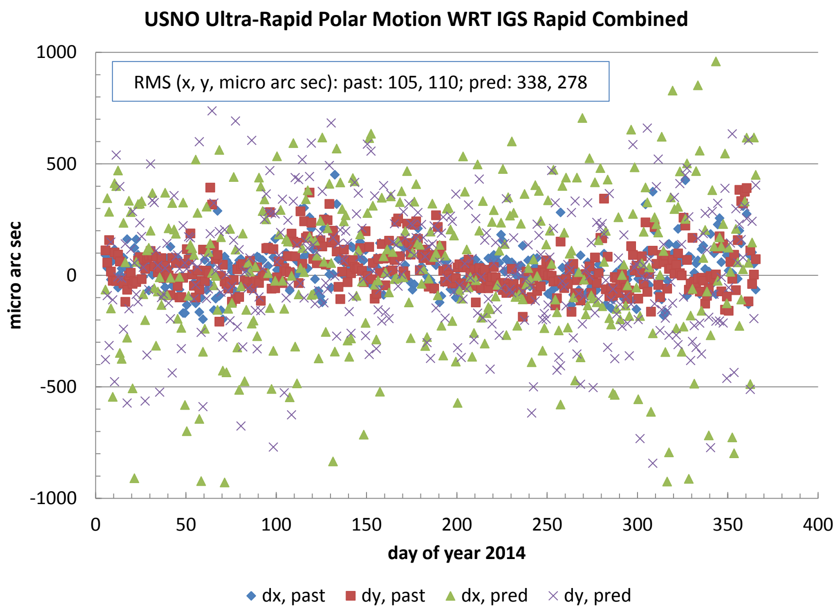

Figure 4: USNO ultra–rapid polar motion estimates minus IGS Rapid Combination values, 2014.

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
1/1/2014 – 12/31/2014	17	19	38	x: 186 y: 108	x: 105 y: 110	x: 338 y: 278	162	1603

ultra–rapid products are expected to be incorporated into the IGS "IGV" combination in 2015; they will also replace USNO's current ultra–rapid submissions to the IGS Combined Ultra–rapid "IGU" at that time.

In 2014, seven–parameter Helmert transformations computed between USNO and IGS ultra–rapid GLONASS orbits had median RMSs of 45 and 107 mm for the 24–h post–processed and 6–h predict portions, respectively. Meanwhile, the USNO GPS+GLONASS ultra–rapid 24–h post–processed polar motion values differed from the 24–hr post–processed segment of the IGS ultra–rapid GPS–only (aka IGU) values, RMS, by 138 and 92 micro arc sec, respectively. These data are shown in Tab. 2/Figs. 5–6.

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	6h predict	past 24h
1/1/2014 – 12/31/2014	45	107	x: 138, y: 92

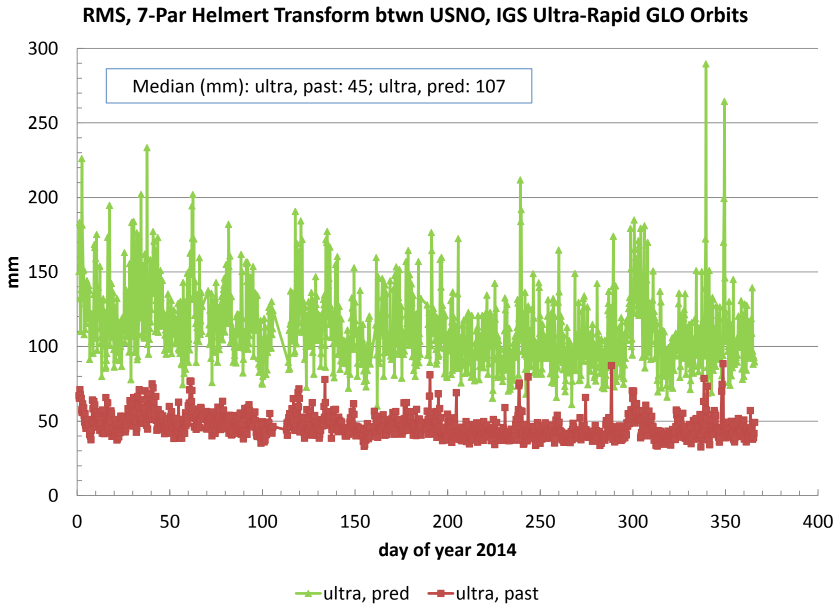

Figure 5: RMS of USNO ultra–rapid GLONASS orbit estimates with respect to IGS Combined Ultra–rapid GLONASS orbits, 2014. "Ultra, past" refers to 24–hour post–processed section of USNO ultra–rapid orbits. "Ultra, pred" refers to first six hours of ultra–rapid orbit prediction. Helmert transformations computed using *Bernese 5.0 Software*.

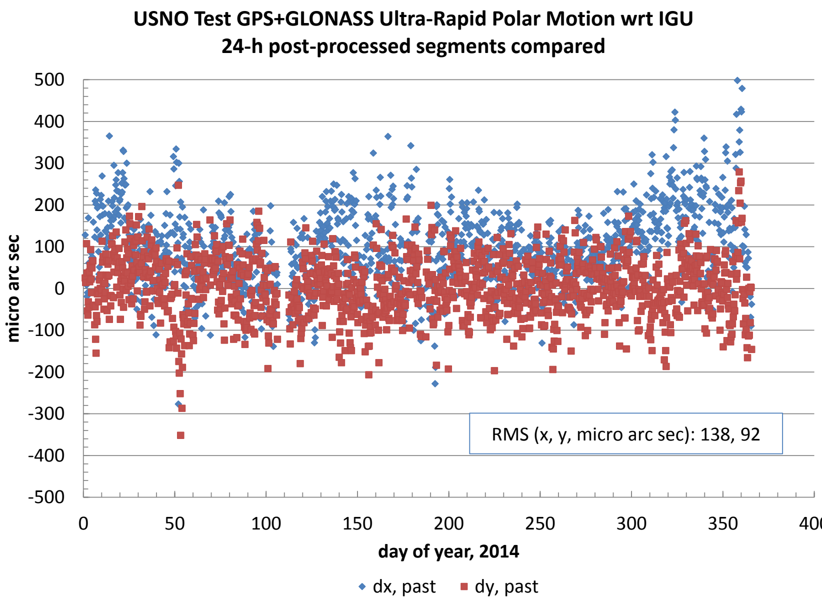

Figure 6: Difference between 24–h post–processed polar motion estimates in USNO test ultra–rapid GPS+GLONASS solution and IGS "IGU" GPS–only ultra–rapid solution, 2014.

The USNO AC acquired *Bernese GNSS Software* V5.2 in 2013 and plans to release official AC products generated using it in 2015. The GPS+GLONASS rapid and ultra–rapid solutions referenced above have been generated using *Bernese GNSS Software* V5.2 since December 2014.

3 USNO AC Conference Presentations/Publications

USNO AC members played an active role at the 2014 IGS Workshop (23–27 June 2014; Pasadena, CA), contributing three posters and chairing three sessions: Plenary Session 09A, *GNSS–Derived Troposphere Delays*, Poster Session 05, *Estimation and Application of GNSS–Based Troposphere Delay*, and the IGS Troposphere Working Group meeting. They also presented their research results at symposia such as *ION GNSS+ 2014* and the *American Astronomical Society Division on Dynamical Astronomy*. Their publications are as follows:

S. Byram and C. Hackman. IGS Final Troposphere Product Update. *IGS Workshop 2014*, Poster Session PS05, Pasadena CA, 2014.

S. Byram and C. Hackman. Multi–GNSS Based Processing at the USNO. *IGS Workshop 2014*, Poster Session PS11, Pasadena CA, 2014.

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WHU Analysis Center Technical Report 2014

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1 Introduction

The IGS Analysis Center of the 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 development version of the *Positioning And Navigation Data Analyst (PANDA) Software* (Liu and Ge 2003).

In this report we give a summary of the IGS related activities at WHU during the year 2013.

2 PANDA software

The *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) for 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 network mode or precise point positioning mode, significantly improving the positioning accuracy of WHU final solutions.

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

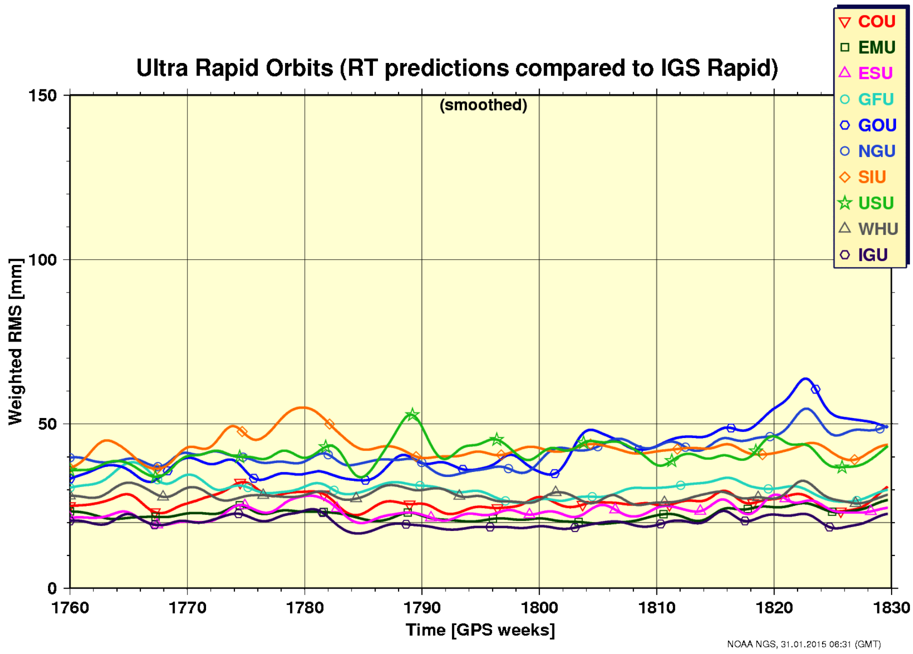

Figure 1: Weighted RMS of WHU ultra–rapid orbits.

3 WHU Analysis Products

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

The quality of the WHU ultra–rapid product is shown in Fig. 1. The accuracy of the predicted ultra–rapid orbit product is 3cm, measured as the WRMS compared with the IGS ultra–rapid orbit (IGU).

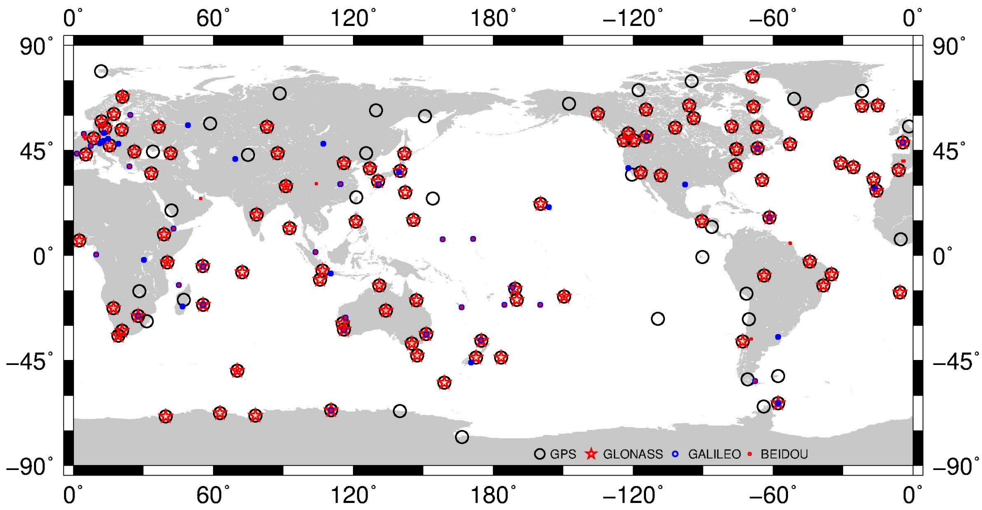

Figure 2: MGEX tracking stations.

4 MGEX Activities

IGS started the Multi–GNSS Experiment (MGEX) campaign since 2012 (Montenbruck et al. 2014). Up to now, more than 90 MGEX tracking stations collect data from the Multi–GNSS system including GPS, GLONASS, Galileo, BeiDou, and QZSS. WHU analyzes MGEX data (Fig. 2) and provides precise satellite orbit and clock solutions based on *PANDA software*. BeiDou orbit and clock products from WHU (called "WHM") are available at: `ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex`.

The accuracy of the GPS satellite orbit provided by GPS+GLONASS combined solution from WHU is about 1cm (1D) compared with IGS final solution (Fig. 3).

The accuracy of the GLONASS satellite orbit provided by GPS+GLONASS combined solution from WHU is about 3cm (1D) compared with IGL final solution (Fig. 5).

The accuracy of the Beidou IGSO (C08) and MEO (C11) satellite orbit provided by GPS+Beidou combined solution from WHU is about 10 cm validated by SLR data. (Fig. 5 and Fig. 6).

The accuracy of the Galileo satellite orbit using GPS+Galileo combined solution from WHU is about 10 cm validated by SLR data. (Fig. 7 and Fig. 8).

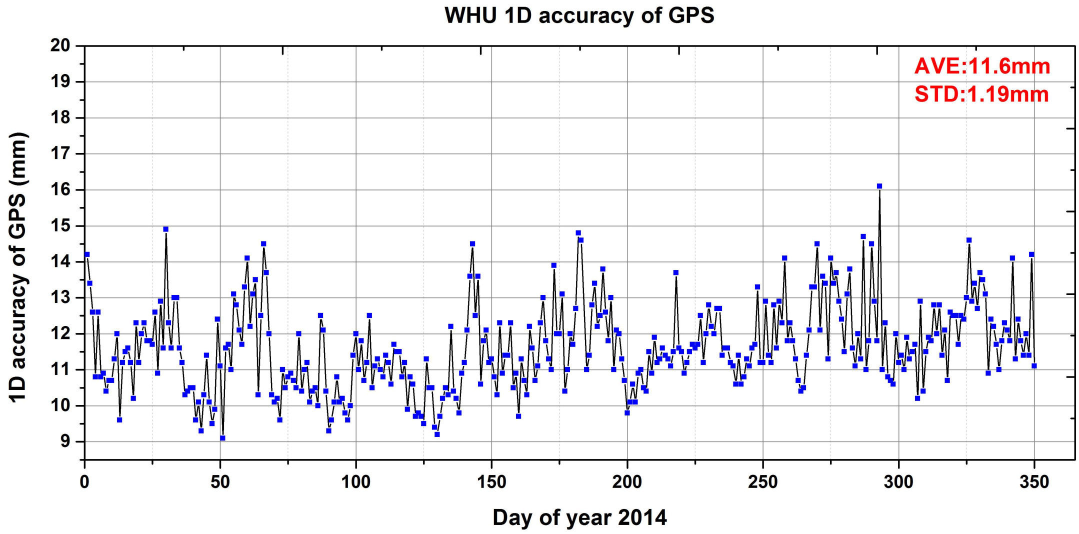

Figure 3: GPS orbit compared with IGS final solution.

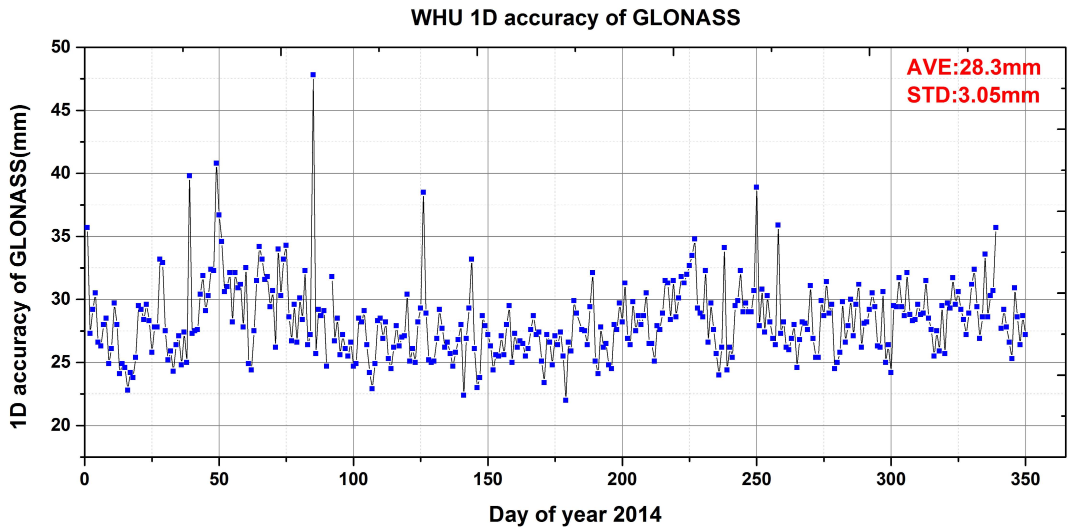

Figure 4: GLONASS orbit compared with IGL final solution.

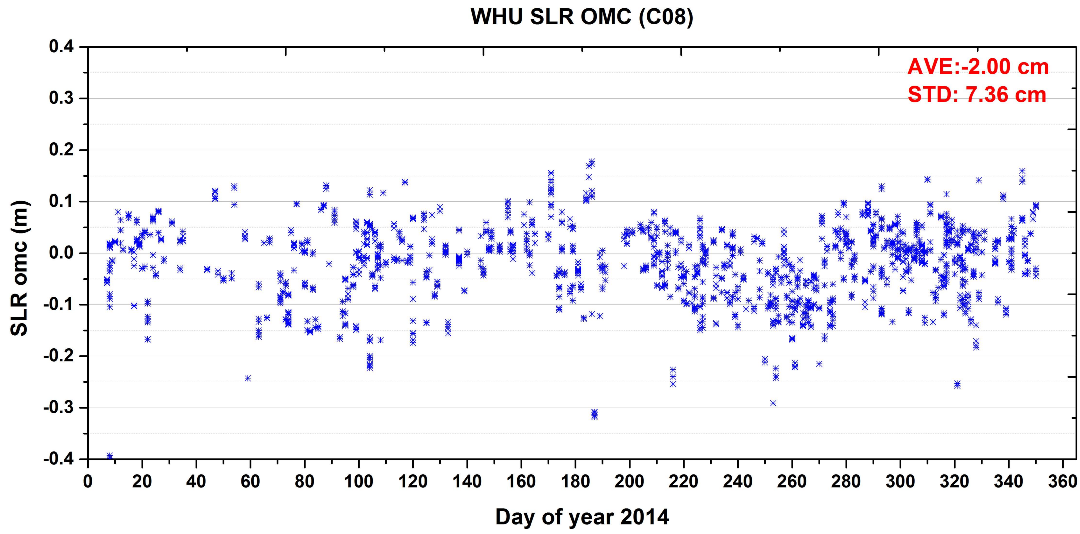

Figure 5: Beidou C08 orbit validation by SLR.

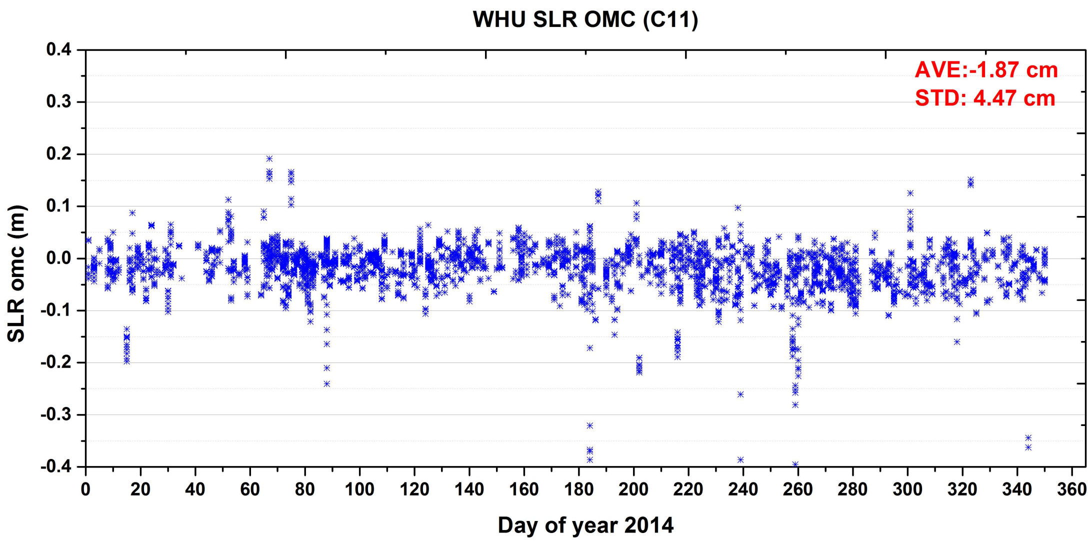

Figure 6: Beidou C11 orbit validation by SLR.

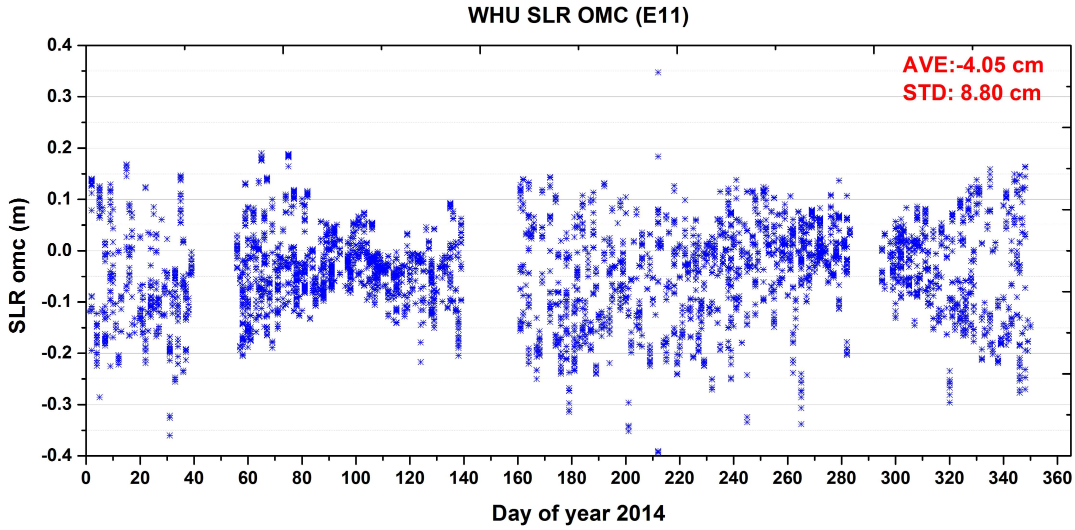

Figure 7: Galileo E11 orbit validation by SLR.

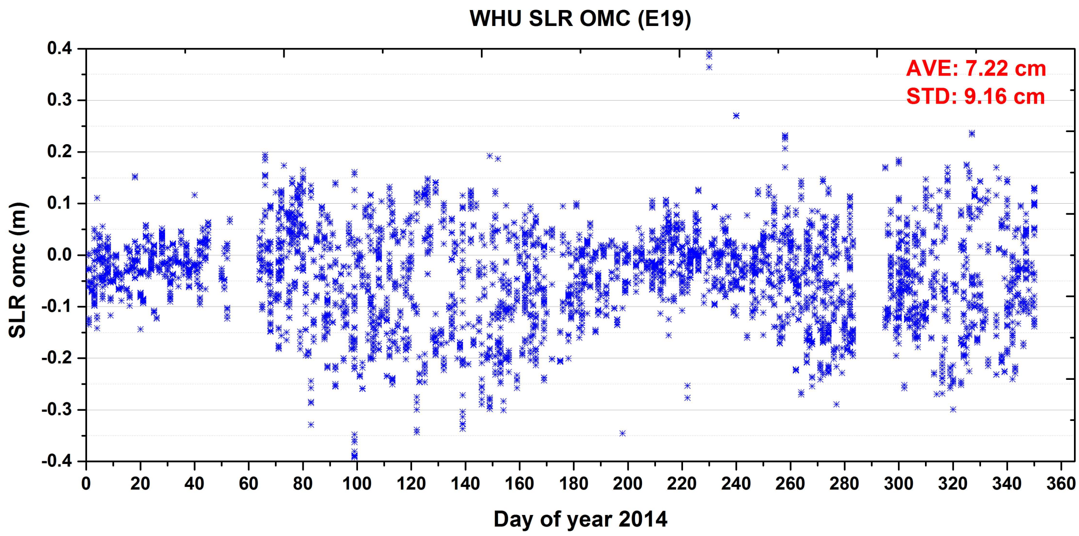

Figure 8: Galileo E19 orbit validation by SLR.

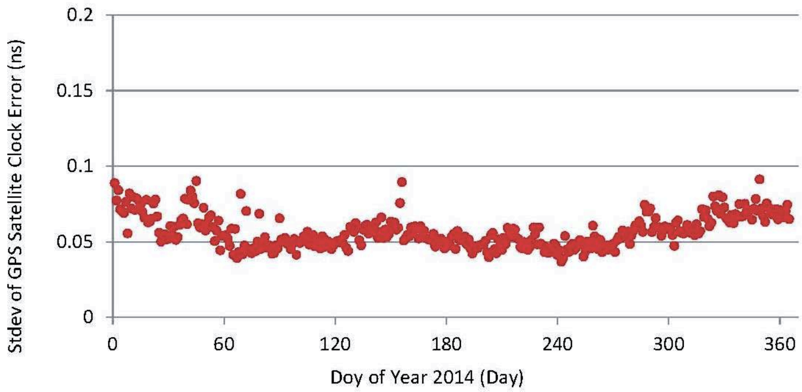

Figure 9: The STD of real time clock error compared with IGS final solution.

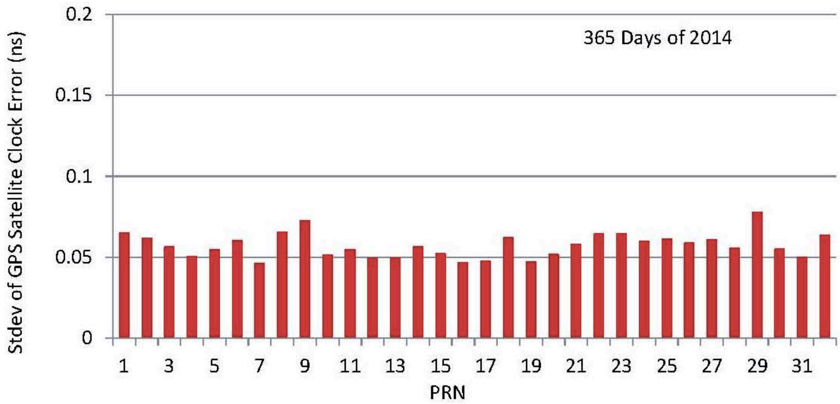

Figure 10: The STD of real time clock error of GPS satellites.

5 Real Time Activities

IGS Real–Time Service officially launched in April 2013, and WHU is one of the first real time analysis centers. The CLK15 and CLK16 streams published at IGS real time service www.igs-ip.net) are the real–time precise satellite orbit and clock products by WHU.

The real time precise orbit is based on ultra–rapid products, which has been introduced in Section 2. The performance of the real time satellite clock products is shown in Fig. 9.

The precision of clock error is about 0.06ns in 2014.The following figure shows the statistic results of each satellite.

The statistical result of each satellite is shown in Fig. 10, and the precisions all GPS satellites have equivalent performance during the year 2014.

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EPN Regional Network Associate Analysis Center Technical Report 2014

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1 Introduction

The IAG (International Association of Geodesy) 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, for instance, involved in the IGS Governing Board, the IGS Real–Time Pilot Project, the IGS GNSS Working Group, the IGS Antenna Calibration Working Group, the IGS Troposphere Working Group, the IGS Multi GNSS Experiment (MGEX), and the IGS Infrastructure Committee.

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), Data Flow Coordinator, Analysis Coordinator, Reference Frame Coordinator, Troposphere Coordinator, and Chairs of the Real–time Analysis, Reprocessing, and multi–GNSS Working Groups.

This paper gives an overview of the main changes in the EPN during the year 2014.

2 Tracking Network

At the end of 2014, the EPN network consisted of 263 continuously operating GNSS reference stations (Fig. 1) from which 31% also belong to the IGS. Before inclusion in the EPN, the EPN Central Bureau (CB) checks the data quality, meta–data, data availability and latency, and the availability of absolute antenna calibrations for the proposed station. These absolute antenna calibrations can be type mean calibrations (provided by the IGS) or individual calibrations. End of 2014, individual calibrations were used at 73 EPN stations.

Eighteen new stations were integrated in the EPN network in 2014 (see Tab. 1). They are indicated with triangles in Fig. 1. All new stations added to the EPN in 2014 are equipped with GPS/GLONASS tracking equipment, bringing the percentage of the EPN stations providing GPS+GLONASS data to 79%. In addition, 160 EPN stations have a receiver capable of tracking GPS L5, although only 60 of them are actually providing RINEX v2.11 data including L5 (see Fig. 2). At the end of 2014, 134 EPN stations (more than half of the EPN, see Fig. 3) operated receivers that are certified "Galileo–ready". This does however not mean that all these stations provide Galileo observations. In fact, only 78 of them indicate in their site log that they provide Galileo observations. As will be shown in Section 3, this does not necessarily mean that these stations are also distributing RINEX files including Galileo observations.

3 RINEX v3

The development of the EPN network towards multi–GNSS is coordinated in a EUREF working group (chaired by E. Brockmann) which started its activities after the EUREF symposium 2010 in Gävle (Sweden). The EPN is working with three main data centers defined as regional data centers (RDC).

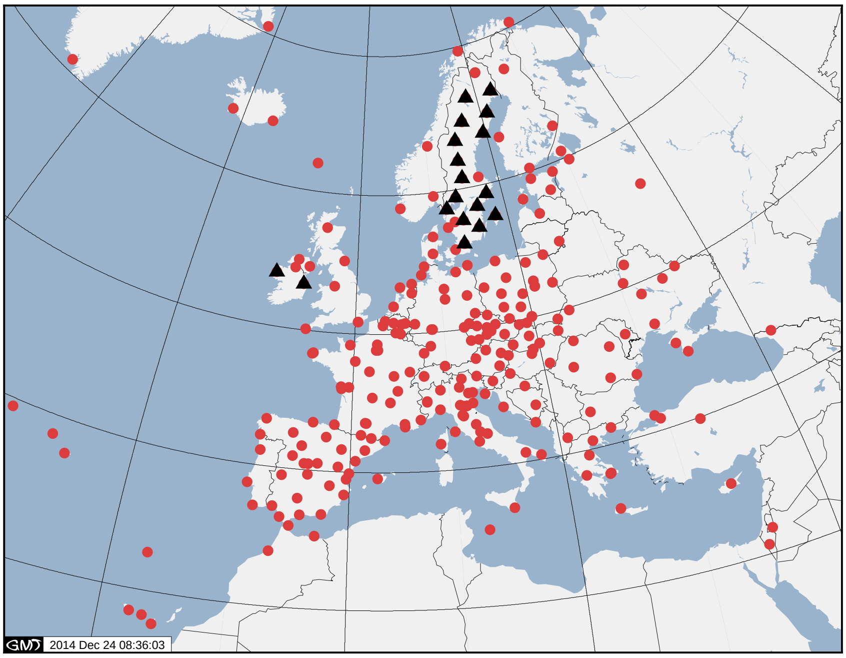

Figure 1: EPN tracking stations, status in December 2014. ▲ indicate new stations included in the network in 2014.

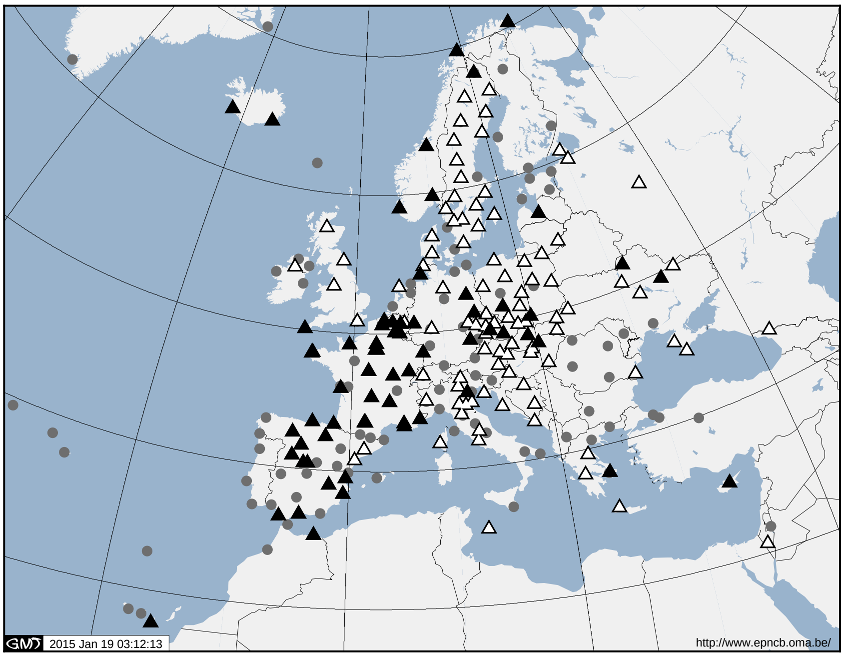

Figure 2: EPN tracking stations capable of tracking L5 indicated with △; those in addition including L5 in their RINEX v2.11 data are indicated by ▲ (status in December 2014).

Table 1: New stations included in the EPN in 2014

4 char–ID	Location	Replacement or new	Sat. Tracking	Antenna Calibration used in EPN analysis
ARJ6	Arjeplog, Sweden	new	GPS+GLO	Individual from GEO++
CASB	CastleBar, Ireland	new	GPS+GLO	Type mean from IGS
HAS6	Hassleholm, Sweden	new	GPS+GLO	Individual from GEO++
JON6	Jonkoping, Sweden	new	GPS+GLO	Individual from GEO++
KAD6	Karlstad, Sweden	new	GPS+GLO	Individual from GEO++
LEK6	Leksand, Sweden	new	GPS+GLO	Individual from GEO++
LOV6	Lovo, Sweden	new	GPS+GLO	Individual from GEO++
NOR7	Norrkoping, Sweden	new	GPS+GLO	Individual from GEO++
OSK6	Oskarshamn, Sweden	new	GPS+GLO	Individual from GEO++
OST6	Ostersund, Sweden	new	GPS+GLO	Individual from GEO++
OVE6	Overkalix, Sweden	new	GPS+GLO	Individual from GEO++
SKE8	Skellefteaa, Sweden	new	GPS+GLO	Individual from GEO++
SVE6	Sveg, Sweden	new	GPS+GLO	Individual from GEO++
TLLG	Dublin, Ireland	new	GPS+GLO	Type mean from IGS
UME6	Umea, Sweden	new	GPS+GLO	Individual from GEO++
VAE6	Vanersborg, Sweden	new	GPS+GLO	Individual from GEO++
VIL6	Vilhelmina, Sweden	new	GPS+GLO	Individual from GEO++
VIS6	Visby, Sweden	new	GPS+GLO	Individual from GEO++

The IGS RINEX3 transition plan, which was endorsed by the IGS Governing Board in December 2014, contains the new RINEX v3 file naming conventions and expects that RINEX v3 data will be put to into the same directories as RINEX v2 data. Presently, only the BKG RDC is hosting EPN RINEX v3 data (using the old RINEX v2 file names) in a separate directory. Implementing the IGS RINEX3 transition plan will require a restructuring of the EPN data centers which will need time.

In the meantime, the number of stations providing RINEX v3 files (using the RINEX v2 file naming conventions) is still growing (see Fig. 3). Currently, 58 EPN stations are delivering RINEX v3 data (51 of them include Galileo observations). Taking into account that 78 EPN stations indicate in their site log that they provide Galileo observations, there is clearly still room for progress. Thirteen stations, mainly Leica and Javad receivers, still provide files with RINEX v3.01 instead of v3.02. Additionally, about 15 stations in Europe contribute data to the IGS–MGEX project.

An important requirement for the routine utilization of the RINEX v3 observation files is the availability of quality check software. EUREF 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 2007). Both allow useful operations such as RINEX header manipulation and the generation of data quality statistics. Several groups run these programs and make the results in form of plots available on their web pages: http://www.pecny.cz/GOP/index.php/gnss/data-center/euref-rnx3;

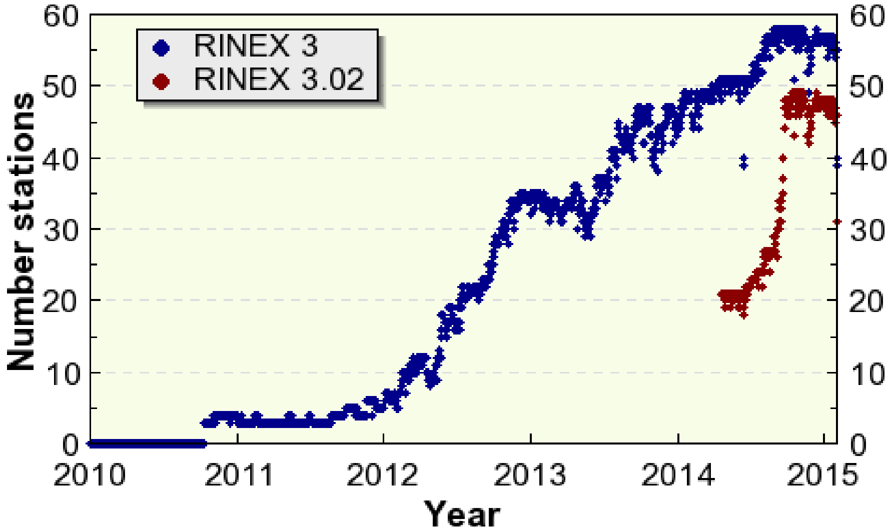

Figure 3: Number of EPN stations delivering RINEX v3 files.

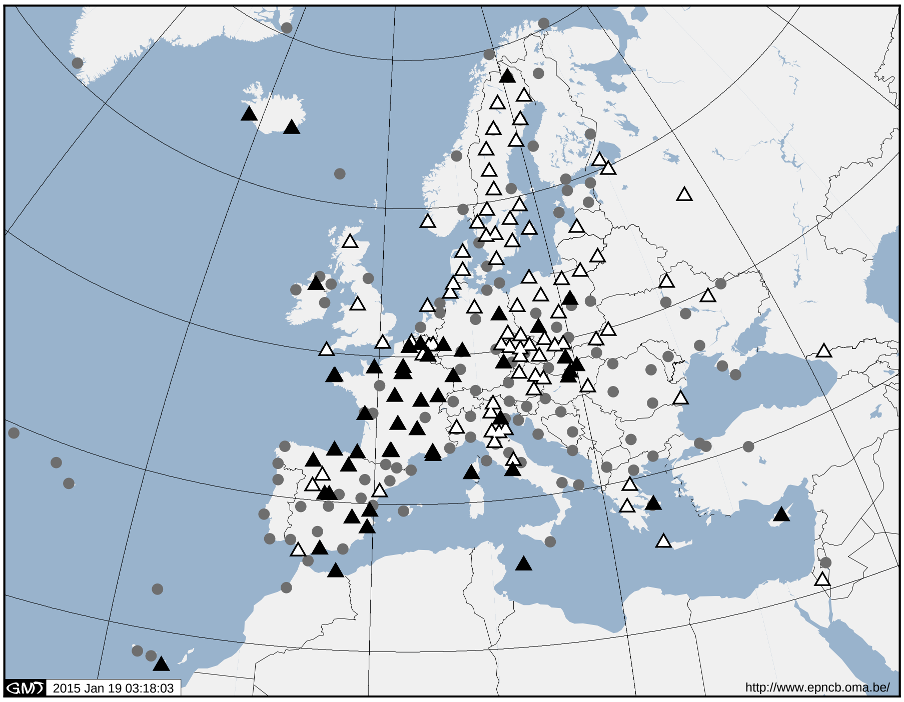

Figure 4: EPN tracking stations (134) capable of tracking Galileo: ▲ submitting RINEX v3 data to EUREF (51); △ not (yet) submitting RINEX v3 data to EUREF.

http://www.swisstopo.admin.ch/swisstopo/geodesy/pnac/html/en/anubis_monitor_r3.html

In addition, the EPN Central Bureau today already routinely cross–checks the RINEX v3 headers against the site log information (similarly to what is done for the RINEX v2 data) and also verifies the conformity of the RINEX v3 headers with respect to the RINEX v3 format description. Station managers are notified in case errors occur. In the course of 2015, the EPN CB web site will be extended with this information.

4 Data Analysis

4.1 Positions

Currently, 16 (from 18 existing) Local Analysis Centers (LACs) deliver SINEX solutions for the weekly EPN combination. Since January 2014, the GOP LAC focuses on the EPN reprocessing activities. The DEO LAC does not submit its solutions anymore since 2009, but is planning to restart routine analysis in 2015. The new Analysis Combination Center (Military University of Technology/Warsaw University of Technology consortium) delivered its first weekly final EPN solution for GPS week 1768 (November 2013). To ensure the coherence of the MUT/WUT combinations during the first months, the same strategy as the one used by the previous ACC (BKG) was applied. Since GPS week 1774 (January 2014), only stations processed by at least three LACs are taken into consideration in the final daily and weekly solutions which enables the detection of outliers and the reliability of the solutions. However, exceptions are made for new stations which are, in the beginning of their lifetime, and still processed by less than three LACs. Since GPS week 1787, the number of reference stations was decreased from 71 to 46 stations in order to exclusively use EPN stations included in the most recent IGb08 realization. The new ACC also continues to deliver rapid daily combinations (since 1770 GPS week) and ultra–rapid daily combinations (since GPS week 1773) which are mainly used for rapid monitoring of the EPN station positions.

All combinations are performed with the *Bernese GNSS Software* (Dach et al. 2013). Prior to the combination process, the LAC SINEX files provided by the different LAC are automatically checked against possible metadata inconsistencies (e.g. antenna types and calibration models, receiver types) and problematic stations are excluded from the combination. Information about these products and coordinate time series are presented at the EPN ACC webpage (http://www.epnacc.wat.edu.pl). For the rapid combinations, such information, together with characteristics of the combined solution and the inconsistencies from the LAC SINEX files, can be found in the combination reports sent to the BKG product center (ftp://igs.bkg.bund.de/EUREF/products/WWWW/eurWWWWmr.sum).

Fourteen of the sixteen LACs use both GPS and GLONASS data (in 2014 two LACs updated their *Bernese software* and started to include GLONASS observations). The

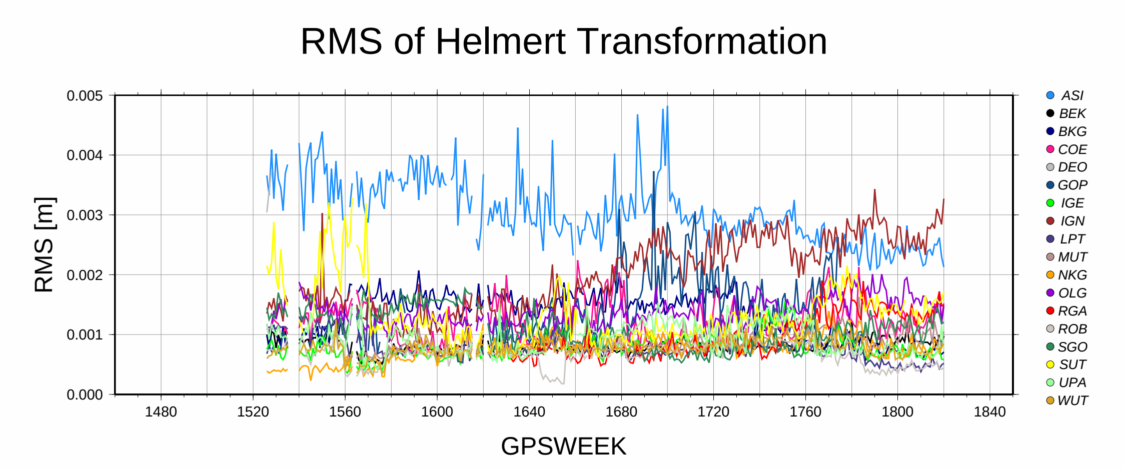

Figure 5: Agreement (RMS of Helmert transformation) between each weekly LACs solution and the weekly EPN combined solution.

Helmert residuals of the weekly individual solutions with respect to the combined solution have in 2014 a mean RMS of 0.6 millimeters for the horizontal components and 2.4 millimeters for the vertical component. A plot of the agreement between each weekly LACs solution and the combined solution (see Fig. 5) is presented online at http://www.epnacc.wat.edu.pl and in the reports available from the EPN CB.

4.2 Troposphere

Beside station coordinates, the 16 LACs also submit zenith total delay (ZTD) parameters on a routine basis. The ZTDs are delivered with a sampling rate of 1 hour, on a weekly basis but in daily files. Along with the ZTDs, tropospheric gradients are submitted since November 2013. The BKG has provided the EPN troposphere coordinator (TC) since 2001. It has been very successful in developing the troposphere estimation and combination from a Special Project into routine operation. In June 2014, Wolfgang Söhne, who assumed the position for more than ten years, handed over the troposphere activities to Rosa Pacione from the Italian Space Agency/Centro di Geodesia Spaziale (ASI/CGS). ASI/CGS started with its routine tropospheric combinations at GPS week 1800 (June 2014).

The most important task of the new TC in 2014 was to implement scripts for the combination of the tropospheric solutions provided by LAC. The tropospheric combination is based on a generalized least square method, following Pacione et al. 2011. The software code was developed in 2008 and it is currently used also in the framework of the EUMETNET EIG GPS Water Vapour Programme (E–GVAP, http://egvap.dmi.dk). The agreement between BKG and ASI combined tropospheric solutions, based on the data of the whole year 2013 and the entire EPN, is at a sub–millimeter level in term of bias and 1 millimeter level in term of standard deviation. The format of the Tropospheric Summary Files has also been reviewed and simplified by removing some tables.

Thanks to the growing computation power, the individual LACs enlarged their networks in 2014. This way, almost all EPN stations are processed by at least four LACs which improves, for example, the outlier detection. On average 254 stations are processed by more than three LACs, 8 by two LACs and only 5 by one LACs. In the last four years of routine operation (2011–2014), the weekly mean biases (see Fig. 6) are within 2 millimeters ZTD level, while their standard deviations range between 1 to 2 millimeters (see Fig. 6) with a few outliers in the last period of routine operation. The jump in the standard deviation time series (see Fig. 6) occurred at GPS week 1800 is related to the use of a different combination software starting from that GPS week.

Alongside the ZTD combination which gives insight into the agreement of the individual solutions to each other, some inter–technique comparisons have been added to the web site of the EPN Central Bureau. The time series of EPN ZTD differences with respect to radiosonde–derived ZTDs are computed for almost 100 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 are available.

4.3 Reprocessing

Currently the EPN working group on Reprocessing conducts a second reprocessing campaign, EPN–Repro2 realized in the IGb08 and it is coordinated by the Bavarian Academy of Sciences and Humanities (BEK). The analysis is being carried out on the EPN data from 1996 till 2013 by five analysis centers. It will include three independent solutions obtained using *Bernese* 5.2, *GAMIT* 10.5 and *GIPSY* 6.2 for the entire EPN and the results of two EPN subnetworks processed with *Bernese GNSS Software* v5.2. The analysis strategy is very much consistent with the recent LAC guidelines for the routine processing of the EPN. The processing of the data is performed as a regional network without orbit, EOP and clock parameter estimation and relies completely on available reprocessed products. Due to the lack of reprocessed combined IGS products (2nd IGS Reprocessing campaign), the reprocessed products provided by CODE and the preliminary reprocessed products by JPL are used.

In preparation of EPN–Repro2, a benchmark test with the different software packages, and based on the same data and network design, has shown good agreement between the different solutions (Völksen et al. 2014). The completion of the EPN–Repro2 daily solutions is expected for February 2014. First results of the combination of the different results will be presented at the next EUREF symposium in June 2015. The importance of

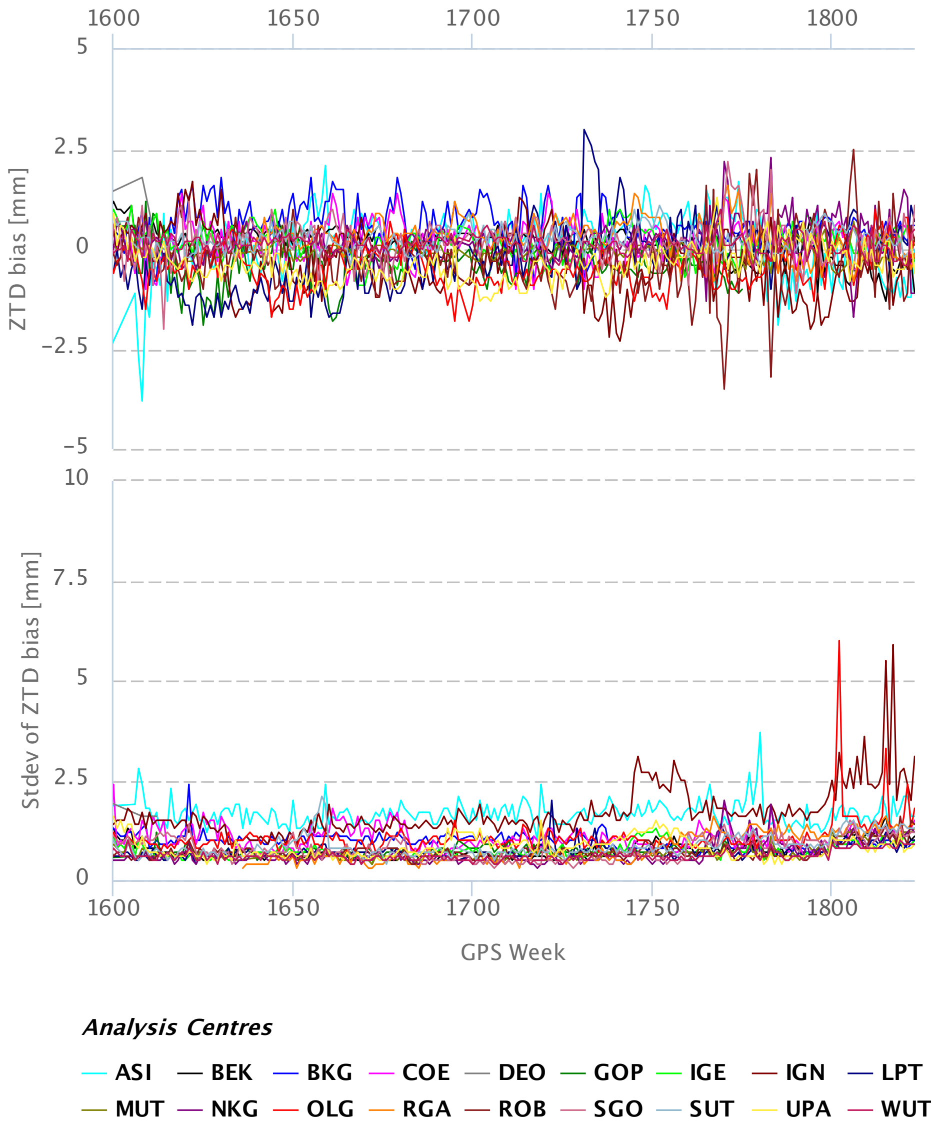

Figure 6: Weekly mean biases of LACs individual ZTD contributions with respect to the combined ZTD solution (mm ZTD); results from last 4 years of routine operation (Top). Standard deviation of weekly mean biases of LACs individual ZTD contributions with respect to the combined ZTD solution (mm ZTD); results from last 4 years of routine operation (Bottom).

the reprocessing activities has also been acknowledge by installing a Dedicated Analysis Center (DAC) for Reprocessing at the Geodetic Observatory Pecny (GOP).

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 *CATREF software* (Altamimi et al. 2007) and updated each 15 weeks. 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 EPN–Repro2 products will become available, the multi–year EPN solution will be updated to be compliant with the latest standards. The EPN IGb08 densification 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 and geophysical modeling. This densification is done by the EPN Reference Frame Coordinator (A. Kenyeres), but actually a Working Group will be formed in 2015 to support the growing needs of the densification activities. 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 the consistent cumulative position/velocity solution. Both combinations are done using the *CATREF software* using 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 2500 as of December 2014. Two contributions (IGN, France and BIGF, UK) are global solutions and therefore the EPN densification shall be considered as a global solution. The densification products will be an essential contribution to several groups and projects as the IAG working group on "*The integration of dense velocity field in the ITRF*", EPOS (European Plate Observatory System) and EUPOS (European Positioning System). This work is still in progress (see Kenyeres et al. 2014).

6 Stream and Product Dissemination

The availability of all EPN real–time streams and products at the three EUREF regional broadcasters located at ASI (`http://euref-ip.asi.it:2101`), BKG (`http://www.euref-ip.net`) and ROB (`http://www.euref-ip.be/`) continued to converge in 2014. For this purpose, the EPN CB compares on–line the status of each mountpoint at the three broadcasters, so that the service providers, station managers and users can immediately see if an outage is caused by one of the casters or the stream provider. The aim is full flexibility, so that every user is able to switch between the casters without loss of availability. The on–line monitoring will be made publicly available in early 2015. For the time being, it is not planned to mix mountpoints providing legal RTCM 3 messages with new mountpoints providing RTCM MSM messages on the three EPN broadcasters. In addition, EUREF is working on guidelines for the EPN broadcasters which will be released in 2015.

REAL-TIME PRODUCTS

Mountpoint	**ASI** (status: 2015-01-29 15:35 UTC)	**BKG** (status: 2015-01-29 15:35 UTC)	**ROB** (status: 2015-01-29 15:35 UTC)
EUREF01	RTCM 3.0 - BKG	RTCM 3.0 - EUREF filter combination	RTCM 3.0 - EUREF filter combination
EUREF02	RTCM 3.0 - BKG	RTCM 3.0 - EUREF filter combination	RTCM 3.0 - EUREF filter combination
RTCM3EPH	RTCM 3 - BKG		

REAL-TIME DATA STREAMS

Mountpoint	**ASI** (status: 2015-01-29 15:35 UTC)	**BKG** (status: 2015-01-29 15:35 UTC)	**ROB** (status: 2015-01-29 15:35 UTC)
ACOR0	RTCM 3.1 - ergnss-ip.ign.es:2101/ACOR0(1)	RTCM 3.1 - ergnss-ip.ign.es:2101/ACOR0(1)	RTCM 3.1 - IGNE, Servicio de Programas Geodesicos
AJAC0	RTCM 3.1 - rgp-ip.ign.fr:2101/AJAC1(1)	RTCM 3.1 - www.igs-ip.net:2101/AJAC0(2)	RTCM 3.1 - none
ALAC0	RTCM 2.3 - ergnss-ip.ign.es:2101/ALAC0(1)	RTCM 3.0 - ergnss-ip.ign.es:2101/ALAC0(1)	RTCM 3.1 - IGNE, Servicio de Programas Geodesicos
ALBA0	RTCM 2.1 - ergnss-ip.ign.es:2101/ALBA0(1)	RTCM 3.0 - ergnss-ip.ign.es:2101/ALBA0(1)	RTCM 3.1 - IGNE, Servicio de Programas Geodesicos
ALME0	RTCM 2.3 - ergnss-ip.ign.es:2101/ALME0(1)	RTCM 2.3 - ergnss-ip.ign.es:2101/ALME0(1)	RTCM 2.3 - IGNE, Servicio de Programas Geodesicos
AUT10	RTCM 3.0 - www.euref-ip.net:2101/AUT10(1)	RTCM 3.0 - none	RTCM 3.0 - none
BELF0	RTCM 3.1 - www.euref-ip.net:2101/BELF0(1)	RTCM 3.1 - Ordnance Survey of Northern Ireland	RTCM 3.1 - Ordnance Survey of Northern Ireland
BELL0	RTCM 3.0 - www.euref-ip.net:2101/BELL0(1)	RTCM 3.0 - ICC Catnet	RTCM 3.0 - ICC Catnet
BOGI0	Last received on 2014-12-17 07:55 UTC	Last received on 2014-12-17 07:55 UTC	Last received on 2014-12-17 07:55 UTC

Figure 7: EPN real–time monitoring at the EPN CB (under construction).

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SIRGAS Regional Network Associate Analysis Center Technical Report 2014

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1 Introduction

The IGS Regional Network Associate Analysis Center for SIRGAS (IGS RNAAC SIR) was established in June 1996 under the responsibility of the Deutsches Geodätisches Forschungsinstitut (Seemüller and Drewes 1998), since January 2015 integrated into the Technische Universität München. The main objective of the IGS RNAAC SIR is the permanent analysis of the SIRGAS reference frame. The present activities of the IGS RNAAC SIR concentrate on (Sánchez 2014)

- the computation of loosely constrained weekly solutions for further combinations of the network (e.g., integration into the IGS polyhedron, computation of cumulative solutions, etc.). These solutions are weekly delivered to the IGS in SINEX format to be combined together with those generated by the other IGS Global and Regional Analysis Centers. They are named `sirwwww7.snx` (`wwww` stands for the GPS week);
- weekly station positions aligned to the same reference frame in which the IGS GNSS orbits are given, i.e., the IGS reference frame. These positions are applied as reference values for surveying applications in Latin America. Their name is `siryyPwwww.crd` (`yy` indicates the last two digits of the year).
- multi–year solutions providing station positions and constant velocities to estimate the kinematics of the reference frame and as support for applications requiring time–dependent coordinates. They are identified by `SIRyyPnn.SNX` (`nn` being the number of the cumulative solution computed in one year).

2 The SIRGAS reference frame

The SIRGAS reference frame was regularly computed by the IGS RNAAC SIR as only one common network until August 31, 2008 (GPS week 1495) (Seemüller et al. 2012). Afterwards, due to the increasing number of stations (about 400 in December 2014), different sub–networks were defined and, at present, the analysis strategy is based on the combination of individual solutions including (Brunini et al. 2012)

- one core network (SIRGAS–C) composed of a set of geographically well–distributed and consistently reliable reference stations (Fig. 1). The main objective of the SIRGAS–C network is to ensure the long–term stability of the reference frame, and it is understood as the primary densification of the ITRF in Latin America and the Caribbean.

- national reference networks (SIRGAS–N) realizing densifications of the core network (Fig. 1). The central purpose of these densifications is to provide accessibility to the reference frame at national and local levels and to facilitate its extension by assimilating new reference stations (mainly those installed by the national agencies responsible for the local reference networks).

3 SIRGAS analysis centers

The SIRGAS–C network is processed by DGFI–TUM as IGS RNAAC SIR. The SIRGAS–N networks are computed by the SIRGAS Local Processing Centers, which operate under the responsibility of national Latin American organizations. At present, the SIRGAS Local Processing Centers are:

- 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)

- CPAGS–LUZ: Centro de Procesamiento y Análisis GNSS SIRGAS de la Universidad del Zulia (Venezuela)

- IBGE: Instituto Brasileiro de Geografia e Estatistica (Brazil)

- IGAC: Instituto Geográfico Agustín Codazzi (Colombia)

- IGM–Cl: Instituto Geográfico Militar (Chile)

- IGN–Ar: Instituto Geográfico Nacional (Argentina)

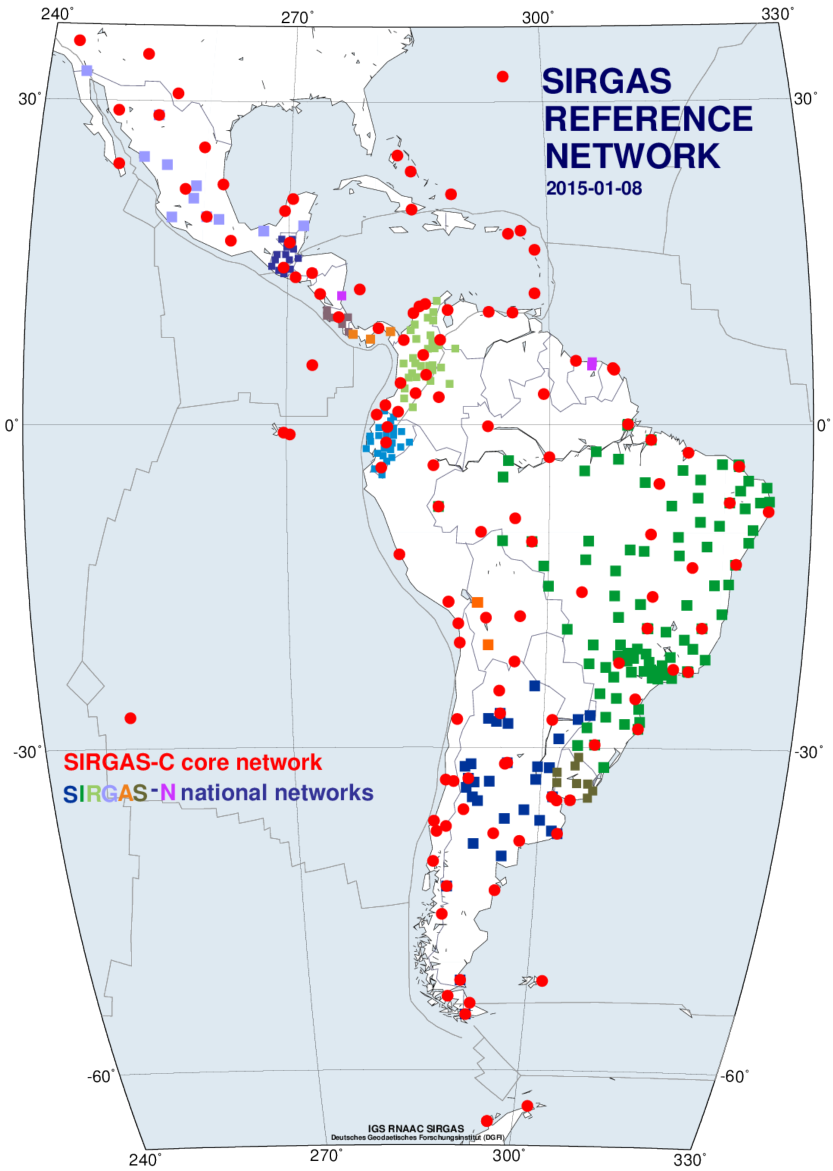

Figure 1: SIRGAS reference network (as of January 2015).

- INEGI: Instituto Nacional de Estadística y Geografía (México)
- SGM: Servicio Geográfico Militar (Uruguay)

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

4 Routine processing of the SIRGAS reference frame

The SIRGAS processing centers follow unified standards for the computation of the loosely constrained solutions (Sánchez et al. 2013). 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 compute these parameters), and positions for all stations are constrained to ± 1 m (to generate the loosely constrained solutions in SINEX format). INEGI (Mexico) and IGN–Ar (Argentina) employ the software *GAMIT/GLOBK* (Herring et al. 2010); the other local processing centers use the *Bernese GPS Software* Ver. 5.2 (Dach et al. 2007, 2013).

5 New processing standards for the SIRGAS reference frame

Since January 2014, the SIRGAS processing centers apply the standards of the IERS Conventions 2010 (Petit and Luzum 2010) and the characteristics specified by the IGS for the second reprocessing of the IGS global network. The main changes with respect to the previous processing strategy are (Sánchez et al. 2015):

- Reference frame: IGS08/IGb08 (Rebischung et al. 2012)
- Antenna phase center model: igs08.atx (Schmid 2011)
- Tropospheric zenith delay modelling based on the Vienna Mapping Function 1 (VMF1, Böhm et al. 2006) with a priori values (∼dry part) from the gridded coefficients provided by J. Böhm at `http://ggosatm.hg.tuwien.ac.at/DELAY/GRID/VMFG` and refinement through the computation of partial derivatives with 2–hour intervals within the network adjustment
- Tidal corrections for solid Earth tides, permanent tide, and solid Earth pole tide as described by Petit and Luzum 2010. The ocean tidal loading is reduced with the

FES2004 model (Letellier 2004) and the atmospheric tidal loading caused by the semidiurnal constituents S1 and S2 is reduced following the model of van Dam and Ray 2010. The reduction coefficients for the ocean tidal loading are provided by M.S. Bos and H.–G. Scherneck at http://holt.oso.chalmers.se/loading. The reduction coefficients for the atmospheric tidal loading are provided by T. van Dam at http://geophy.uni.lu/ggfc-atmosphere/tide-loading-calculator.html.

- Non–tidal loadings like atmospheric pressure, ocean bottom pressure, or surface hydrology are not reduced.

At present, the SIRGAS processing centers are recomputing the daily normal equations backwards until January 1997 applying these new standards.

6 Modelling post–seismic deformations in the SIRGAS region

The Maule 2010 earthquake in Chile generated the largest displacements of geodetic observation stations ever observed in terrestrial reference frames (Sánchez et al. 2013). Coordinates changed by up to 4 m, and deformations were measurable in distances of up to to more than 1000 km from the epicenter. The station velocities in the regions adjacent to the epicenter changed dramatically after the seism; while they were oriented eastward with approximately 2 cm/y before the event, they are now directed westward with about 1 cm/y (Sánchez 2014; Sánchez et al. 2015). The 2010 Baja California earthquake in Mexico caused displacements on the dm level also followed by anomalous velocity changes. The main problem for geodetic applications is the fact that there is no reliable reference frame available in the region. To overcome this inconvenience, DGFI–TUM, acting as the IGS–RNAAC–SIR, computed a new multi–year solution for the SIRGAS reference frame (Fig. 2) considering only the four years after the seismic events (mid–2010 ... mid–2014). The obtained station positions and velocities refer to the IGb08 reference frame, epoch 2013.0. The averaged rms precision is ±1.4 mm horizontally and ±2.5 mm vertically for the station positions at the reference epoch, and ±0.8 mm/y horizontally and ±1.2 mm/y vertically for the constant velocities. Based on this solution (called `SIR14P01`), a new continuous deformation model for SIRGAS was computed (Fig. 3) following the strategy implemented by Drewes and Heidbach 2012. It is clear that the tectonic structure in South America has to be redefined. The area south of 35°S to 40°S was considered as a stable part of the South American plate. Now we see that there are large and extended crustal deformations.

7 Outlook

The present SIRGAS activities concentrate on the reprocessing of the weekly SIRGAS normal equations backwards until January 1997 applying the new standards. The IGS

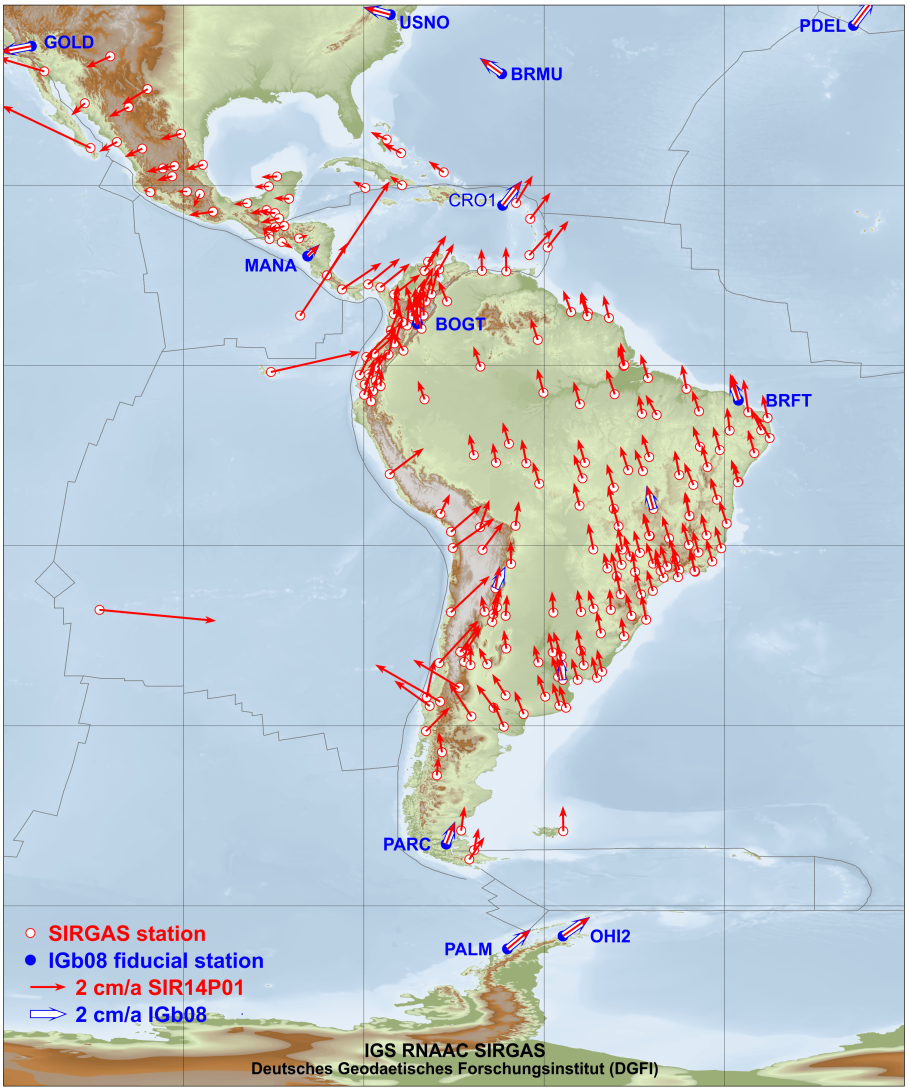

Figure 2: Horizontal velocities of the multi–year solution SIR14P01 (IGb08, 2013.0).

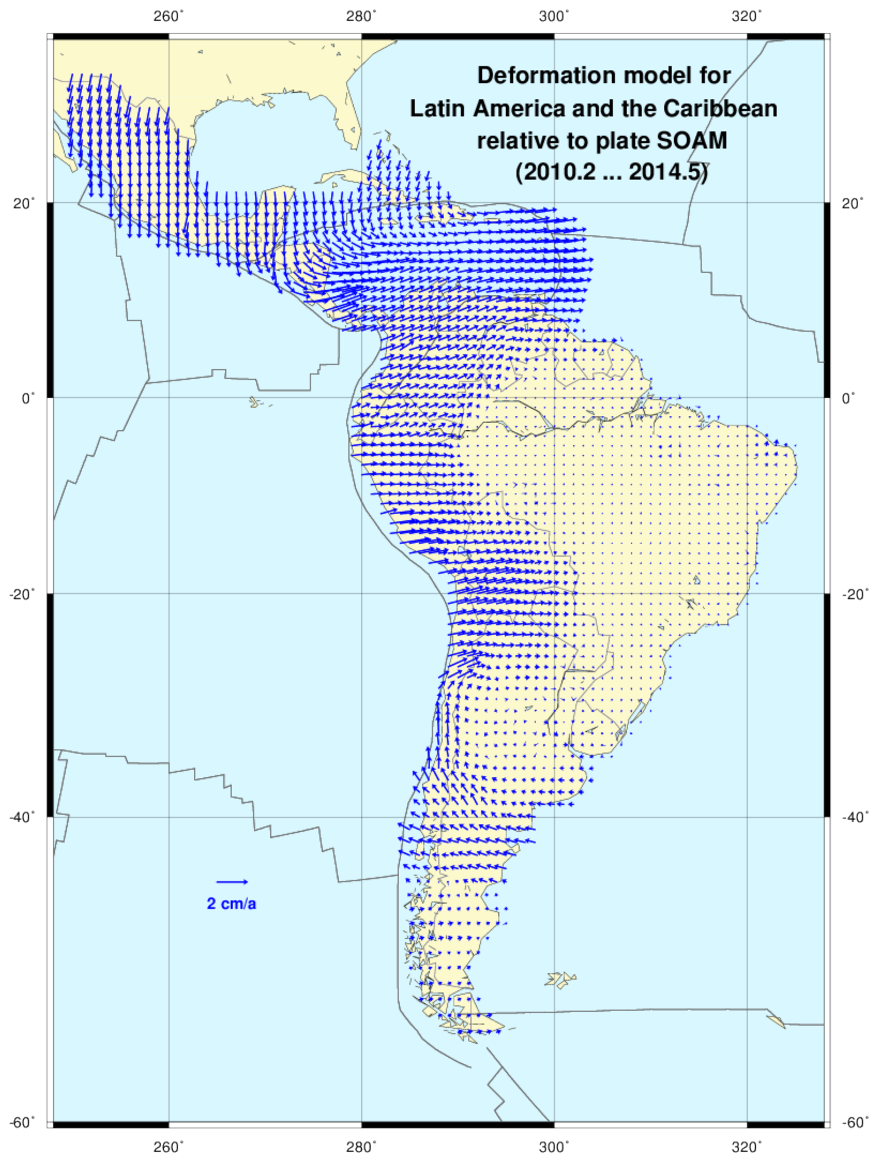

Figure 3: Post–seismic deformation model after the 2010 earthquakes in Latin America.

RNAAC SIR takes care of the computations from 1997 until August 2008, when the first SIRGAS Local Processing Centers started operating. From September 2008 until December 2013, the reprocessing includes the combination of the individual (reprocessed) solutions delivered by the SIRGAS Local Processing Centers for the SIRGAS–N national networks. Once the reprocessing is completed, a cumulative solution for the SIRGAS reference frame including time series analysis and seismic effects shall be computed.

8 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 2014

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1 Summary of Activities in 2014

The infrastructure committee consists of the members listed in Tab. 1. The IC broadly participated and helped organize the IGS workshop 2014 in Pasadena, coordinating one poster session, one presentation session and two splinter sessions. We produced the RINEX 3 transition plan drafts and revised it as need after all the inputs, and got it approved in the December 2014 GB meeting. We helped to monitor adherence to the RINEX 2.11 standard in the IGS data centers; no evolution of the RINEX 2.11 format is allowed and thus no data from Beidou, etc should be present in those files. We helped to promote the use of RINEX 3 data using the specified "long names".

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

2 Activity plan in 2015

- Continued IGS workshop 2014 recommendations implementation:
  - Implementation of the RINEX 3 transition plan (as detailed below)

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

  - To help promote a GNSS metadata XML exchange format with IGS and international partners
  - To start an L1 CA Navigation Bit Stream system

- RINEX 3 transition plan continued implementation following the steps outlined in the plan approved by the GB in December 2014 meeting:
  - NC/IC actions; new station IDs, site log new field, adapting site guidelines, adapting the IGS Station Log Manager
  - DC actions; Accept and check new long–name files, write Rx3 streams to the correct names, consider effect on product files storage
  - AC actions; encourage all ACs to process RINEX 3 files with new names, RFWG to consider SINEX changes to accommodate the new 'a9' station IDs, consider the impact on clock and tropo files as well.
- To better support the Network Coordinator by having more frequent 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 2014

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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 30 years, the CDDIS has provided continuous, long term, public access to the data (mainly GNSS–Global Navigation Satellite System, SLR–Satellite Laser Ranging, VLBI–Very Long Baseline Interferometry, and DORIS–Doppler Orbitography and Radiopositioning Integrated by Satellite) and products derived from these data required for a variety of 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 2014 are summarized below; this report also includes any recent changes or enhancements made to the CDDIS.

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 recently 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 the primary and secondary/failover system. 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 server. Data centers, stations, and analysis centers push files to the CDDIS incoming server. Processing of incoming files for the on–line archive is performed in a separate environment that also includes a database server 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 11.7 Tbytes in size of which 11 Tbytes (95%) is devoted to GNSS data, products (710 Gbytes), and ancillary information. All data and products are accessible through subdirectories of ftp://cddis.gsfc.nasa.gov/gnss (a symbolic link to ftp://cddis.gsfc.nasa.gov/gps).

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

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 2014

Data Type (GNSS)	Avg. No. Sites/Day	No. Unique Site	Avg. Volume/Day	Total Volume/Year	No. Files	Directory Location
Daily	475	534	1,100 Mb	400 Gb	735K	`/gnss/data/daily`
Hourly	310	341	383 Mb	140 Gb	6,705K	`/gnss/data/hourly`
High–rate	166	200	2,096 Mb	765 Gb	9,750K	`/gnss/data/highrate`

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. Nearly 175K daily station days from 534 distinct GNSS receivers were archived at the CDDIS during 2014. 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 341 hourly sites (over 6.7 million files) were archived during 2014.

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 200 high–rate sites (nearly 10 million files) were also archived in the CDDIS in 2014.

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

Table 3: GNSS MGEX Data Archive Summary for 2014

Data Type (GNSS)	Avg. No. Sites/Day	No. Unique Site	No. Files	Avg. Volume/Day	Directory Location
Daily	100	115	35.1K	500 Mb	`/gnss/data/campaign/mgex/daily`
Hourly	50	54	17.1K	100 Mb	`/gnss/campaign/mgex/data/hourly`
High–rate	40	47	13.6K	1,350 Mb	`/gnss/campaign/mgex/data/highrate`

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. The daily files are 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 receive a snapshot of data availability and quality by viewing the contents of such a summary file.

3.1.2 MGEX Archive

During 2014 the CDDIS continued the archiving of data from participating multi–GNSS receivers as well as products derived from the analysis of these data. The data include newly available signals (e.g., Galileo, QZS, SBAS, and BeiDou). 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 created by CDDIS to summarize data in RINEX V3 format. Products derived in support of MGEX by three to six ACs are also available through the CDDIS (`/gnss/products/mgex/WWWW`).

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 provided by the CDDIS for the operational data sets; it contains all the unique broadcast navigation messages for the day. The file is denoted `brdmDDD0.YYp.Z` and found in daily subdirectories within the MGEX archive at CDDIS

(`/gnss/data/campaign/mgex//daily/rinex3/YYYY/DDD/YYp`).

In order to promote usage of RINEX V3 and allow users (and data centers) to become familiar with the format and file naming conventions, ESA began delivery of data from MGEX stations using both RINEX V2 and V3 filename formats. The CDDIS established a daily subdirectory for these files 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 provided a new product, differential code biases (DCBs) 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. Two files are available, daily satellite and daily satellite and station biases, for 2013–2014 in CDDIS directory `/gnss/products/mgex/dcb`. Additional details on the DCB product are available in IGSMail message 6868 sent in February 2014.

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 clocks). 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`.

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 2014, the IGS analysis centers provided products for the second IGS reprocessing campaign (repro2). The CDDIS will provide support through upload of files from the ACs and online archive of these products (`/gnss/products/WWWW/repro2`).

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+GLO) /glonass/products/WWWW (GLO only)
Troposphere	Combination	2.6 Mb/day, 940 Mb/year	/gnss/products/troposphere/YYYY
Ionosphere	4+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	500 Mb/week	/gnss/products/WWWW/repro2

Note: WWWW=4–digit GPS week number; YYYY=4–digit year; GLO=GLONASS

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. Work continued in 2014 to make the system operational and in spring 2014, the CDDIS caster was fully installed for broadcasting product streams in real–time. The caster runs the NTRIP (Network Transport of RTCM via internet Protocol) format.

The majority of the work in 2014 involved development of a registration process that satisfied NASA security requirements and collected information required by the IGS RTS. 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 100K 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 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. Furthermore, 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 both the BKG and IGS casters. Data streams have also been tested, provided through JPL for receivers in NASA's Global GPS Network. This network of roughly seventy globally distributed, geodetic quality, dual frequency receivers, will add 1Hz data streams to those current available from the IGS RTS.

Once the CDDIS caster is operational, the system will serve as a 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.

The CDDIS has also developed software to capture real–time data streams into fifteen–minute high–rate files. This capability requires further testing as the CDDIS caster becomes operational and data streams from real–time stations are added.

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. 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. 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. 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

Fig. 1 summarizes the usage of the CDDIS for the retrieval of GNSS data and products in 2014. This figure illustrates the number and volume of GNSS files retrieved by the user community during 2014, categorized by type (daily, hourly, high–rate, MGEX data, products). Nearly 370 million files (over 50 Tbytes), excluding robot downloads, were transferred in 2014, with an average of nearly 30 million files per month. Fig. 2 illustrates the profile of users accessing the CDDIS IGS archive during 2014. The majority of CDDIS users were once again from hosts in Europe, Asia, and North America.

5 Recent Developments

5.1 CDDIS Website

Work on an update of the CDDIS website was completed in early 2014. In addition to a refresh of the appearance of the website, the content was reviewed and updated. An application for the enhanced display and comparison of the contents of IGS, ILRS, and IDS site logs was completed in 2014. The Site Log Viewer is an application for the enhanced display and comparison of the contents IAG service site logs. 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.

A second application, the CDDIS Archive Explorer, is currently under development to aid in discovering data available through the CDDIS. The application will allow 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 will include a listing of sites (or other metadata) or data holdings satisfying the user input specifications. Such a user interface will also aid CDDIS staff in managing the contents of the archive.

5.2 Next Generation Hardware

Funding was identified in 2013 to procure a computer system refresh for the CDDIS. The CDDIS system engineer reviewed current and near–term requirements and developed a hardware procurement strategy. Hardware was procured in mid–2014 with installation beginning in late 2014 and scheduled for completion and testing in early 2015. The system will be installed within the EOSDIS computer facility and network infrastructure providing 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

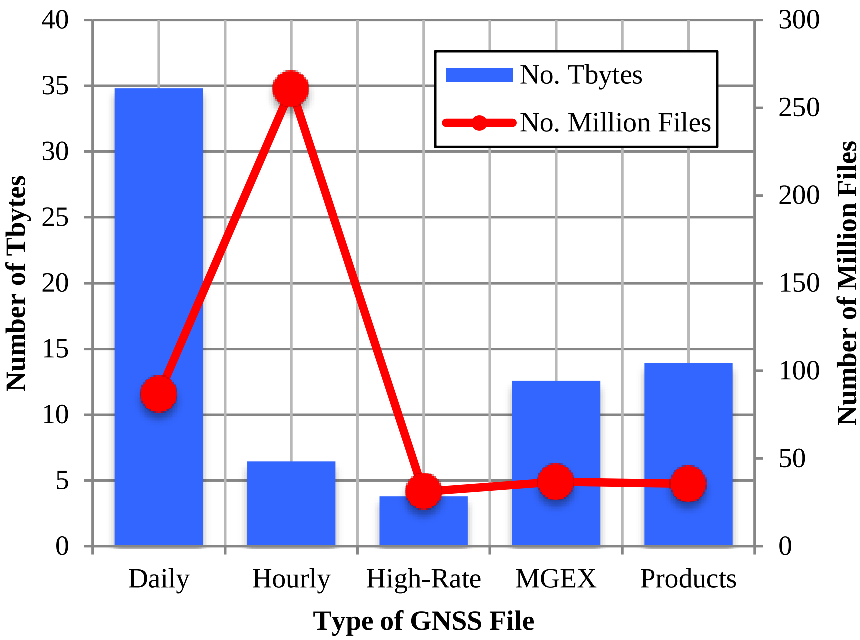

Figure 1: Number and volume of GNSS files transferred from the CDDIS in 2014.

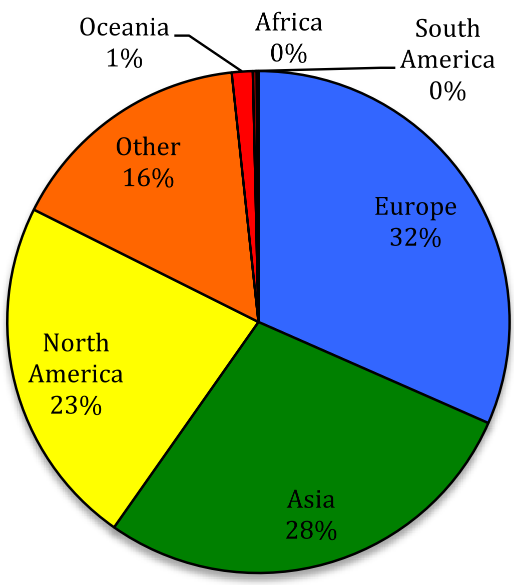

Figure 2: Geographic distribution of IGS users of the CDDIS in 2014.

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 large (XX Tbyte) storage system to easily accommodate future growth of the archive.

5.3 Metadata Developments

The CDDIS has recently made 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 (EOS) Clearinghouse (ECHO) 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 ECHO and the metrics collection effort.

The CDDIS has implemented Digital Object Identifiers (DOIs) to select IGS data sets (daily GNSS data). 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 2014 and presented papers on or conducted demos of their activities within the IGS, including:

C. Noll, P. Michael, N. Pollack, L. Tyahla, "Supporting GGOS through the Crustal Dynamics Data Information System", Abstract EGU2014–7174 presented at 2014 EGU General Assembly, Vienna Austria, 28 Apr.–02 May.

C. Noll, F. Boler, H. Habrich. "Data Centers: Status and Progress", presented at IGS 20th Anniversary Workshop, Pasadena CA, 23–27 Jun.

C. Noll, P. Michael, "Recent Developments at the CDDIS", presented at IGS 20th Anniversary Workshop, Pasadena CA, 23–27 Jun.

P. Michael, C. Noll, J. Roark. "CDDIS Real–Time Developments", presented at IGS 20th Anniversary Workshop, Pasadena CA, 23–27 Jun.

C. Noll, P. Michael, N. Pollack. "Recent Developments in Space Geodesy Data Discovery at the CDDIS", Abstract IN11C–3623 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.

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.

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 support the IGS MGEX. The experiment is an excellent opportunity to prepare the data centers for archive of data in RINEX V3. The CDDIS will coordinate with the Infrastructure Committee, the Data Center Working Group, and other IGS data centers to develop a transition plan and introduce RINEX V3 data into the "operational" GNSS data directory structure, making it easier for users to access these data.

The CDDIS plans to make its real–time caster operational in the coming year as part of the IGS Real–Time Service. CDDIS staff will work with the IGS to identify stations for streaming to its caster. 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. The CDDIS staff will need to develop a revised interface software to the EOSDIS' next generation URS (version 4). The staff will also automate 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 time to look at updating this method to a web–based approach that can utilize the EOSDIS URS infrastructure. CDDIS will investigate the best methods to incorporate 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

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

References

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

Noll, C., Y. Bock, H. Habrich, and A. Moore. Development of data infrastructure to support scientific analysis for the International GNSS Service. *Journal of Geodesy*, 83 (3–4):309–325, 2009. DOI: 10.1007/s00190–008–0245–6.

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2014

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1 North reference point (NRP)

As outlined in IGSMAIL-6987, the Antenna Working Group elaborated a definition of the so-called north reference point (NRP) that was added to the IGS file `antenna.gra` (available at ftp://igs.org/pub/station/general) at the end of October 2014. The NRP designates the element of the antenna that has to be oriented toward the north direction. There are four major features:

- MMI: man-machine interface
- NOM: north orientation mark (placed on antenna by manufacturer)
- RXC: receiver connector (connect antenna to external receiver)
- UNK: unknown

If a north orientation mark (NOM) is present and can be clearly identified, it will usually be selected to be the NRP. If not, in most cases a receiver connector (RXC) or a man-machine interface (MMI) can serve as the NRP instead. If none of the four major features is applicable, `antenna.gra` provides twelve secondary features and connector designations in order to define the azimuthal antenna orientation.

A considerable amount of time had to be spent on the compilation of the NRP definitions for all antenna types registered in `antenna.gra` in accordance with the phase center corrections contained in `igs08_wwww.atx` on the one hand and further calibrations performed by the IGS calibration institutions on the other hand. In some cases, the NRP definition had to be harmonized between different institutions. The NRP designator was added both to the individual antenna.gra sketches and to the machine-readable section at the end of the file.

At the beginning of January 2015, antenna.gra contained 201 different antenna types. For 189 of them, one of the major features was applicable (NOM: 87, MMI: 45, RXC: 43, UNK: 14). Help on identifying the NRP of outdated or uncalibrated equipment (antenna types with NRP = UNK) is greatly appreciated.

2 Updates and content of the antenna phase center model

Table 1 lists 11 updates of the absolute IGS antenna phase center model igs08_wwww.atx that were released in 2014. Eight of them are related to changes of the satellite constellation, and three 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 Tab. 1.

Table 2 gives an overview of the data sets contained in the IGS phase center model. The numbers refer to igs08_1822.atx that was released in December 2014. For GPS and GLONASS, there are 83 and 92 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.

At the IGS Workshop 2014 in Pasadena, it was recommended to adopt conventional phase center offset (PCO) values for Galileo, BeiDou and QZSS satellite antennas taking into account the IGS-conventional axis definition related to the yaw-steering attitude mode. A draft version of igs08_wwww.atx including the new GNSS already exists. It will be published together with a paper on GNSS satellite geometry and attitude models. For the time being, conventional PCO values can be found on the web pages of the IGS Multi-GNSS Experiment (http://www.igs.org/mgex).

Apart from the satellite antennas, the IGS model meanwhile contains phase center calibration values for 264 different receiver antenna types. 85 of them are certain combinations of an antenna and a radome, whereas the remaining 179 antenna types are not covered by a radome. As Tab. 2 shows, igs08_1822.atx contains, among others, 126 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 163 different antenna types (126 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 1: Updates of the phase center model `igs08_wwww.atx` in 2014 (`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
1780	21-FEB-14	6866	Added G064, R714 (R18)
			Decommission date: G049 (G30), R724
1781	28-FEB-14	—	Added `TPSPN.A5 NONE`
			Corrected date: G010
1785	28-MAR-14	—	Added `TRM55970.00 NONE`
			Decommission date: G036
1787	08-APR-14	6895	Added G049 (G06)
1788	14-APR-14	6899	Added R754
			Decommission date: R714 (R18)
1793	19-MAY-14	6914	Added G067
			Decommission date: G049 (G06)
			Added `STXS9+X001A NONE`
1804	04-AUG-14	6953	Added G068, R755
			Decommission date: G039, R725
			Added `AERAT1675_120 SPKE`
1805	11-AUG-14	6955	Corrected date: R725, R755
			Added `LEIGG03 NONE`
1808	05-SEP-14	6965	Added G035 (G03)
			Decommission date: G033
1816	31-OCT-14	6989	Added G069
			Decommission date: G035 (G03)
			Corrected NRP: `JAV_GRANT-G3T NONE`
			Corrected name: `STXS9PX001A NONE`
1822	10-DEC-14	—	Added `JAVTRIUMPH_1M NONE`
			`JAVTRIUMPH_1MR NONE`
			`JAVTRIUMPH_2A NONE`
			`JAVTRIUMPH_LSA NONE`

Table 2: Number of data sets in `igs08_1822.atx` (released in December 2014)

Satellite antennas	Number	Receiver antennas	Number
GPS	83	`ROBOT`	126
GLONASS	92	`FIELD`	90
Galileo	0	`COPIED`	34
BeiDou	0	`CONVERTED`	14
QZSS	0		

Table 3: Calibration status of 452 stations in the IGS network (`logsum.txt` of 9 January 2015, `igs08_1822.atx`) compared to former years

Dates	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%**

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, 452 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general`) on 9 January 2015 were considered. At that time, 102 different antenna/radome combinations were in use within the IGS network. The calibration status of these antenna types was assessed with respect to the phase center model `igs08_1822.atx` that was released in December 2014.

Eight 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 80% of all IGS stations. Whereas the portion of stations with phase center corrections derived from relative field calibrations (purely elevation-dependent) hardly changed in recent years, a steady decrease of IGS stations covered by uncalibrated radomes can be noticed.

This decrease results from an upgrade of the equipment at operational stations or from the decommissioning of stations with outdated equipment, but also from an extension of the network with properly calibrated antennas. In order to reach a coverage of 100%, IGS Site Guidelines do not allow converted field calibrations or uncalibrated equipment “at new or upgraded stations”.

Bias & Calibration Working Group Technical Report 2014

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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/bcwg/. For an overview of relevant GNSS biases, the interested reader is referred to (Schaer 2012).

2 Activities in 2014

- Regular generation of P1–C1 bias values for the GPS constellation (based on *indirect* estimation, see Fig. 1) and maintenance of receiver class tables was continued at CODE/AIUB.
- P1–P2 bias values for GPS and GLONASS (see Fig. 2 and Fig. 3.) are a by-product of the ionosphere analysis. Temporal resolution for global ionosphere modeling was increased at CODE in 2014 (from 2 to 1 hour).

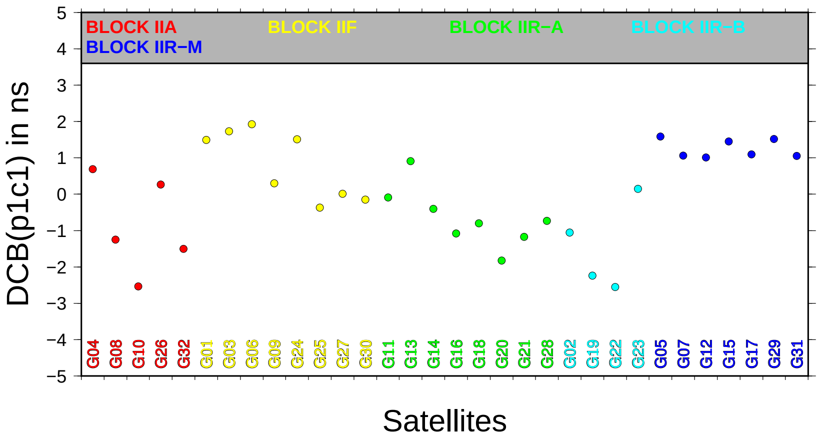


Figure 1: Monthly set of P1–C1 differential code biases for the GPS constellation, for December 2014, computed at CODE.

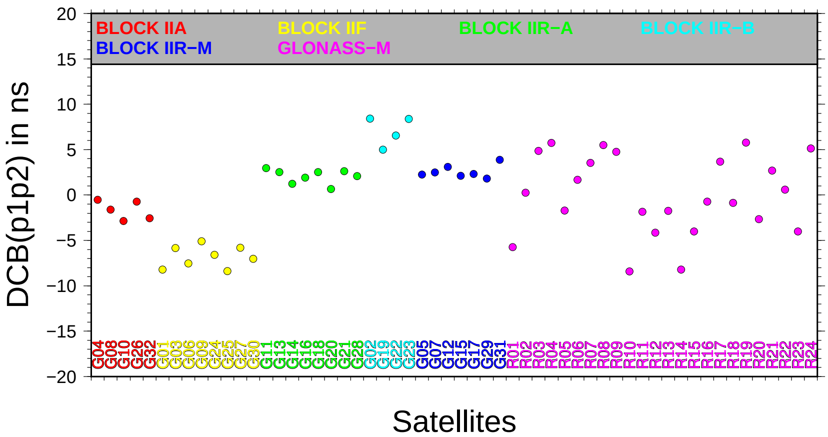


Figure 2: Monthly set of P1–P2 differential code biases for the GPS and GLONASS constellation, for December 2014, computed at CODE.

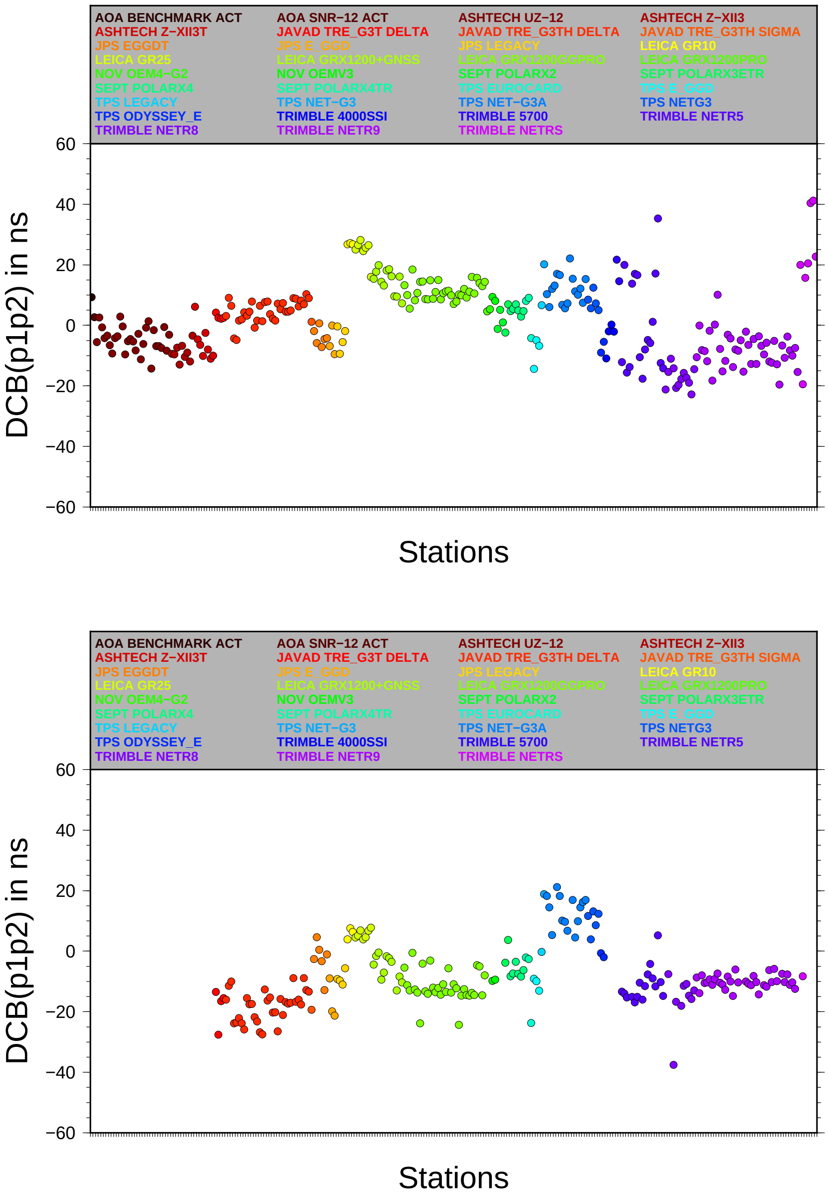


Figure 3: Monthly set of P1–P2 differential code biases for the GPS (top) and GLONASS (bottom) receiver components, for December 2014, computed at CODE.

- 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 (see Fig. 4, Fig. 5, and Fig. 6).
- In June 2014, we started to produce GNSS DCB result files from our clock and ionosphere analysis lines in bias-SINEX format (preliminary version 0.01).
- 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/y2014/odata2_d335.txt`
  `ftp://ftp.unibe.ch/aiub/igsdata/y2014/odata2_d335_sat.txt`
  Internally, the corresponding information is extracted and produced using metadata stored in an xml database (established in December 2014). The switch to this xml-based data monitoring did not affect the provided RINEX summaries.
- This RINEX monitoring service is provided in addition for MGEX observation data (available in RINEX3 format). See `ftp://ftp.unibe.ch/aiub/mgex/y2014/`.

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–P2 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.

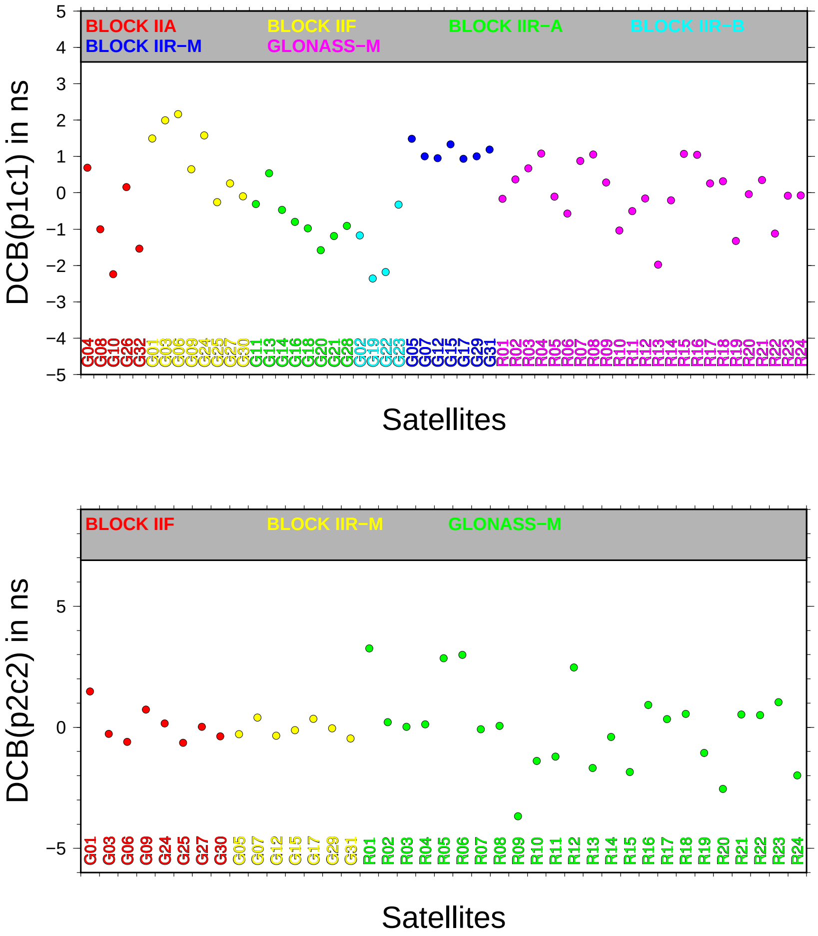
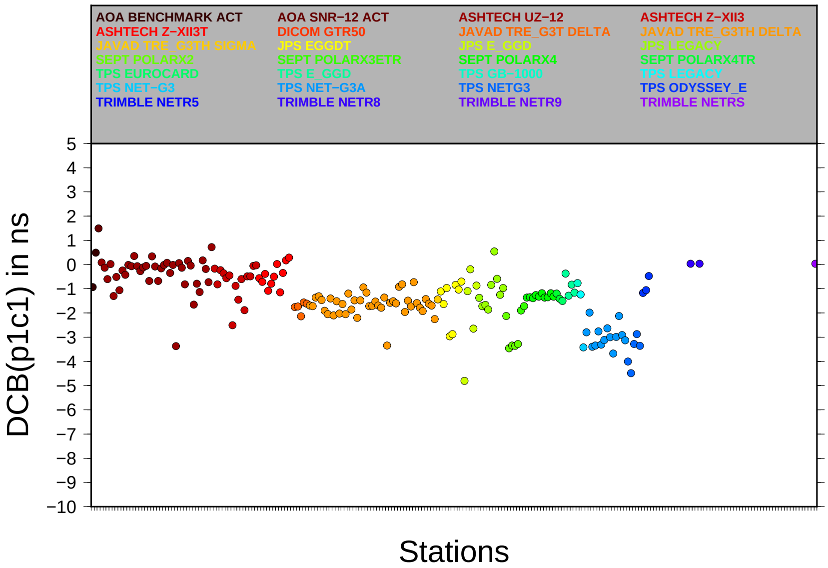


Figure 4: Monthly set of P1–C1 (top) and P2-C2 (bottom) differential code biases for the GPS and GLONASS constellation, for December 2014, computed at CODE.



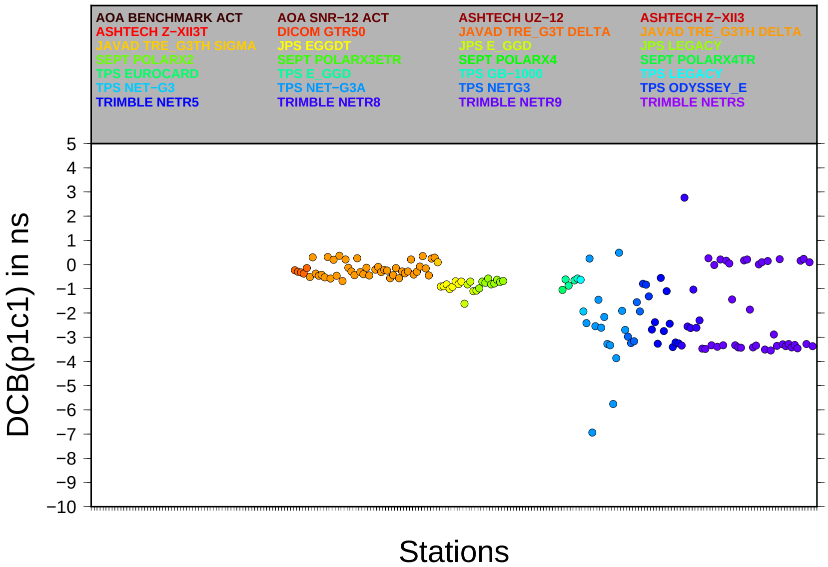


Figure 5: Monthly set of P1–C1 differential code biases for the GPS (top) and GLONASS (bottom) receiver components, for December 2014, computed at CODE.

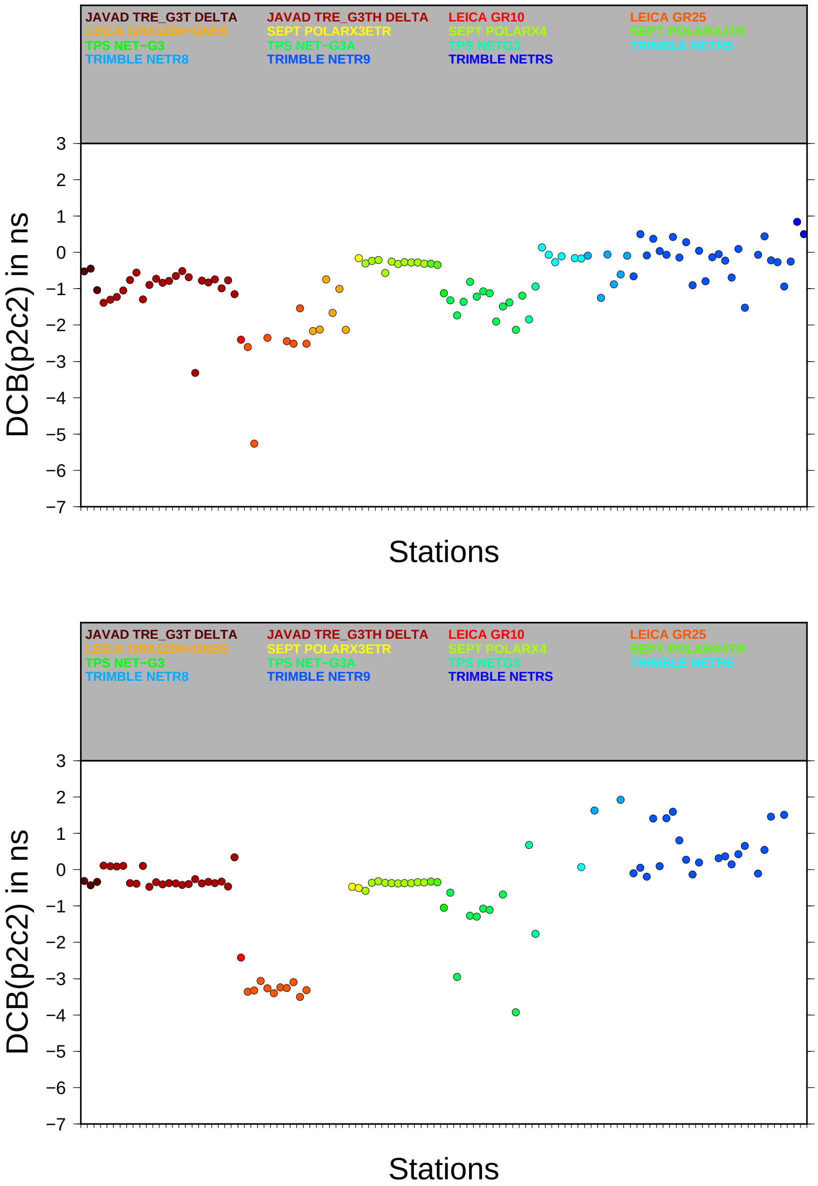


Figure 6: Monthly set of P2–C2 differential code biases for the GPS (top) and GLONASS (bottom) receiver components, for December 2014, computed at CODE.

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Data Center Working Group Technical Report 2014

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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

The DCWG met in conjunction with the Multi–GNSS Experiment (MGEX) Working Group during the 2014 IGS Workshop in Pasadena, CA in June 2014. The main issues discussed at this DCWG splinter meeting revolved around supporting RINEX V3 and integrating the MGEX archive of data in RINEX V3 format into the operational IGS archives at the DCs. Two main topics were addressed: merging RINEX V3 data into the archives and accepting data using the new RINEX V3 filename format.

The current parallel 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 will promote use of multi–GNSS data and the new format. The MGEX Working Group has suggested development of a transition plan for adding the MGEX data, and hence RINEX V3 data, to the operational archives. Participants agreed that members of the IGS infrastructure (DCs, the IC, ACs, etc.) should develop this transition plan. It was proposed to include three six–month phases: a preparation phase, followed by an implementation phase and a finalization phase, with full integration of RINEX V3 into the archives by the end of 2015. RINEX V2 for MGEX stations and stations capable of generating RINEX V3 would end at this time.

Those ACs attending the DCWG meeting agreed to utilize the filename convention specified in the RINEX V3 documentation. The DCs, however, will need software tools to create these new filenames from RINEX V2 filenames until stations and receiver manufacturers can create the new filenames directly. Tools also need to be made available to the DCs for data QC and metadata extraction as well as tools for the ACs and users to convert RINEX V3 to RINEX V2.

The RINEX V3 format should also address navigation files. The current format documentation specifies one file per station for observation data; therefore, the format should specify one file per station that includes navigation messages from all GNSS constellations. A tool may need to be developed for this capability rather than depend upon generation in the receiver.

The following recommendations were generated from the June 2014 DCWG meeting:

1. 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: The IGS Infrastructure Committee has drafted this transition plan for comment. The plan works toward the "one network one archive" concept, merging the RINEX V2 and V3 files currently maintained in separate structures at the data centers, into one archive structure. The IC has recommended the IGS Governing Board provide guidance on next steps.
2. Provide software tools that DCs can use to continue to provide needed QC and metadata extraction enabling creation of data status information.
   – Progress: Possible tools have been discussed but not identified for general use through the IGS infrastructure.
3. 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: The transition plan has identified the need for these tools.

The above recommendations reiterate those from the 2012 IGS Analysis Workshop:

1. The DCs recommend continuing the efforts by the Infrastructure Committee and the RINEX WG to agree on new file names.

   – Progress: The new filename convention is included in the RINEX V3 transition plan. To date, RINEX V3 data utilized in support of MGEX are archived at data centers (CDDIS and IGN) in separate directory structures. To improve/encourage data access and usage, the RINEX V3 transition plan states the DCs will use the new filenames and incorporate RINEX V3 data within the operational directory structure.

2. Until the RINEX V3 filename convention is finalized, separate directories for distinguishing between files created from streams and by receivers will be established by all DCs.

   – Progress: The DCWG has not addressed this recommendation to archive of high–rate files from real–time streams vs. receivers. However, the RINEX V3 filename convention has been finalized and is included in the latest RINEX V3 documentation. With the adoption of the proposals outlined in the RINEX V3 transition plan, stream–created data will be clearly identified by filename.

3. All DCs explore transition options for a follow on compression scheme to replace UNIX "compress" as early as possible.

   – Progress: IGS users reported to DCs that the decompression tools for UNIX compress (".Z") is an outdated method for data compression. It is recommended that the IGS infrastructure change to a standard compression format as early as possible. Plans for transition from UNIX compress to another compression scheme, e.g., gzip, will be coordinated with testing of RINEX V3 data flow.

3 Future Plans

One topic discussed at the IGS Infrastructure Committee meeting at the 2014 IGS Workshop involved metadata, particularly in the area of site logs. The IGS CB has introduced the Site Log Manager System, which is utilized at the IGS Central Bureau for handling IGS site logs and 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, are proposing email discussions and/or telecons to allow participants in this effort to collaborate and plan for a 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. If feasible the group would like to plan for future meetings on this collaboration, perhaps in conjunction with community–held meetings (e.g., EGU, AGU, IGS workshops, etc.).

The DCWG will also work with the IGS DCs to implement the recommendations developed during the 2012 and 2014 workshops. In particular, the DCWG will work with the MGEX Working Group and the Infrastructure Committee to finalize the RINEX V3 Transition Plan and work toward implementing the plan itself. 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 recent IGS Workshops including assessment and monitoring of station performance and data quality, generating metrics on these data.
- RINEX file naming convention: The DCWG will work with the IC and the RINEX WG on implementation of the new IGS RINEX file naming convention.
- 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) (tbc)
- 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 2014

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1 Space Radio–Diagnostics Research Center
University of Warmia and Mazury in Olsztyn, Poland (SRRC/UWM)
2 Geodesy and Geomatics Engineering, University of New Brunswick, Canada
3 Jet Propulsion Laboratory, California Institute of Technology
4 IONSAT, Universitat Politecnica de Catalunya (UPC), Barcelona, Spain

1 Introduction

The Ionosphere Working group started the routine generation of the combined 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 (Technical University of Catalonia, Barcelona, Spain). Independent computation of rapid and final VTEC maps are used by each analysis center: Each IAAC 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

The members of the ionosphere working group are listed in Tab. 1. Dr. Reza Ghoddousi–Fard, from the Canadian Geodetic Survey of Natural Resources Canada (NRCan), has solicited to be a member of the IGS Ionosphere WG. Taking into account that all of

Table 1: Members of the ionosphere working group

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

opinions about Dr. Ghoddousi–Fard's membership application have been positive, we are glad to welcome Dr. Ghoddousi–Fard to the WG.

3 Products

- 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 × 5 deg. × 2.5 deg. (UTxLon.×Lat.),
  - availability with a latency of 11 days
- Rapid GIM
  - combination of CODE, ESA, JPL and UPC iono products conducted by UWM
  - temporal and spatial resolution – at 2 hours × 5 deg. × 2.5 deg. (UT×Lon.×Lat.),
  - availability with a latency of less than 24 hours
- 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 × 5 deg. × 2.5 deg. (UTxLon.×Lat.),

4 Key accomplishments

- IGS Global ionosphere predicted products for 1 and 2 days ahead (pilot product). These new IGS products are currently based on predicted ionosphere maps prepared by UPC and ESA.
- IGS Global ionosphere maps with 1 hour time resolution. These new IGS products are currently based on ionosphere maps prepared by UPC, ESA and CODE.
- IGS Global Ionosphere Maps (GIMs) now include differential code biases (DCBs) for GLONASS satellites.
- The pilot phase of the new IGS ionospheric product – TEC fluctuation maps

5 Recommendations after IGS Workshop 2014, Pasadena, USA

- Higher temporal resolution of IGS combined GIMs – the IAACs (UPC, JPL, ESA and CODE) agreed on providing their maps in IONEX format, with a resolution of 1 hour from 2015.
- Starting a new potential official product – TEC fluctuation maps using ROTI over the Northern Hemisphere to monitor the dynamic of oval irregularities (carried out by UWM; Krankowski), JPL (Pi) and UPC (Hernandez–Pajares) in the future to be started as official/routine product after performance evaluation period (beginning 2015).
- Close cooperation with National Central University from Taiwan regarding usage of occultation measurements from Formosat/Cosmic mission for future validation of IGS GIMs.
- Cooperation with IRI COSPAR group for improving IRI TEC.

6 Announcements after IGS Workshop 2014, Pasadena, USA

- Natural Resources Canada (NRCan) is resuming the activities on global VTEC modelling. After a performance evaluation period, NRCan can again become an IAAC (Reza Ghoddousi–Fard, April 2015).

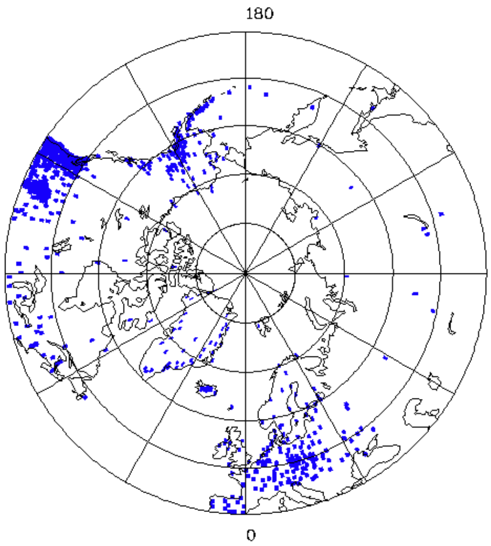

Figure 1: The locations of the stations around the North Geomagnetic Pole.

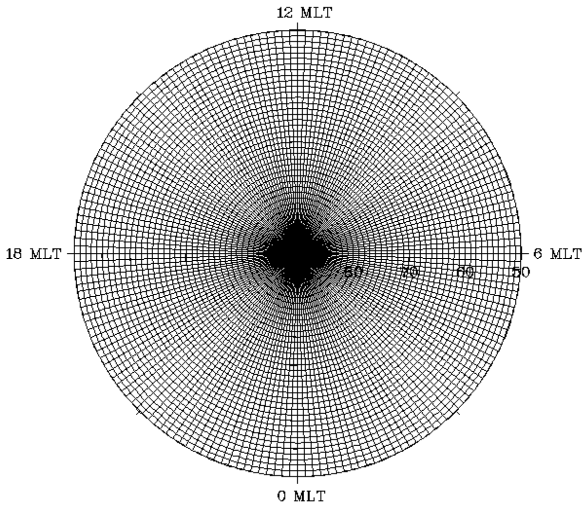

Figure 2: The grid of ROTI maps in polar coordinates with grid 2 degree (magnetic local time) and 2 degree (geomagnetic latitude).

- The Institute of Geodesy and Geophysics (IGG), Chinese Academy of Sciences, Wuhan, China (Yunbin Yuan, beginning 2015) is computing on a routine basis global VTEC maps, and it can become a new IAAC after a performance evaluation period (Yunbin Yuan).
- A new proposed format (SCINTEX) for slant ionospheric information (such as S4, sigmaPhi, ROT and STEC) has been recently proposed and is under consideration in the IGS ionospheric community due to its significance for potential applications.

7 The pilot phase of the new IGS ionospheric product

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

According to the resolution of the IGS Ionosphere Working Group, which was passed during the IGS Workshop 2014 in Pasadena, the new product – the ionospheric fluctuation maps – was established as a pilot project of the IGS service. Due to small changes in solar irradiance levels and various geophysical parameters in the atmosphere and ionosphere, TEC fluctuations are calculated as a function of a spherical geomagnetic latitude and magnetic local time.

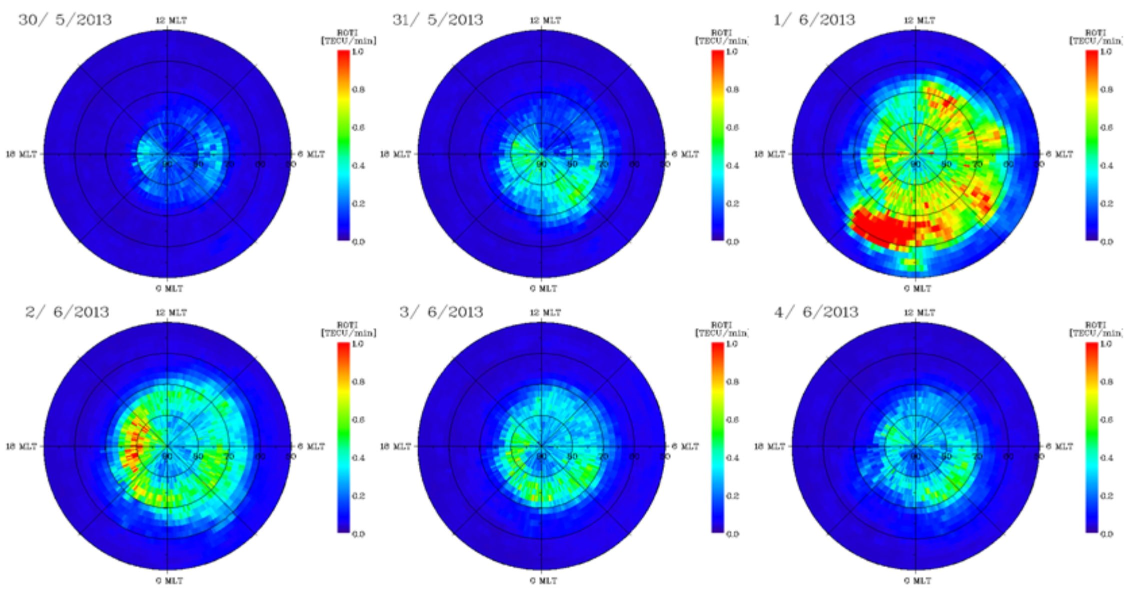

Figure 3: Evolutions of the daily ROTI maps for 30 May – 4 June 2013.

In the updated version of the product, more than 700 permanent stations (available both from UNAVCO and EUREF databases) have been incorporated into the 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 represents the ROT deviation over a 5–minute periods with 1–minute resolution. This ionospheric fluctuation service allows the estimation of the levels of TEC fluctuations levels from 50 degrees to the pole (in geomagnetic coordinates). The results are shown a visualization as daily ROTI maps in polar coordinates on a uniform 2 degree (magnetic local time) and 2 degree (geomagnetic latitude) grid. Every grid cell represents the weighted ROTI values included in the cell.

The final TEC fluctuation maps are written in a modified IONEX format. ROTI data are stored in ASCII format based on a grid of 2 by 2 degrees – geomagnetic latitude from 89 degrees to 51 degrees with step 2 and corresponding to magnetic local time (00–24 MLT) along with polar coordinates from 0 to 360 degrees (Cherniak et al. 2014b, c).

8 JPL Ionospheric Analysis Center Technical Report Contribution for 2014

The Jet Propulsion Laboratory (JPL) continued its role as an Ionospheric Associate Analysis Center (IAAC) for the International Global Navigation Satellite System (GNSS) Service

	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
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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.

(IGS) in 2014. The primary objective was the retrieval, analysis and validation of GIM products at the daily basis (Mannucci et al. 1998) and their deliveries to the NASA Crustal Dynamics Data Information System (CDDIS). These maps were generated in IONEX format (Schaer et al. 1998) and include daily estimates of GPS satellite and ground–based receiver DCBs, as well as 2.5° latitude by 5° longitude by 2 hour IGS standard resolution vertical TEC (VTEC) maps. The continued deliveries of rapid and final IONEX maps have been one of our highest priorities. In addition to our primary objective, we began modifying our software to incorporate additional GNSS signals of opportunity, such as those provided by the GLONASS constellation. As a result, we investigated JPL's GIM performance upon including the additional signals, which fall within the activities of IAAC. Preliminary results are shown below.

8.1 JPL Global Ionosphere Maps

Table 2 lists the JPL GIM products delivered daily by JPL to the CDDIS in 2014. The maps are routinely derived using slant total electron content (STEC) arcs measured by carrierŨphase and pseudorange ionospheric TEC observables gathered from approximately 200 sites globally, distributed as uniformly as possible, from available dual–frequency GPS receivers in the IGS network. Both rapid and final JPL IONEX products are available every day in 2014 and we will continue to deliver timely, and high–quality GIM products to the CDDIS in 2015 and beyond.

Table 2: JPL AC IONEX Contributions Delivered to the CDDIS

Product	Description
`jplrJJJ0.YYi.Z`	Rapid (i.e., 1–day delay), GPS–derived, daily ionospheric map
`jplgJJJ0.YYi.Z`	Final (i.e., 3–day delay), GPS–derived, daily ionospheric map

8.2 GLONASS Impact on GIM

Numerous ground–based receivers have the capability to track both GPS and GLONASS satellites, offering a denser set of TEC measurements for remotely sensing the ionosphere. To assess the impact of GLONASS observables on JPL GIM performance, we conducted the following experiment. First, we estimated 2D gridded VTEC maps using only GPS observables, and second we generated 2D gridded VTEC maps using both GPS and GLONASS observables. Preliminary results from Butala et al. 2014 demonstrated a positive impact of GLONASS on JPL GIM products as summarized below. Despite this conclusion, we note that there may exist inconsistencies between the GPS and GLONASS data sets and further investigation and analyses are required. Based on our initial results, JPL plans to integrate GLONASS measurements into our standard GIM products in 2015, accompanied by an investigation of the contribution of GLONASS observations to GIM.

Figure 5 shows the GIM–derived receiver bias estimates at the IGS station in Brasilia (BRAZ, –15.94°N, –47.88°E) as a function of time in May 2014. Two cases are considered: using GPS data alone in red, and using GPS plus GLONASS measurements in blue. Note the GPS+GLONASS (blue) derived station biases are slightly more repeatable, exhibiting a smaller standard deviation compared to using GPS (red) data alone. The decrease in standard deviation is more striking given the increase in unknown receiver bias parameters required to process the GLONASS data, one for each receiver and satellite pair as opposed to only one for each receiver in the GPS only case. We plan to investigate additional stations and monitor the behavior of the standard deviation to provide additional quality assessment of the products. Figure 6 displays a comparison of JPL GIM VTEC to VTEC measured by an independent data source, in this study the space–borne dual–frequency ocean altimeter Ocean Surface Topography Mission (OSTM or Jason–2, see the OSTM/Jason–2 Products Dumont et al. 2009 or Tseng et al. 2010). The bar chart shows the consistent and sometimes significant improvement between Jason–2 and combined GPS and GLONASS GIM day–time VTEC. We note that the results seem spatially biased compared to the Jason–2 orbital tracks in ocean regions that are typically areas of generally sparser GNSS receiver coverage. In addition, Jason–2 may have its own instrumental bias that must be accounted for in the VTEC comparison (Hausman and Zlotnicki 2010). We will continue to analyze GLONASS observables and their impact on GIM products.

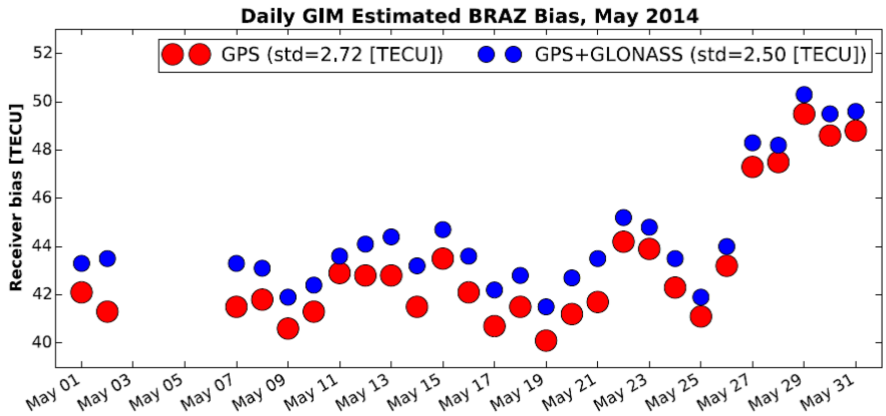

Figure 5: JPL GIM bias time–series for station BRAZ derived for GPS data alone (GPS) and combined GPS and GLONASS data (GPS+GLONASS) for May, 2014. Data were not available for May 3–6. Note the decreased station bias standard deviation (std) in the GPS+GLONASS result.

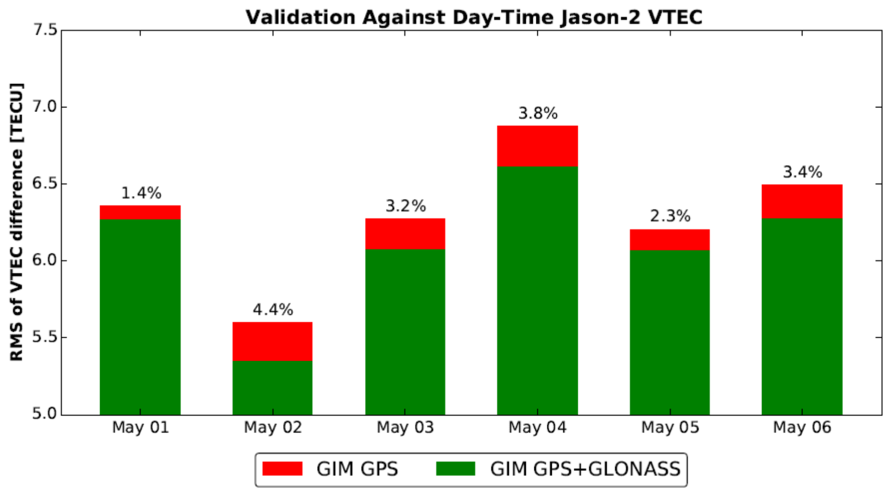

Figure 6: Day–time root mean square (RMS) of the difference between measured Jason–2 VTEC and JPL GIM VTEC derived from GPS alone (red) and combined GPS and GLONASS data (green). Each bar annotation indicates the daily improvement in the day–time VTEC difference RMS. Note the consistent and often significant improvement of the GPS and GLONASS GIM VTEC compared to that measured by an independent source.

9 Ionosphere–Related Work by Personnel Affiliated with UNB

Activity during 2014 included development of an improved ionospheric modelling technique using GPS and empirical–orthogonal–function fits. This work is an attempt to make estimated ionospheric parameters more physically meaningful and effective. The approach uses data–driven empirical orthogonal functions (EOF) to replace arbitrary functions to match better the horizontal variability of the ionosphere and estimate inter–frequency hardware biases with the EOF–fit ionosphere representation. This modelling technique has been implemented in both 2D and 3D scenarios and assessed with data from a regional GPS network. It was demonstrated with the network that the approach can give better results in terms of lower residuals compared to the standard UNB technique. Comparisons of the outputs of the approach with independent data sources are ongoing.

Work was also carried out on the use of global and regional ionospheric corrections for faster convergence of precise point positioning (PPP). It was demonstrated that the use of both global ionosphere maps and ambiguity resolution can potentially reduce the convergence time of PPP to 10–cm horizontal accuracies from 30 to 4.5 minutes (68th percentile), under favourable ionospheric conditions. However, instantaneous ambiguity resolution could not be achieved using ionosphere maps based on the single–layer model, and ionospheric corrections from a regional network in the form of slant delays were required for this purpose.

In collaboration with colleagues at the Jet Propulsion Laboratory, UNB participated in several ionosphere–related investigations. Radio occultation data provided by UNB's GPS Attitude, Positioning, and Profiling (GAP) instrument, one of several making up the Enhanced Polar Outflow Probe (e–POP) platform on the Canadian CASSIOPE satellite, has been used to study intermediate–scale plasma density irregularities in the polar ionosphere. In another study, ground–based GPS measurements have been used to study the ionospheric impact of the 2013 Chelyabinsk asteroid's entry into the Earth's atmosphere. And in yet another work, ionospheric disturbances caused by the 2011 Tohoku–Oki Earthquake have been detected at a height of 450 km using total electron content and atmospheric density perturbations derived from measurements made from instruments on board the Gravity Recovery and Climate Experiment (GRACE) spacecraft.

In collaboration with colleagues at the University of Calgary, the relationship between aurora and the phase scintillation index (sf) has been investigated. A possible relation between the "phase scintillation without amplitude scintillation" phenomenon observed at high latitudes and GPS phase fluctuations during aurora has been hypothesized. It is shown that under–estimating the Fresnel frequency during auroral periods is causing observation of "phase scintillation without amplitude scintillation" at auroral latitudes. Initial investigations have also been carried out on the effect of "patchy pulsating aurora" and auroral arcs on GPS signals. It is seen that patchy pulsating aurora, given its larger spatial extent, affects GPS signals in a more pronounced manner than auroral arcs.

10 Publications 2014

1. Banville, S., P. Collins, W. Zhang, R.B. Langley, Global and Regional Ionospheric Corrections for Faster PPP Convergence, *NAVIGATION: Journal of the Institute of Navigation*, 61(2):115–124, doi:10.1002/navi.57.

2. Bilitza, D., Altadill, D., Zhang, Y., Mertens, Ch., Truhlik, V., Richards, P., McKinnell, L–A, Reinisch, B., 2014, The International Reference Ionosphere 2012 – a model of international collaboration. *J. of Space Weather and Space Clim*, Vol. 4, AO7, 2014.

3. Cherniak, Iu., Zakharenkova, I.E., Dzubanov, D., Krankowski, A., 2014a, Analysis of the ionosphere/plasmasphere electron content variability during strong geomagnetic storm, *Advances in Space Research*, 54(4):586–594, 2014.

4. Cherniak, Iu., Krankowski, A., Zakharenkova, I.E., 2014b, Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and Service, *Radio Science*, 49:653–662, 2014, DOI: 10.1002/2014RS005433.

5. Cherniak, Iu., Zakharenkova, I.E., Krankowski, A., 2014c, The approaches for the ionosphere irregularities modeling on the base of ROTI mapping, Earth, *Planets and Space (EPS)* 66:165, 2014, doi:10.1186/s40623-014-0165-z

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7. Gulyaeva, T.L., Arikan, F., Hernandez–Pajares, M., and Veselovsky, I.S., 2014, North–south components of the annual asymmetry in the ionosphere. *Radio Science*, 49(7):485–496.

8. Hernández–Pajares, M., Ã. Aragón–Ángel, P. Defraigne, N. Bergeot, R. Prieto–Cerdeira, and A. García-Rigo, 2014, Distribution and mitigation of higher–order ionospheric effects on precise GNSS processing, *J. Geophys. Res.: Solid Earth*, 119(4):3823–3837, doi:10.1002/2013JB010568.

9. Li, Z., Yuan, Y., Wang, N., Hernandez-Pajares, M., and Huo, X., 2014, SHPTS: towards a new method for generating precise global ionospheric TEC map based on spherical harmonic and generalized trigonometric series functions. *Journal of Geodesy*, 89(4):331–345.

10. Limberger, M., Liang, W., Schmidt, M., Dettmering, D., Hernández-Pajares, M., and Hugentobler, U., 2014, Correlation studies for B–spline modeled F2 Chapman parameters

obtained from FORMOSAT–3/COSMIC data. *Ann. Geophys*, 32:1533–1545.

11. Monte, E., Hernandez-Pajares, M., 2014, Occurrence of solar flares viewed with GPS: Statistics and fractal nature, *Journal of Geophysical Research: Space Physics*, 119(11):9216–9227.

12. Yang, Y.-M., A. Komjathy, R.B. Langley, P. Vergados, M.D. Butala, and A.J. Mannucci, The 2013 Chelyabinsk Meteor Ionospheric Impact Studied Using GPS Measurements, *Radio Science*, 49(5):341–350, doi:10.1002/2013RS005344. Paper featured on issue cover.

13. Yang, Y.-M., X. Meng, A. Komjathy, O. Verkholyadova, R.B. Langley, B.T. Tsurutani, and A.J. Mannucci, 2014, Tohoku-Oki Earthquake Caused Major Ionospheric Disturbances at 450 km Altitude over Alaska, *Radio Science*, 49(12):1206–1213.

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15. Zakharenkova, I.E., Cherniak, Iu., Krankowski, A., Shagimuratov, I.I., 2014b, Vertical TEC representation by IRI 2012 and IRI Plas models for European midlatitudes, *Advances in Space Research*, 55(8):2070–2076.

16. Zhang, W., A. Komjathy, S. Banville, and R.B. Langley, Ionospheric Modeling Using GPS: Greater Fidelity Using a 3D Approach, *GPS World*, 25(2):59–65.

11 Presentations/Posters/Meeting Proceedings 2014

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13 Plan for activities in 2015

The following actions to be considered:

- Higher temporal resolution of IGS GIMs – 1 hour, combination conducted by UWM to be started as official/routine product (April 2015)
- Starting a new official/operational product – TEC fluctuation changes over North Pole to study the dynamic of oval irregularities (carried out by UWM to be started as official/routine product after performance evaluation period (Spring of 2015).
- The new IAAC from the Natural Resources Canada (NRCan) (Reza Ghoddousi–Fard, end of March 2015)
- Cooperation with IRI COSPAR group

Future improvements are determined by users' requirements (number of users has significantly increased during the last 16 years).

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Multi–GNSS Working Group Technical Report 2014

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1 Introduction

The Multi–GNSS Working Group (MGWG) has been established by the IGS to build up experience in the use of new satellite navigation systems and modernized signals. As part of this task, the MGWG coordinates the performance of the Multi–GNSS Experiment (MGEX) which comprises the build–up of a new network of sensor stations, the characterization of the user equipment and space segment, the development of new concepts and data processing tools, and, finally, the generation of early data products. MGEX is considered as a preparatory step for a future multi–GNSS pilot service that will integrate the new constellations into the established IGS product and service portfolio. A list of current MGWG members and their respective contributions is given in Tab. 1.

2 Network

The MGEX network has continued to grow from approximately 90 stations at the beginning of 2014 to roughly 110 stations at the end of the year (Fig. 1). This has mainly been achieved through a large number of new stations contributed by Geoscience Australia (GA). These stations now offer a notably improved coverage of BeiDou and QZSS tracking in the Asia–Pacific region. Roughly 70 stations of the MGEX network provide multi–GNSS real–time data streams that can be accessed through BKG's MGEX caster (http://mgex.igs-ip.net/). About ten sites of the MGEX network are equipped with hydrogen maser clocks that offer access to a highly–stable time scale for GNSS system characterization as well as orbit and clock product generation.

Table 1: Multi–GNSS Working Group members and task areas (status in December 2014)

Name	Institution	
Rolf Dach	AIUB	Orbit and clock products, SP3 format extension (SP3d)
Jan Dousa	GOPE	Quality control
Ahmed El–Mowafy	CUT	Quality control
Heinz Habrich	BKG	Data archives
Satoshi Kogure	JAXA	Orbit and clock products, QZSS mission interface
Richard Langley	UNB	Public outreach, GNSS constellation monitoring
Huiciu (Yolanda) Liu	BACC	Quality control
Oliver Montenbruck	DLR/GSOC	Chair MGWG, MGEX coordination, network, DCB product, data and product analysis (BeiDou, Galileo, QZSS, IRNSS)
Felix Perosanz	CNES	Orbit and clock products
Chris Rizos	UNSW	External representation (ICG, IGMA, ...)
Axel Rülke	BKG	Data quality control, real–time streams
Tim Springer	ESOC	Data processing strategies
Peter Steigenberger	DLR & TUM	Orbit and clock products, broadcast ephemeris product
Maik Uhlemann	GFZ	Orbit and clock products
Rene Warnant	ULG	Ionosphere
Qulie Zhao	Wuhan Univ.	BeiDou

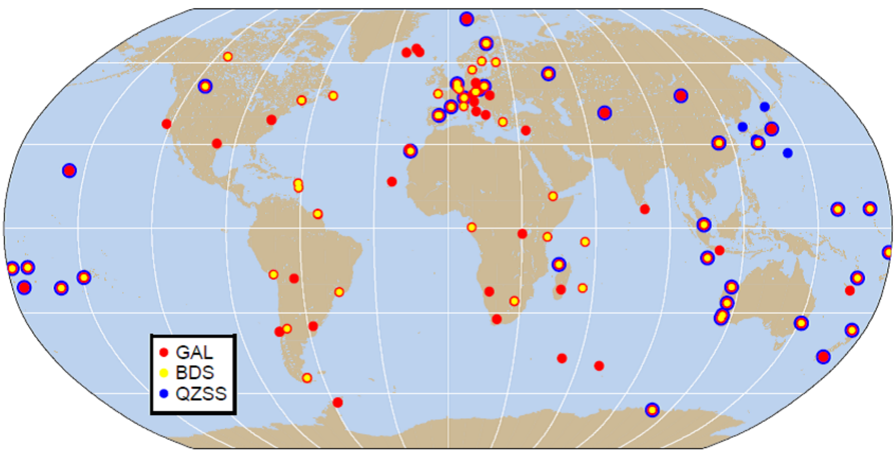

Figure 1: Distribution of MGEX stations supporting tracking of QZSS (blue), Galileo (red), and BeiDou (yellow) as of October 2014.

Despite rapid progress in the deployment of the new Indian Regional Navigation Satellite System (IRNSS), none of the MGEX stations is presently hosting IRNSS–capable receivers. Further efforts need to be made to deploy such receivers as a prerequisite for familiarization with this system and for the generation of early IRNSS products.

To avoid a divergence of MGEX and legacy–IGS data holdings, a RINEX 3 transition plan has been prepared under the lead of the IGS Infrastructure Committee (IC) and released by the IGS Governing Board (GB) in December 2014. The transition plan provides the framework for migrating to RINEX–3 as the primary data format and the use of RINEX–3–style long file names, while making provisions (e.g. converters) to support the old RINEX 2 format for stations and/or analysis centers that are not able to adapt to the new standards. Implementation of the transition plan is foreseen for 2015, after which a harmonized IGS data archive with full multi–GNSS support will be available.

For quality control (QC) of multi–GNSS RINEX 3 files, various tools have been prepared within the frame of the "*quality control task force*". These tools, which were presented at the IGS Workshop (Rülke et al. 2014), include Anubis (developed by the Geodetic Observatory Pecny), BQC (developed by the Beijing Aerospace Control Center) and the BNC tool of BKG. Selected QC analyses have, furthermore, been conducted by Curtin University (El-Mowafy 2014a, b, 2015a, b).

3 Products

Precise orbit and clock products supporting various subsets of old and new GNSSs are contributed by various MGEX analysis centers (ACs) including AIUB, CNES/CLS, GFZ, JAXA, TUM, and Wuhan University. Supported constellations include Galileo, QZSS, and, since early 2014 also BeiDou. No IRNSS support is available, though, due to the lack of corresponding GNSS monitoring stations.

For Galileo IOV, a good internal consistency of solutions from different ACs has been demonstrated (Prange et al. 2014a; Steigenberger et al. 2014b). Day–boundary overlaps, orbit fits and comparisons between ACs demonstrate a precision of about 10 cm for orbit products based on 3–day data arcs. However, systematic errors of up to ±20 cm can be clearly recognized from satellite laser ranging measurements as well as clock analyses. Due to the exceptional stability of the hydrogen masers operated by most of the IOV satellites, radial orbit determination errors can be recognized from periodic variations in the estimated clock offsets. These radial errors, which affected all solutions in the same manner, could ultimately be traced to the use of a standalone CODE solar radiation pressure (SRP) model. While highly successful for GPS satellites with near–cubic satellite bodies, the original CODE model with one–per–rev parameters is unable to fully account for the radiation pressure of a stretched cuboid. Use of a dedicated a priori model (Montenbruck et al. 2014e) was found to remove the orbit–periodic errors in the Galileo orbit determination and result in a reduction of peak errors by up to a factor of four. As an alternative to the cuboid a priori model, the consideration of twice–per–rev terms in an extended version of the CODE model has been proposed by AIUB to mitigate SRP induced orbit modeling errors. As part of the MGEX AC coordination, efforts will be made to arrive at a harmonized, or at least consistent, formulation of SRP perturbations in the Galileo orbit modeling.

For QZSS, orbit and clock products continue to be delivered by JAXA and TUM. Differences between the two products amount to roughly 1.3 m (3D rms; Steigenberger and Kogure 2014). An improved agreement is usually obtained during periods of yaw–steering attitude, while a moderate degradation can be observed in orbit–normal mode. Consistent modeling of these attitude modes as well as the associated solar radiation pressure effects has been identified as a prerequisite for further improvements of the orbit quality.

For BeiDou precise orbit and clock products are routinely generated and distributed by Wuhan University and GFZ since early 2014 based on data of the MGEX network (Deng et al. 2014). In addition, past data of Wuhan University have been made available for 2013. As of mid–2014, roughly 50 stations of the MGEX network contributed BeiDou observations, however, many of these stations are outside the visibility range of the satellites in inclined geosynchronous orbit (IGSO) and geostationary orbit (GEO) and support "*only*" orbit determination of satellites in medium altitude Earth orbit (MEO). For the MEO and IGSO orbits a consistency at the few–decimeter level is achieved for the GFZ and Wuhan University orbit products (Fig. 2). For GEO satellites, in contrast, substantially larger errors at the 1 to 10 m level are encountered. In particular, the along–track component is difficult to determine due to the static viewing geometry of these satellites. As a possible means to cope with these problems, the combined processing of GNSS and SLR observations has been suggested, but no practical experience has been gained so far.

As a contribution to improved BDS orbit determination, phase center offsets and variations for the BeiDou MEO and IGSO satellites have been estimated by ESOC from MGEX observations (Dilssner et al. 2014). Use of theses corrections for routine orbit determination and product generation is presently under consideration by the MGEX ACs.

Complementary to the precise orbit and clock products, TUM & DLR continue to provide daily multi–GNSS broadcast ephemeris files for GPS, GLONASS, Galileo, BeiDou, QZSS, and Satellite Based Augmentation Systems (SBAS). Continued efforts are made to further improve the consistency of this product and to cope with receiver/firmware specific discrepancies in the decoded ephemerides of different stations. A systematic performance comparison of broadcast versus precise ephemerides for legacy and new constellations has been presented in Montenbruck et al. 2014e.

Finally, a multi–GNSS differential code bias (DCB) product covering all observed signals and tracking modes of GPS, GLONASS, Galileo, and BeiDou is provided by DLR for use within the MGEX project. The DCBs are based on daily averages of ionosphere–corrected pseudorange observations (Montenbruck et al. 2014b) and include both satellite

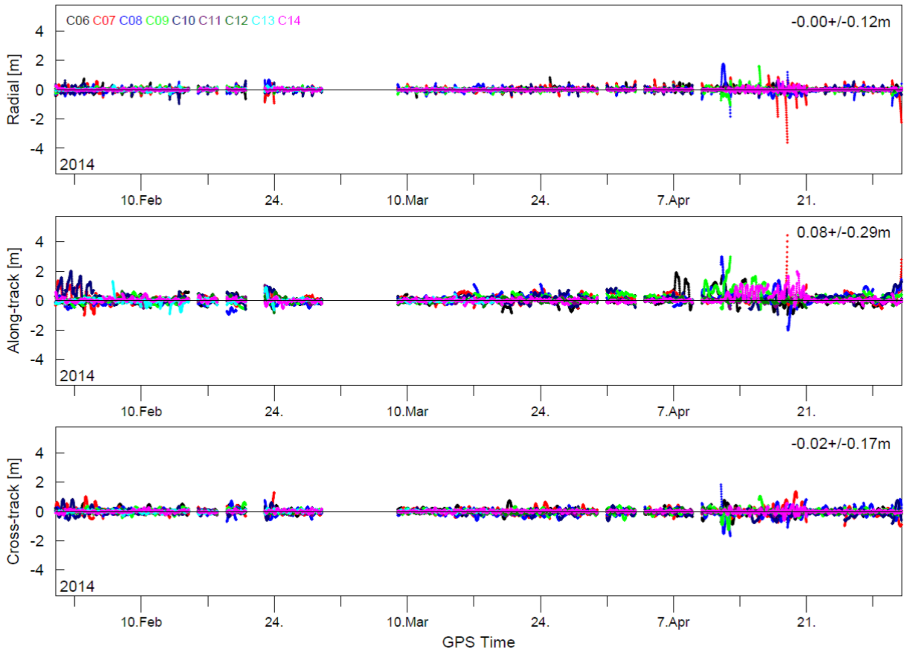

Figure 2: Orbit differences between GFZ and Wuhan University products for the BeiDou MEO (C11–C14) and IGSO satellites (C06–C10) over a 3–month period (February to April 2014).

and station–specific biases. For ease of use, 7–day averages of the satellite DCBs are also provided. Both data sets make use of a prototype implementation of the proposed Bias SINEX format. In view of limited variability, updates to the MGEX DCB products are released on a quarterly basis.

4 GNSS Evolution

Within 2014, three GPS Block IIF satellites, two GLONASS–M satellites, one GLONASS–K1 satellite, two Galileo FOC satellites and two IRNSS satellites have been launched. The new GPS IIF satellites have replaced outdated Block IIA satellites and contribute to a continued improvement of the average clock stability and signal–in–space range error (SISRE) of this constellation. They have also increased the number of L5–capable GPS satellites to eight, i.e., about one third of the active GPS constellation.

Only one of the FOC satellites has started transmission of signals in late 2014 following an extended orbit raising period to partly compensate a launcher orbit injection failure. Very early orbit and clock determination results for this satellite (E18) have been included in TUM's routine Galileo product for MGEX but do not yet allow a thorough performance assessment.

Despite the release of a first open service signal ICD for IRNSS, no public GNSS observations are presently available for this constellation. Orbit determination is thus limited to satellite laser ranging measurements. Analyses of Montenbruck et al. 2015 indicate a SISRE of the IRNSS navigation message of several meters, which is mostly consistent with the broadcast user range accuracy.

In late April 2014, the GPS control segment has started the routine generation and transmission of CNAV messages by most of the GPS Block IIR–M and IIF satellites. These offer a better continuity than the legacy LNAV message, but can only achieve an equal or better SISRE performance when uploaded on a daily basis (Steigenberger et al. 2015). Such daily uploads are routinely performed from the beginning of 2015 onwards. Combined CNAV/LNAV ephemerides files including GPS and QZSS are provided by TUM & DLR. They are based on a subset of 10 stations of the MGEX network and updated on a daily basis.

5 Standardization

The Multi–GNSS WG has contributed to further evolve the RINEX 3 standard in close interaction with other IGS working groups. Among others, a proposal for the incorporation of IRNSS observation data and navigation messages has be developed, which is under review for the upcoming 3.03 version of RINEX.

For the modeling of antenna phase center offsets and variations an agreement has been reached by the MGWG and the Antenna WG, to harmonize the axis convention of the satellite body frame (+z in boresight direction, ±y–axis along solar panel rotation axis) for old and new constellations. Where applicable, the positive x–axis is chosen in such a way that the +x panel is sunlit during nominal yaw steering. A dedicated report identifying the spacecraft axis in manufacturer and IGS convention and providing antenna and reflector coordinates is under preparation and shall be released in the first quarter of 2015 along with a new multi–GNSS ANTEX file.

6 Public Outreach

The MGEX website (`http://igs.org/mgex`) has been migrated to the new IGS web portal and is now presented in a new layout. While efforts continue to provide up–to–date information to all MGEX users, frequent updates of the web pages can no longer be supported due to the introduction of a new contents management system and the shortage of IGS Central Bureau staff.

Achievements of the MGEX project have been advertised in various overview papers and magazine articles (Montenbruck et al. 2014g, h) as well as numerous conference and workshop presentations (including Asia–Oceania Regional Workshop on GNSS, Phuket; COSPAR, Moscow; CSNC, Nanjing; EGU, Vienna; ENC, Rotterdam; EUREF, Vilnius; FIG Congress, Kuala Lumpur; Geodätische Woche, Berlin; IEEE Workshop on Asia–Pacific Satellite Navigation and Positioning, Brisbane; PNT, Washington; REFAG, Luxembourg). Most notably, the achievements and status of the MGEX project were highlighted in numerous presentations of MGWG members during the IGS Workshop in Pasadena.

Acronyms and Abbreviations

AIUB	Astronomisches Institut der Unversität Bern
BACC	Beijing Aerospace Control Center
BKG	Bundesamt für Kartographie und Geodäsie
CLS	Collecte Localisation Satellites
CNES	Centre National d'Etudes Spatiales
CONGO	Cooperative Network for GNSS Observation
CUT	Curtin University of Technology
DLR	Deutsches Zentrum für Luft– und Raumfahrt
ESA	European Space Agency
ESOC	European Space Operations Center
GA	Geoscience Australia
GFZ	Deutsches GeoForschungsZentrum
GOPE	Geodetic Observatory Pecný
GSOC	German Space Operations Center
IAPG	Institute of Astronomical and Physical Geodesy
JAXA	Japan Aerospace Exploration Agency
MGM–net	Multi–GNSS Monitoring Network
REGINA	REseau GNSS pour l'IGS et la Navigation
RTCM	Radio Technical Commission for Maritime Services
TUD	TU Delft
TUM	Technische Universität München
ULG	Université de Liège
UNB	University of New Brunswick
UNSW	University of New South Wales

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Real–Time Service Technical Report 2014

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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 Center in Darmstadt, Germany (ESA/ESOC). Support is provided by 160 station operators, multiple data centers, and 10 analysis centers 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.

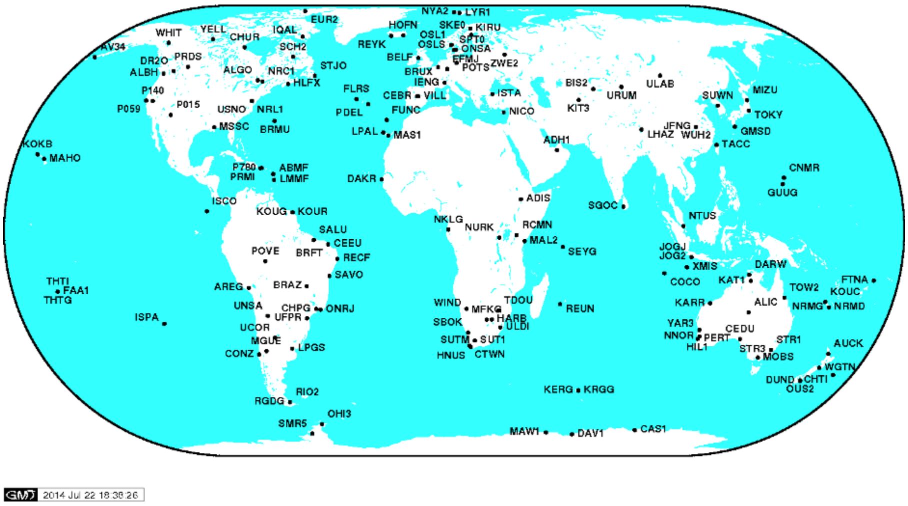


Figure 1: RTS Receiver Network.

2 RTS Infrastructure

The RTS is based on the IGS global infrastructure of network stations, data centers and analysis centers that provide the "world's standard" high–precision GNSS data products. Figure 1 shows the distribution of sites in the current Real Time network.

The RTS product streams are combination solutions generated by processing individual solutions from participating Real-time Analysis Centers (RTAC). The effect of combining the different RTAC results is a more reliable and stable performance than that of any single AC's product. Operational responsibility for the generation of the official RTS combination products lies with the IGS Real Time Analysis Center Coordinator (RTACC), currently the European Space Agency's Space Operations Center in Darmstadt, Germany (ESA/ESOC).

The RTS is supported by the IGS for free and open access by all users, as far as dissemination resources allow. The RTS has been operational since April 2013. IGS strives to deliver its products on a highly available basis, however, due to the volunteer nature of IGS, availability of products is not guaranteed.

As NTRIP is an RTCM open standard, no special licensing is associated with its use. Commercial entities interested in integrating RTS into their equipment should contact the IGS Central Bureau to for additional information and support. The RTS product streams are available through designated product distribution centers around the world. Users may register online through the IGS Real-time Service website to subscribe to casters operated by BKG, IGS Central Bureau and CDDIS.

3 RTS Products

The RTS Products consist of GNSS satellite orbit and clock corrections to the broadcast ephemeris, as well as data streams from the global network of high–quality GNSS receivers.

The RTS products are distributed as RTCM SSR correction streams broadcast over the Internet using the NTRIP protocol. The corrections are expressed within the International Terrestrial Reference Frame 2008 (ITRF08). The initially offered products include GPS–only correction streams, as well as an experimental GPS+GLONASS correction stream that is anticipated to be fully integrated within the RTS in the near future. The RTS products are disseminated in the form of RTCM SSR streams. The technical content of the RTS products is described in the Table 1.

The products, designated at IGS01/ICG01 and IGS02, contain corrections only for the GPS satellites. The experimental product, designated at IGS03, contains corrections for GPS and GLONASS. The RTCM v3 streams may be used to support development and testing of real-time Precise Point Positioning (PPP) and related applications.

The IGS continuously monitors the accuracy of its products through inter–comparison

Table 1: RTS Product Streams

Center	Description	NTRIP Mountpoint
ESOC	GPS–only combination–epoch-wise approach (CoM/APC)	IGC01/IGS01
BKG	GPS–only combination–Kalman filter approach (APC)	IGS02
with TU Prague	GPS+GLONASS combination–Kalman filter approach (APC)	IGS03
BKG	GPS and GPS + GLONASS RT orbits	CLK00/10
with TU Prague	and clocks using IGU orbits (CoM/APC)	CLK01/11
CNES	GPS RT orbits and clocks based on IGU orbits (CoM/APC)	CLK92/93
	GPS+GLONASS orbits and clocks (CoM/APC)	CLK90/91
DLR	GPS RT orbits and clocks based on IGU orbits	CLKC1/A1
	GPS+GLONASS orbits and clocks (DLR caster)	CLK21
ESOC	RT orbits and clocks using NRT batch orbits every 2 hours (ESOC)	CLK50/51
	and using IGU (ESOC2) (CoM /APC)	CLK52/53
GFZ	RT orbits and clocks and IGU orbits (CoM/APC)	CLK70/71
GMV	RT orbits and clocks based on NRT orbit solution (CoM/APC)	CLK81/80
Geo++	RT orbits and clocks (APC) (Geo++ caster)	RTCMSSR
NRCan	RT orbits and clocks using NRT batch orbits every hour (APC)	CLK22
TUW	RT clocks based on IGU orbits (CoM/APC) (out of service)	CLK80/81
WUHAN	RT clocks based on IGU orbits (CoM/APC)	CLK15/16

of results between Analysis Centers and the IGS Rapid and Final products. The orbit and clock comparisons for the IGS01 combination over the last several years are shown in Fig. 2 and Fig. 3. Fig. 4 shows the clock comparisons for the individual ACs, with the IGS01 results superimposed in black. The effectiveness of the combination approach in removing outliers in the individual AC solutions is clearly demonstrated.

Some outliers are still apparent in the combination. These are mainly caused by the larger orbit prediction errors associated with eclipse–related events for GPS Block IIA and Block IIF satellites. Additional Block IIF events have been associated with non–nominal ground–commanded attitude manoeuvres.

The results for the experimental GLONASS AC solutions are shown in Fig. 5 There are clear periods when some of the solutions deteriorate. These are due to RTCM encoding errors that are currently under investigation.

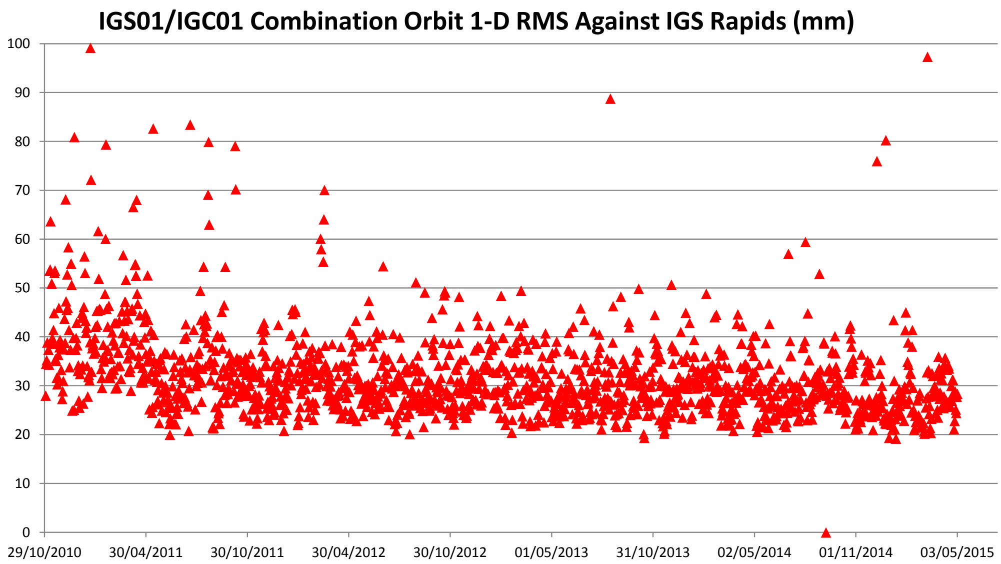


Figure 2: RTS Combination Daily Orbit Comparison Statistics.

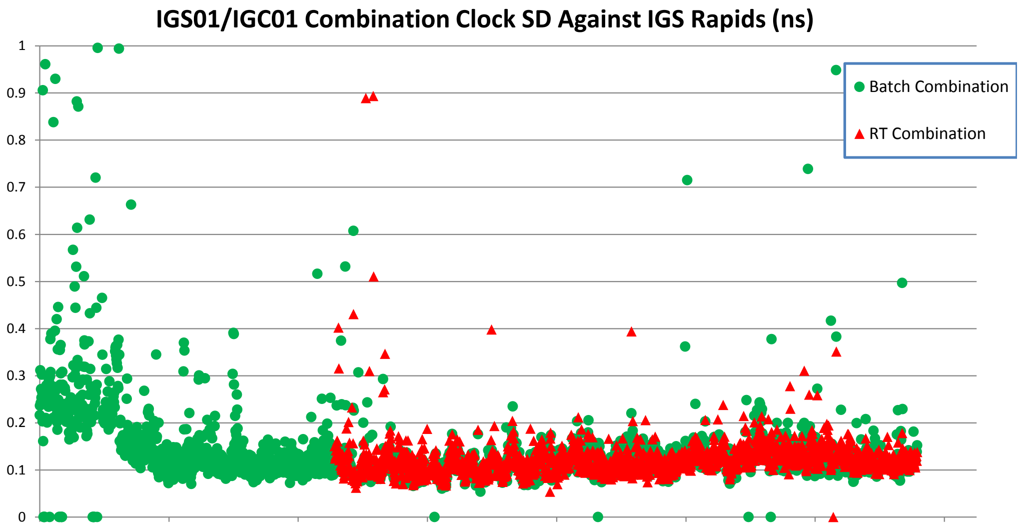


Figure 3: RTS Combination Daily Clock Comparison Statistics.

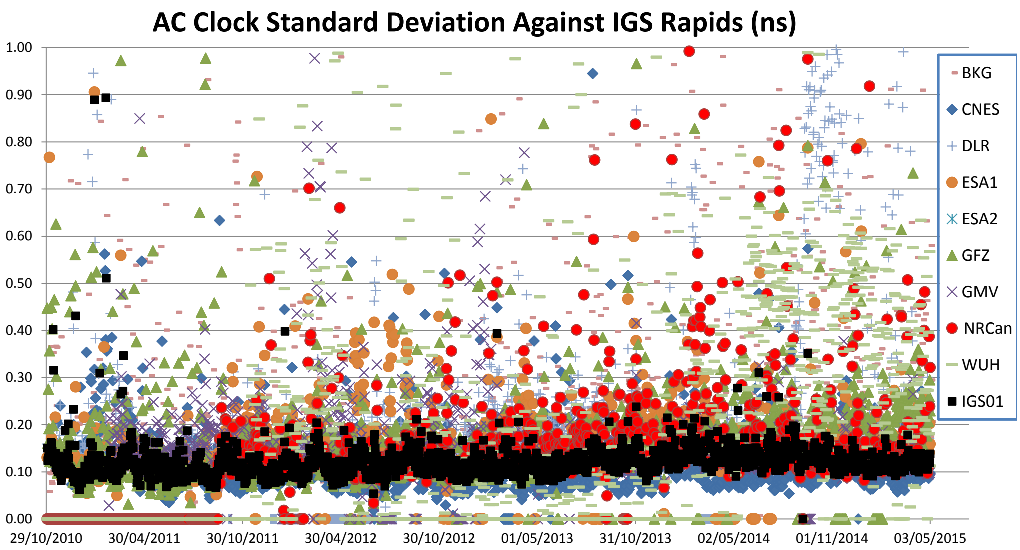
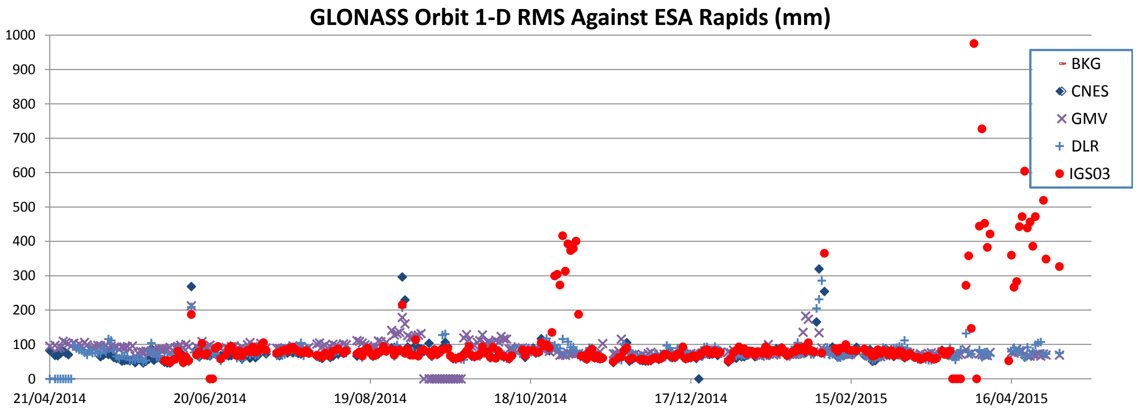


Figure 4: RTS AC and Combination Solution Daily Clock Comparison Statistics.



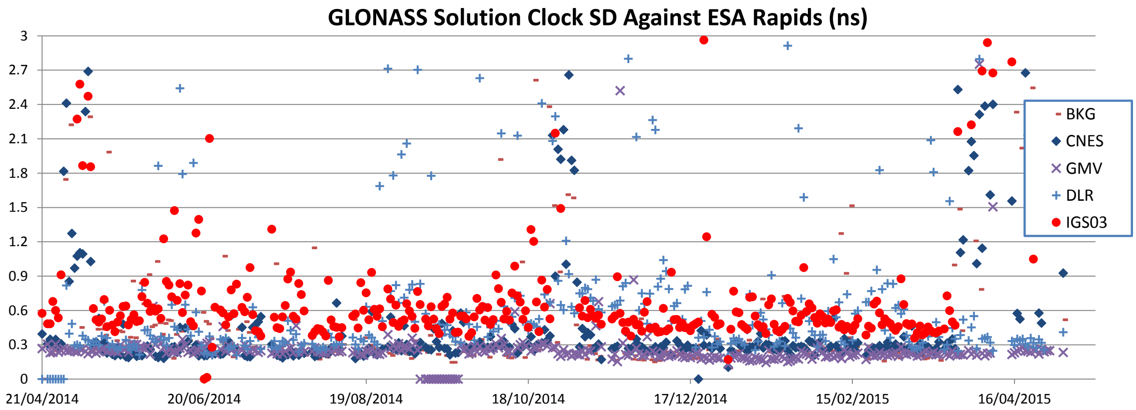


Figure 5: RTS GLONASS Solution Daily Comparison Statistics.

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For more information, please visit the RTS website (http://rts.igs.org).

Reference Frame Working Group Technical Report 2014

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1 Introduction

Besides a continuous quality monitoring of the IGS SINEX combination products, the main activity of the Reference Frame Working Group in 2014 was the preparation of the IGS contribution to ITRF2014, which will consist of daily combinations of the AC SINEX solutions from the IGS 2nd reprocessing campaign (repro2). After an overview of the operational IGS SINEX combination results in 2014 (Sect. 2) and a brief review of the current status of the IGb08 Reference Frame (Sect. 3), this report will finally present results from preliminary combinations of the AC repro2 SINEX solutions (Sect. 4).

2 Recent IGS SINEX combination results

Figure 1 shows the RMS of the Analysis Center (AC) station position residuals from the daily IGS SINEX combinations of year 2014, i.e. the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed. Except a bump in GFZ's RMS during weeks 1807–1820 due to an issue in the implementation of the 2nd order ionospheric corrections, the overall tendency over 2014 was an improvement of the inter–AC agreement achieved through successive updates of the AC's analysis strategies listed below.

- On week 1803, MIT started using their repro2 settings for their operational products, leading to slightly lower RMS in all three components.

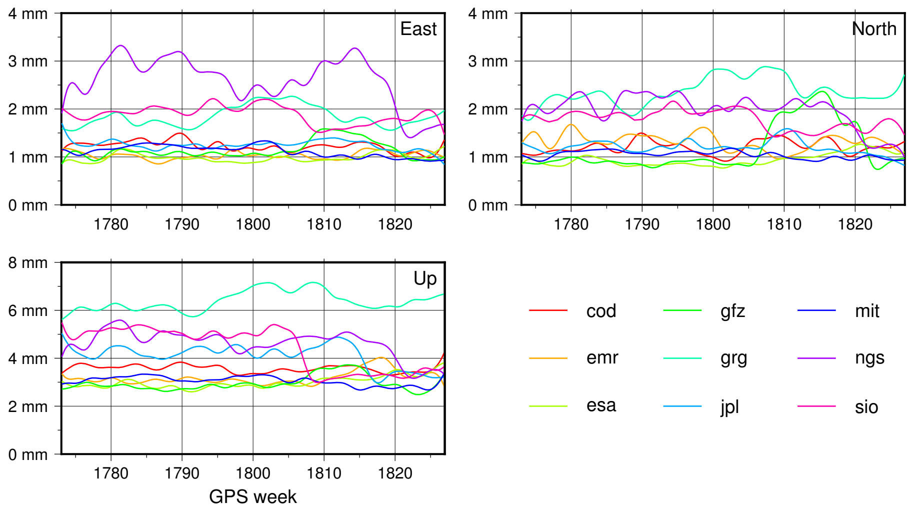

Figure 1: RMS of AC station position residuals from the 2014 daily IGS SINEX combinations. All time series were low–pass filtered with a 10 cycles per year cut–off frequency.

- On week 1807, SIO made major updates to their analysis strategy. The SIO solutions have since then been included with weight in the daily IGS SINEX combinations, except for the pole rates.
- On week 1816, JPL started using their repro2 settings for their operational products, leading to notably lower RMS in the vertical component.
- On week 1820, NGS made several updates to their analysis strategy, leading to notably lower RMS in all three components.

Figures 2 and 3 show the AC Earth Orientation Parameter (EOP) residuals from the IGS SINEX combinations of year 2014. The inter–AC agreement on EOPs has not shown any significant evolution over 2014. The different features noted by Rebischung et al. 2014a can in particular still be observed:

- Sub–seasonal and abrupt variations in the X–pole and Y–pole rate estimates of several ACs, possibly due to GLONASS orbit modeling deficiencies. A particularly abrupt excursion is visible in GRG's residuals around week 1803.
- A strong predominance of MIT's LOD estimates in the combination. This predominance is now known to be related to the use by MIT of inter–day constraints on empirical orbit parameters (T. Herring, personal communication).

Finally note that GRG's LOD estimates have been included with weight in the daily IGS SINEX combinations since week 1777.

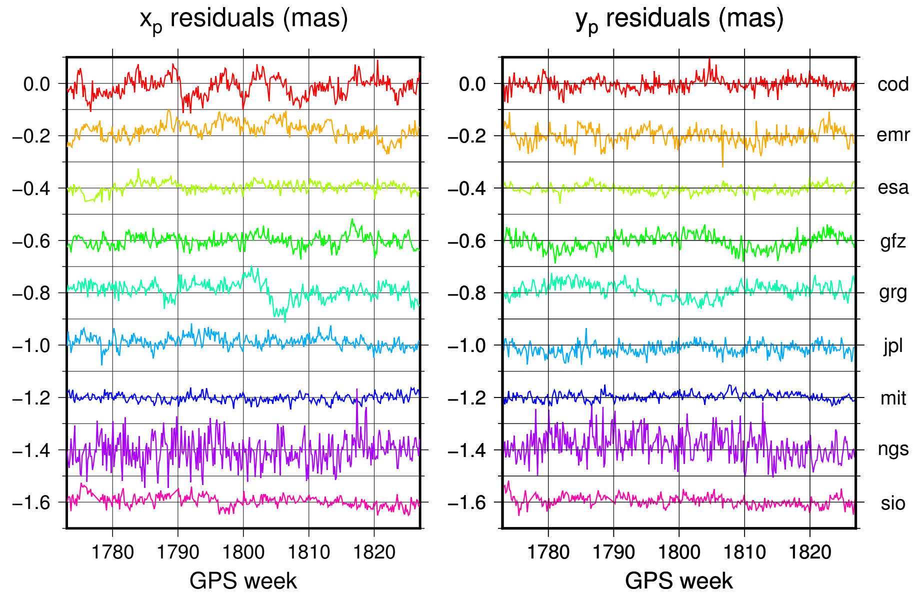

Figure 2: AC pole coordinate residuals from the 2014 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 0.2 mas for clarity.

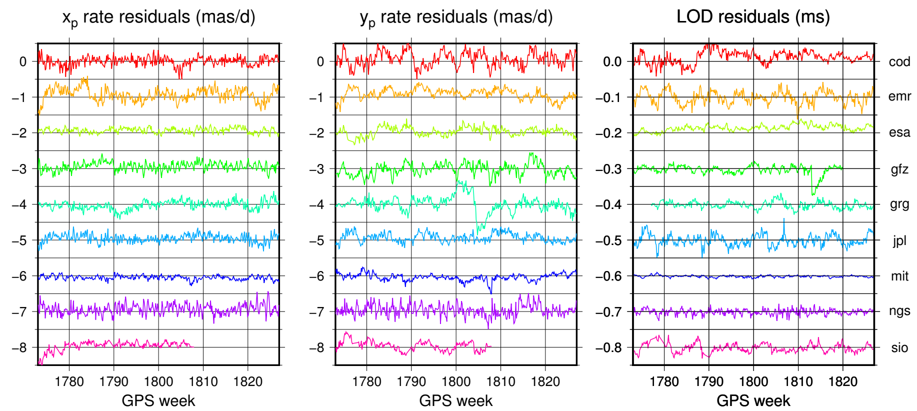

Figure 3: AC pole rate and LOD residuals from the 2014 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 1 mas/d and 0.1 ms for clarity.

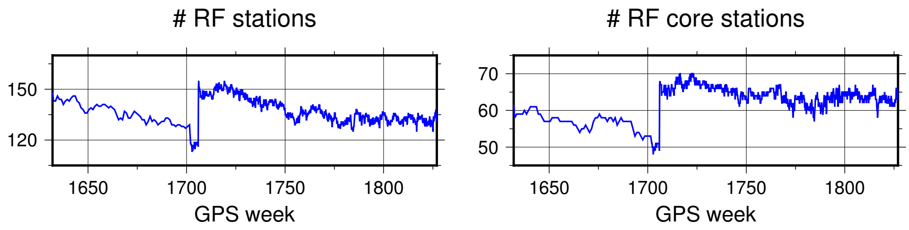

Figure 4: Numbers of usable RF stations and RF core stations in recent IGS combined SINEX solutions.

3 Status of the IGb08 Reference Frame

In 2014, the number of usable IGb08 Reference Frame (RF) stations and the number of RF core stations used to align the IGS daily combined solutions to IGb08 have fortunately remained fairly constant, around 132 and 63 respectively (Fig. 4). In fact, only two IGb08 stations became unusable as RF stations because of equipment changes in 2014, while two others stopped transmitting data. The distribution of the usable IGb08 core stations is still rather satisfactory. However, the accuracy of the IGb08 reference station coordinates has kept degrading because of growing station velocity propagation errors. Over 2014, the global level of agreement between the IGS daily combined solutions and IGb08 has been around 4 mm for horizontal station positions and 10 mm for station heights, about twice as in 2009. This growing disagreement is a concern for the accuracy and stability of the Reference Frame realized by the IGS products and will get worse until a new Reference Frame based on the future ITRF2014 is adopted.

4 Preliminary results from the repro2 SINEX combinations

Eight IGS Analysis Centers (ACs) have now completed a second reanalysis campaign (repro2) of the GNSS data collected by the IGS global tracking network back to 1994, using the latest available models and methodology, with the main purpose of providing the IGS contribution to ITRF2014. A first round of daily combinations of the AC repro2 SINEX solutions was performed in October 2014 and revealed quality issues in the contributions of several ACs (Rebischung et al. 2014b). The concerned ACs have since then re–submitted improved products, so that 7 out of 9 AC contributions will eventually be included with weight in the final repro2 SINEX combinations (Tab. 1). GRG's contribution will be included for comparison only due to outstandingly large residuals in the North and Up components (Fig. 5). Over their common time span, only one of both GFZ contributions (i.e., GFZ's TIGA contribution – GTZ) will be included with weight, as double weight would otherwise be given to the GFZ AC.

Figure 5 shows the WRMS of the AC station position residuals from the latest preliminary

Table 1: AC contributions to the IGS 2nd reprocessing campaign (current status)

AC	Time span (GPS weeks)	Inclusion in final repro2 SINEX combinations
COD	0730 – present	with weight
EMR	0769 – present	with weight
ESA	0782 – present	with weight
GFZ	0730 – 1824	with weight after week 1721
GRG	0938 – present	for comparison only
JPL	0730 – present	with weight
MIT	0730 – present	with weight
GTZ	0730 – 1720	with weight
ULR	0782 – 1773	with weight

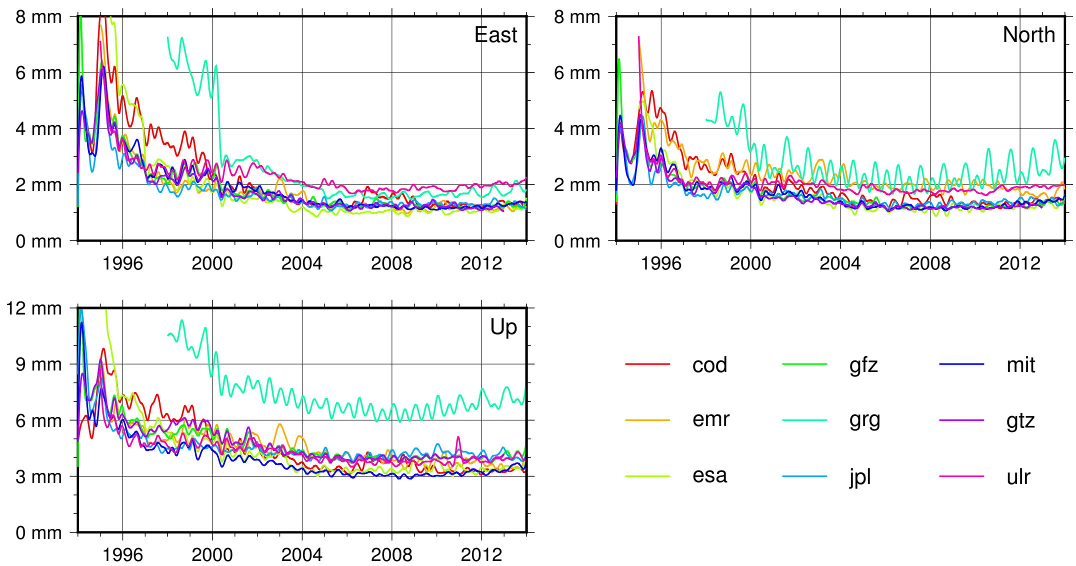

Figure 5: WRMS of AC station position residuals from preliminary combinations of the daily AC repro2 SINEX solutions. All time series were low–pass filtered with a 2.5 cycles per year cut–off frequency.

round of daily repro2 SINEX combinations. Note that the GFZ, GTZ and ULR were here still included for comparison only. With the exception of GRG, the AC WRMS are, after 2004, homogeneously within $1 - 2$ mm in the horizontal components and $3 - 4$ mm in the Up component. However, before 2000 and even more before 1997, a clear degradation of the inter–AC agreement can be noted. Since it was much less pronounced in the results from the weekly repro1 SINEX combinations, this degradation is likely related to the use of daily data integrations in repro2.

Table 2: WRMS of the EOP residual time series from the latest preliminary round of daily repro2 SINEX combinations. (ACs included with weight in these combinations are indicated in bold.)

AC	X–pole (μas)	Y–pole (μas)	X–pole rate (μas/d)	Y–pole rate (μas/d)	LOD (μs)
COD	**34.7**	**33.3**	**175.4**	**184.0**	**10.8**
EMR	**40.0**	**44.5**	**218.2**	**183.0**	**23.8**
ESA	**25.6**	**25.8**	**138.6**	**143.5**	**9.8**
GFZ	38.6	40.5	198.9	198.1	11.9
GRG	34.7	29.5	152.2	194.5	8.3
JPL	**31.0**	**28.1**	**169.3**	**172.5**	**16.2**
MIT	**16.9**	**16.4**	**62.7**	**70.1**	**2.0**
GTZ	31.9	32.1	175.9	166.0	10.5
ULR	32.5	33.4	201.5	207.8	23.5

Table 2 contains the WRMS of the EOP residual time series from the same round of preliminary repro2 SINEX combinations. Plots of these series can be found in Rebischung et al. 2014b. A predominance of MIT's estimates can be noted for all EOPs. It is more pronounced for the pole rates than for the pole coordinates, and even more pronounced for LOD, like in the operational SINEX combinations (Sect. 2). With the exception of MIT, the inter–AC agreement on EOPs is at the level of $30 - 40\,\mu$as for the pole coordinates, 150–200μas/d for the pole rates and $10 - 20\,\mu$s for LOD (after LOD bias corrections based on the IERS Bulletin A have been applied).

The scales of the daily repro2 AC SINEX solutions show an excellent agreement with each other, at the level of $0.3 - 0.5$ mm WRMS. The inter–AC scale rate differences are in particular below 0.05 mm/yr for the 5 ACs included with weight so far (Rebischung et al. 2014b), which could favor a contribution of GNSS to the definition of the ITRF2014 scale rate. On the other hand, compared to the repro1 results, no substantial decrease of the inter–AC origin discrepancies could be observed. The preliminary repro2 combined geocenter time series is moreover still showing considerable differences with SLR–derived geocenter time series (Rebischung et al. 2014b).

The final repro2 daily combined SINEX solutions will be delivered to the IERS before the end of February 2015.

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Tide Gauge Benchmark Monitoring Working Group Technical Report 2014

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Introduction

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

The main aims of the TIGA Working Group are:

- Maintain a global virtual continuous `GNSS@TG` 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.

For the year 2014, the TIGA–WG has continued with the reprocessing of the TIGA network, which was in parallel to the repro2 campaign of the IGS. Nearly 800 `GNSS@TG` stations and IGS08b core sites are processed by the TIGA Analysis Centers. End of 2014 first submissions had been made to the IGS repro 2 for the inclusion into the ongoing ITRF update.

The following part provides details for each TIGA component.

BLT TIGA Analysis Center/ULX Combination Center

N. Teferle, A. Hunegnaw, R. Bingley, and D. Hansen

Reprocessing

The consortium of British Isles continuous GNSS Facility (BIGF) and the University of Luxembourg TAC (BLT) has produced minimally constrained SINEX solutions from its reprocessing using the *Bernese GNSS Software* (BSW) version 5.2 for the period 1995 to 2013. The BLT reprocessing strategy follows closely that of (Steigenberger et al. 2006) while incorporating recent model developments and the latest International Earth Rotation and Reference Systems Service (IERS) 2010 conventions (Petit and Luzum 2010). We summarize our network DD processing in Tab. 1. In the DD strategy we have included all IGb08 core stations in order to achieve a consistent reference frame implementation and daily position estimates for up to 450 stations are available (See Fig. 1).

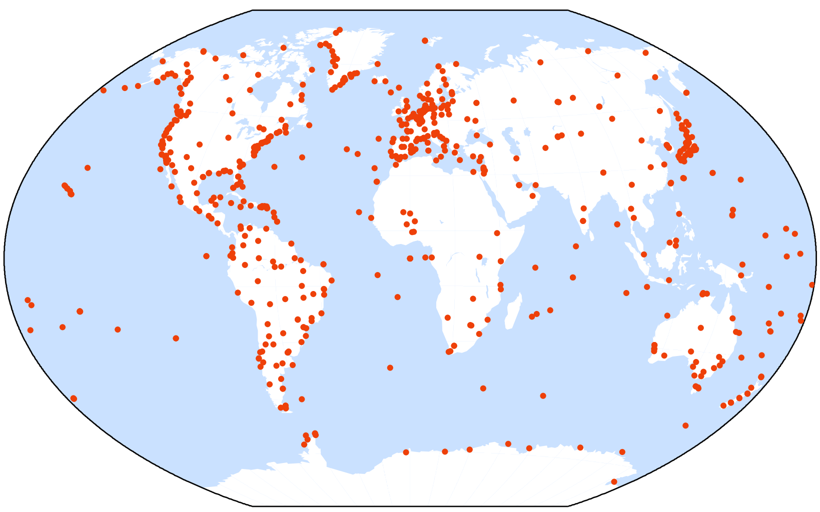

Figure 1: GPS network processed at BLT for TIGA.

Table 1: Summary of the GPS data processing strategy at the UL

Parameters	Description
GPS software	*Bernese Software* Version 5.2 (Dach et al. 2007)
Data	Double–differenced phase and code observations from up to 450 stations per day
Elevation cut–off angle	3 degree and elevation dependent weighting (w = cos2z, z: zenith angle)
Ionospheric refraction	Ionospheric–free linear combination (L3) is employed together with the 2nd order correction
Tropospheric refraction	An a priori dry tropospheric delay (Saastamoinen) computed from standard atmosphere. For wet part continuous piecewise – linear troposphere parameters estimated in 2–hour intervals, plus gradients in north–south and east–west directions at 24–hour intervals. The slant delay information is mapped to the zenith using the VMF1 mapping function.
Earth orientation	C04 series IERS Bulletin B
Antenna PCV	IGS absolute elevation and azimuth dependent PCV `igs08.atx` file (`http://igscb.jpl.nasa.gov/igscb/station/general/pcv_archive`)
Earth and polar tide	IERS2010 (Petit and Luzum 2010)
Ocean Loading	Computed using FES2004 ocean tide model (`http://holt.oso.chalmers.se/loading`)
Datum	No–Net–Rotation (NNR) and No–Net–Translation (NNT) with respect to IGb08 (Rebischung et al. 2012). However, any conditions such as NNT or No–Net–Scale (NNS) or a combination of them can be applied since we save the normal equations of our DD processing
Ambiguity Resolution	Resolved to integers up to 6000 km using different techniques depending on the baseline length
Meta data	Intensive meta data check

Combination

The University of Luxembourg (ULX) also acts as a TIGA Combination Center (TCC). One of the objectives of the TIGA Working Group is to produce consistent station coordinates on a weekly basis in the form of SINEX files, which are useful for multi–solution combinations, i.e. following largely the example of the routine IGS combinations. At ULX we aim to explore the potential in improving the precision and accuracy of the station coordinates and station velocities through network analysis. So far, only three of five TAC solutions have been completed and are now available for a preliminary multi–year combination. These include the solutions of the British Isles continuous GNSS Facility – University of Luxembourg consortium (BLT), the GeoForschungsZentrum (GFZ) Potsdam, and of the University of La Rochelle (Fig. 2). It is noteworthy that all three contributing TACs have analyzed global networks with a consistent set of reference frame stations, i.e. the IGb08 core stations. Taking these individual TAC solutions ULX has computed a first combination using two independent combination software packages: *CATREF* and *GLOBK*. A preliminary study confirms that the two independent combinations as implemented by ULX agree well and demonstrates that either of the two independent software packages may be used by the TCC. However, the coordinate differences exhibit regionality, i.e. they show some regional variations in scatter and biases (see Fig. 3). An issue that requires further investigation for long–term combinations.

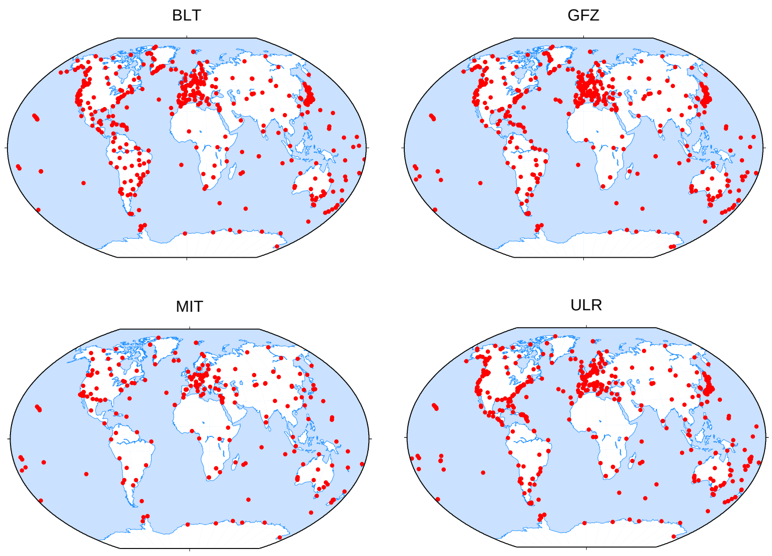

Figure 2: TIGA and IGS AC solutions used for the preliminary TIGA combination in this study. MIT solution was included to improve the redundancy in our combination. It will be replaced when other TIGA solutions become available.

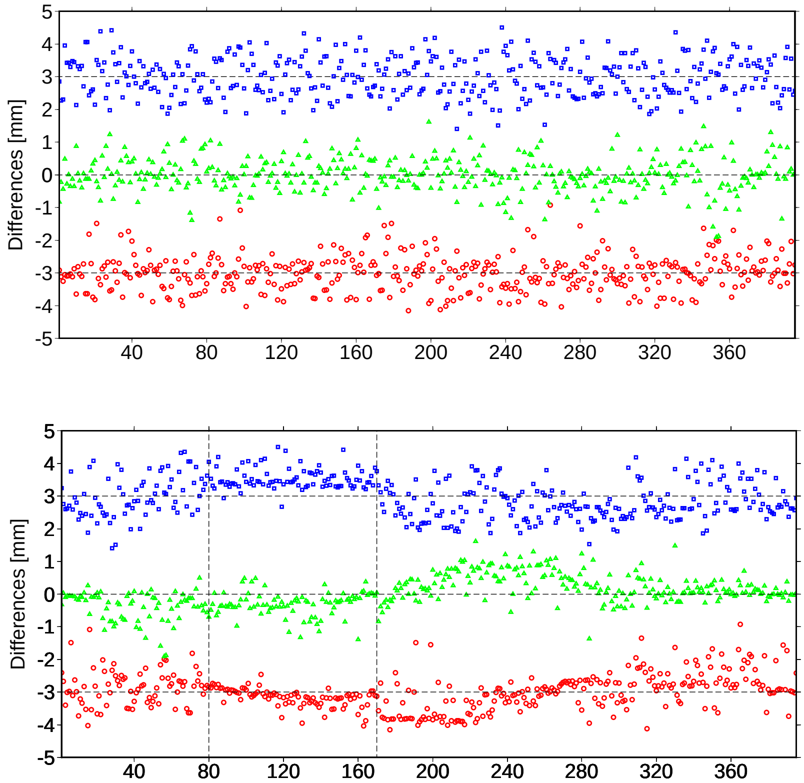

Figure 3: Coordinate differences for 400 stations between the CATREF/GLOBK combination of eight IGS AC solutions for December 2011. Green circles represent the coordinate differences for the X, red for the Y and blue for the Z component. For clarity the Y and Z components are offset by 3 mm. (top) The differences are arranged alphabetically according to station four characters ID. (bottom) The differences are arranged regionally according to station DOMES number ID. For example, the coordinate differences between stations 80 and 170 (the two vertical dotted lines) show those stations located in North America.

DGFI TIGA Processing

L. Sánchez

The Deutsches Geodätisches Forschungsinstitut, since January 2015 integrated into the Technische Universität München (DGFI–TUM), processes a global network with about 450 continuously operating GNSS stations as contribution to the TIGA working group (Fig. 4). The analysis strategy is aligned to IERS Conventions 2010 and to the GNSS–specific guidelines defined by the IGS for the second reprocessing of its global network (http://acc.igs.org/reprocess2.html). The main processing characteristics are:

- Reference frame: IGS08/IGb08 (Rebischung et al. 2012)
- Basic observable: ionosphere–free linear combination
- Sampling rate: 30 sec
- Elevation cut–off angle: 3 deg
- Elevation–dependent weighting of observations: 1/cos2z, where z is the zenith distance
- A–priori values for the estimation of satellite orbits, satellite clock offsets, and EOP are the IGb08–based satellite products and EOP generated by the IGS processing center CODE (Center for Orbit Determination in Europe, ftp://ftp.unibe.ch/aiub/CODE)
- Phase ambiguities for L1 and L2 solved after the quasi–ionosphere free (QIF) strategy described in Dach et al. 2007. The ionosphere models of CODE (ftp://ftp.unibe.ch/aiub/CODE) are used as input to increase the number of solved ambiguities
- Antenna phase center model: `igs08.atx` (Schmid 2011)
- Tropospheric zenith delay modelling based on the Vienna Mapping Function 1 (VMF1, Böhm et al. 2006) with a priori values (∼dry part) from the gridded coefficients provided by J. Böhm at http://ggosatm.hg.tuwien.ac.at/DELAY/GRID/VMFG and refinement through the computation of partial derivatives with 2 h intervals within the network adjustment
- Tidal corrections for solid Earth tides, permanent tide, and solid Earth pole tide as described by Petit and Luzum 2010. The ocean tidal loading is reduced with the FES2004 model (Letellier 2004) and the atmospheric tidal loading caused by the semidiurnal constituents S1 and S2 is reduced following the model of van Dam and Ray 2010. The reduction coefficients for the ocean tidal loading are provided by M.S. Bos and H.–G. Scherneck at http://holt.oso.chalmers.se/loading. The

reduction coefficients for the atmospheric tidal loading are provided by T. van Dam at http://geophy.uni.lu/ggfc-atmosphere/tide--loading--calculator.html

- Non–tidal loadings like atmospheric pressure, ocean bottom pressure, or surface hydrology are not reduced.
- Daily free normal equations are computed by applying the double difference strategy using the *Bernese GNSS Software* V5.2 (Dach et al. 2007, 2013). The baselines are formed by maximizing the number of common observations for the associated stations. The processed network is classified in four clusters of ca. 120 stations each.
- The seven daily free normal equations corresponding to a GPS week are combined into a weekly free normal equation using also the *Bernese GNSS Software* V5.2.

Daily and weekly solutions for the time period covered from January 2007 to December 2012 are already reprocessed. At present, a preliminary multi–year solution is being computed to evaluate the consistency between the epoch–solutions.

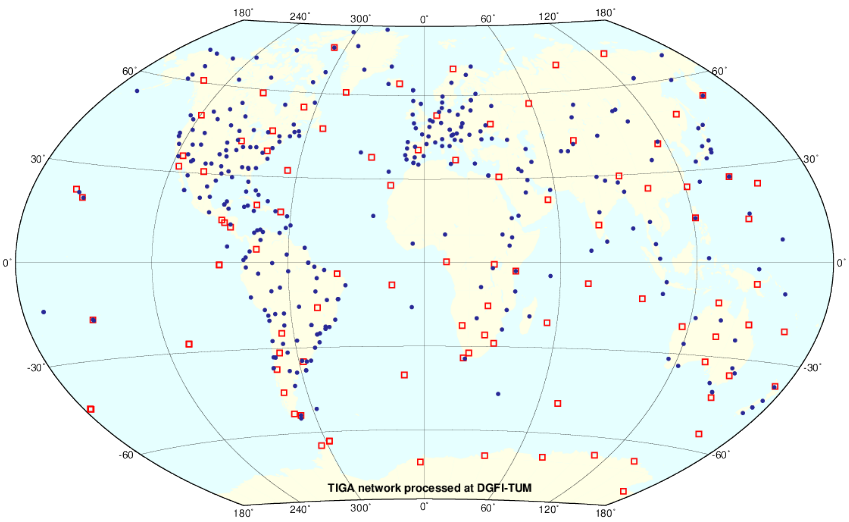

Figure 4: TIGA network processed at DGFI–TUM.

Tide Gauge data reprocessing at GFZ

Zhiguo Deng

The solutions of the GFZ TIGA REPRO2 (GTZ) will also contribute to IGS 2nd Data Reprocessing Campaign (IGS REPRO2) with the GFZ IGS REPRO2 (GFZ) solution. Following the 2nd IGS reprocessing finished in 2010 some improvements were implemented into the latest GFZ software version *EPOS.P8*: reference frame IGb08 based on ITRF2008, antenna calibration `igs08.atx`, geopotential model (EGM2008), higher–order ionospheric effects, new a priori meteorological model (GPT2), VMF mapping function, and other minor improvements.

The GNSS data is collected through the SONEL data center (`www.sonel.org`) of the Global Sea Level Observing System (GLOSS). GNSS data of the globally distributed tracking network of 794 stations for the time span from 1994 until end of 2012 are used for the GFZ TIGA REPRO2.

In the IGS repro2 combination the GTZ and GFZ solution are included (IGSMAIL–7055). Now the combination solution is now available. The station position RMS of the 9 solutions with respect to the Repro2 daily combined solution are given in Fig. 7 (East, North and Up in mm). The GFZ/GTZ solutions show consistent high accuracy during the whole period.

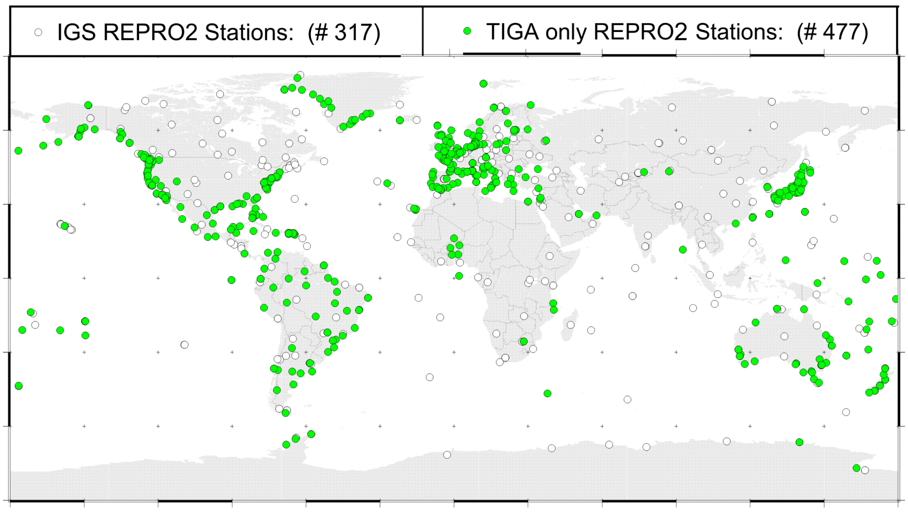

Figure 5: Global distribution of the TIGA reprocessed GPS stations for GFZ REPRO2 (white dots) and TIGA (green+white dots).

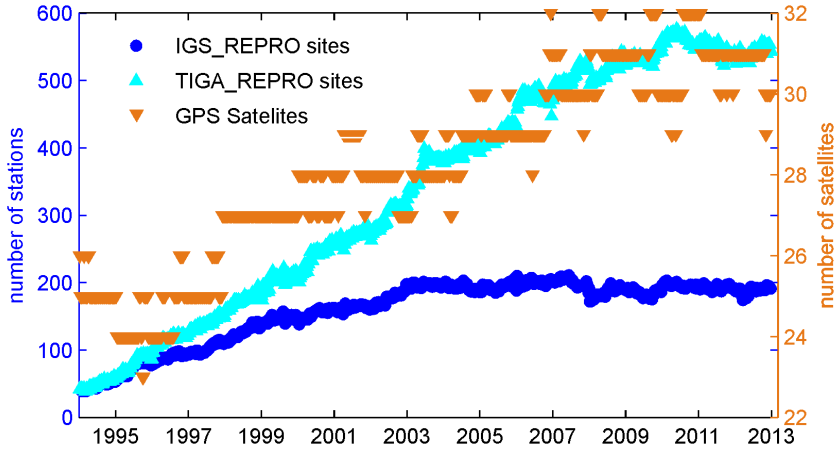

Figure 6: Weekly Number of stations and satellites included in the GFZ REPRO2 and TIGA REPRO2. TIGA REPRO2 is based on the same set of GFZ REPRO2 stations, so that the difference to IGS_REPRO2 shows the number of processed TIGA only stations.

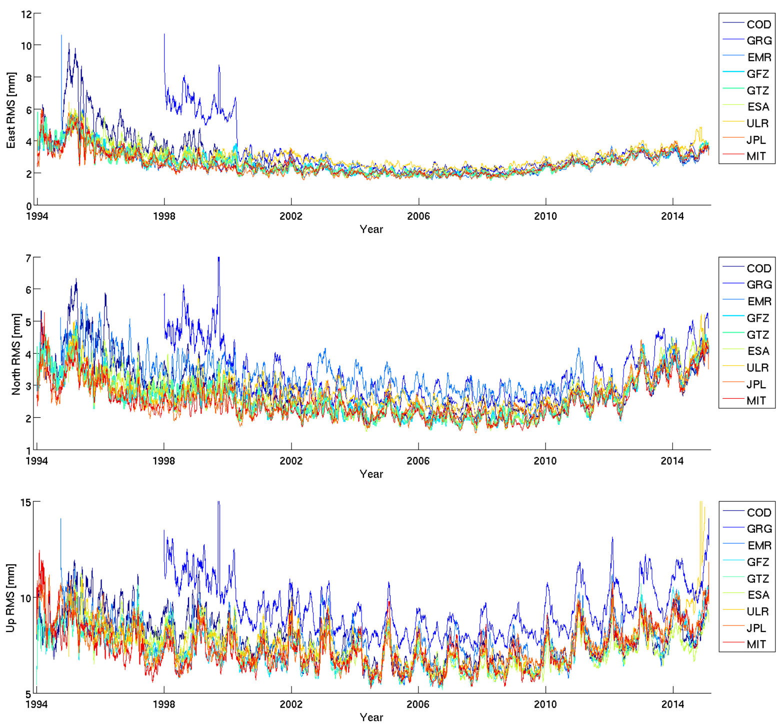

Figure 7: Station position residuals with respect to the Repro2 daily combined solutions. In general the weighted RMS of the GFZ and GTZ station coordinates are better than average.

ULR TIGA Analysis Center

M. Gravelle, A. Santamaría–Gómez, and G. Wöppelmann

The University of La Rochelle (ULR) analysis center has participated to the International GNSS Service (IGS) Repro2 and TIGA campaigns which aim at reprocessing worldwide GPS data for high precision products such as satellite orbits & clocks and terrestrial reference frame (station positions and velocities). The ULR analysis center has the particular aim of reprocessing the densest network of GPS stations nearby tide gauges whose data have been collected through the SONEL (http://www.sonel.org) data assembly center.

Daily positions estimates between 1995.0 and 2015.0 have been obtained for a set of 749 stations worldwide distributed using the *GAMIT/GLOBK software*. The combination and alignment of the daily network solutions to the International Terrestrial Reference Frame (ITRF2008), including estimation of station velocities, is performed using the *CATREF software*.

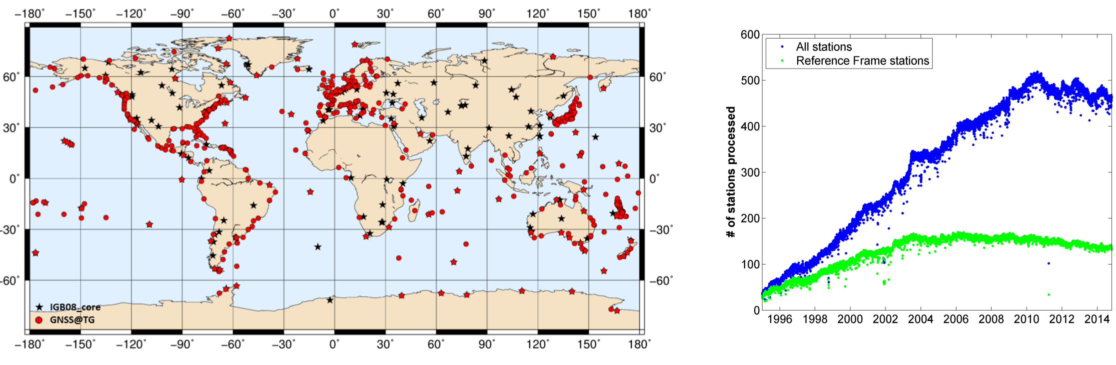

Figure 8: Network of reprocessed stations at ULR (left) and number of stations reprocessed per day (right).

SONEL Data Center

M. Gravelle, M. Guichard, E. Prouteau, and G. Wöppelmann

Status of the network

The SONEL data center (www.sonel.org), hosted by the University of La Rochelle, collects, analyses and archives GNSS data and metadata from almost 800 permanent stations nearby (<15 km) tide gauges (CGPS@TG) (Fig. 9). Among these stations, SONEL provides the data and metadata of the 122 TIGA stations (Fig. 10). Figure 11 shows the evolution of the number of RINEX files from GNSS@TG stations archived in SONEL. The distribution of the stations record length is plotted on Fig. 12.

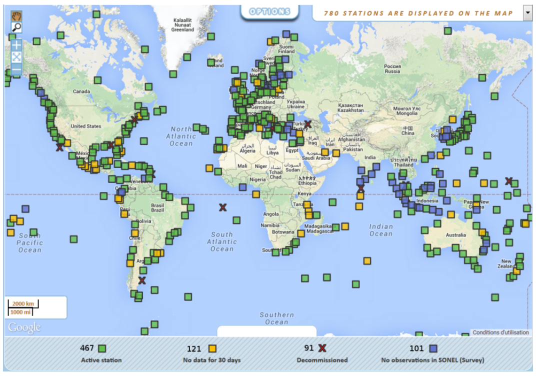

Figure 9: GNSS@TG network (www.sonel.org).

Figure 10: TIGA GNSS network (www.sonel.org).

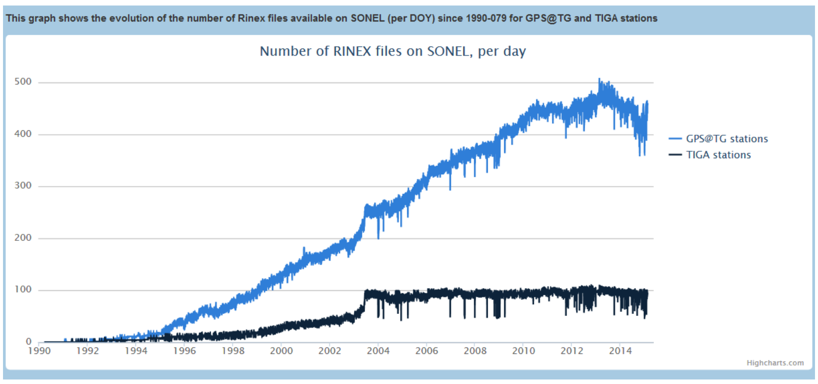

Figure 11: Evolution of the number of RINEX files from GNSS@TG stations archived in SONEL (www.sonel.org).

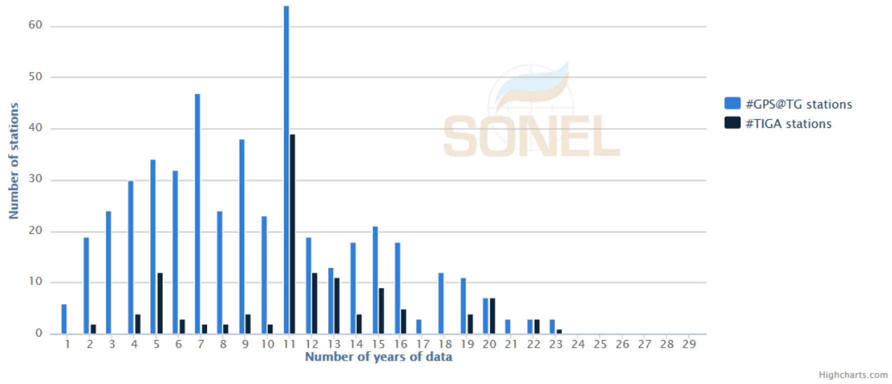

Figure 12: Stations record length histogram of the GNSS@TG in SONEL. Only stations with more than 70% of valid data are taken into account.

Quality check plots

Tools have been developed to automate the analysis and the quality control of the collected GNSS data. Dynamic plots displaying the tracking performance of the stations are updated daily and provided on each station webpage in the SONEL portal (Fig. 13).

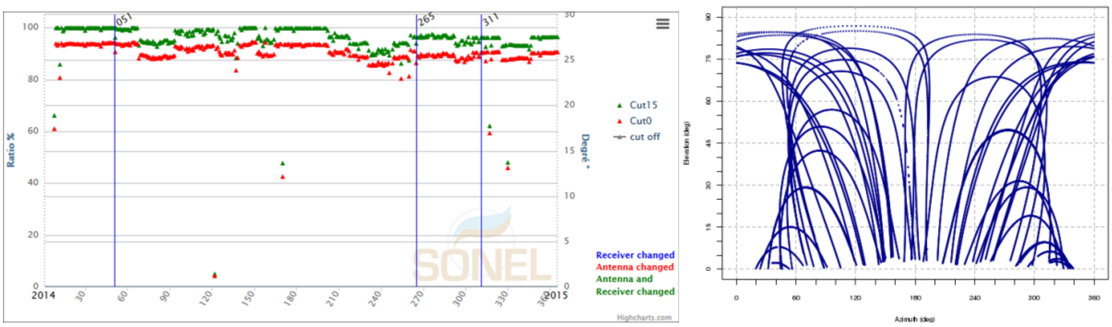

Figure 13: Examples of quality check plots for SCOA station.

GNSS@TG geodetic ties

In addition to the data and metadata collection, SONEL strives to get the geodetic tie between the GNSS station and the co–located tide gauge (Fig. 14). While the geodetic tie is known only for 17% out of 779 GNSS stations archived in SONEL, this number reaches 63% for the TIGA stations (Fig. 15).

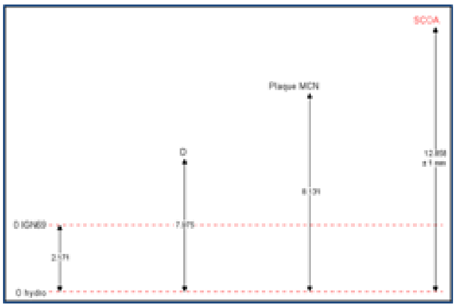

Figure 14: SONEL levelling results diagram for St Jean de Luz tide gauge.

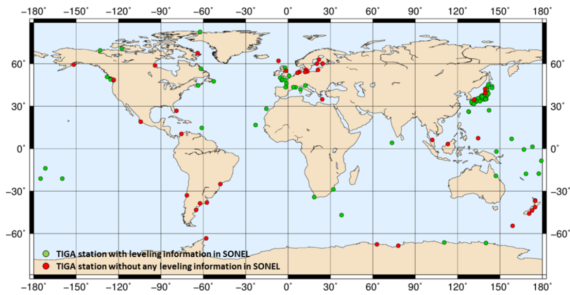

Figure 15: Status of TIGA stations with geodetic ties available at SONEL.

Collaboration with other data centers

SONEL is recognized as GNSS at tide gauges Data Assembly Center for the UNESCO/IOC Global Sea Level Observing System (GLOSS, http://www.gloss-sealevel.org) and strives to develop the interoperability with the other GLOSS data centers, especially with the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org) database.

Evolution of the SONEL website access

Evolution of the SONEL website access is shown in Fig. 16 and Tab. 2.

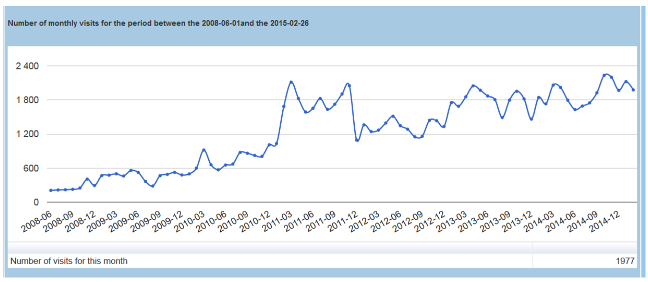

Figure 16: Evolution of the number of visits per month. Status at 2015/02/26.

Total number of visits	22854
Number of visitors	16674
Number of viewed pages	56322
Average number of viewed pages by visit	2.46

Table 2: Number of visits between 2014-01-01 and 2014-12-31

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Appendix A. TIGA Working Group Members in 2014

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	Germany
Norman Teferle	TAC/Combination	University of Luxembourg	Luxembourg
Richard Bingley	TAC	University of Nottingham	UK
Ruth Neilan	IGS Central Bureau	ex officio	USA
Jake Griffith	IGS AC coordinator	ex officio	USA
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 2014

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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 chairs the IGS TWG. Dr. Sharyl Byram 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 2014

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 2011–4. The average number of quality–checked station result files submitted per day in 2014 was 326, comparable to the 2013 average value of 325. These files can be downloaded from ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd; users downloaded 12.3 million files in 2014 (Noll 2015).

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).

The IGS estimates GNSS–related parameters, e.g., satellite orbits, satellite–clock corrections, in 24–hour batches, causing discontinuities to appear between parameter values computed at the end of one 24–hr measurement block and the beginning of the next. (The GNSS measurements themselves are recorded continuously.) IGS FTEs exhibit such day–boundary discontinuities of about 4 − 7 mm RMS (depending on location), complicating IGS FTE use in certain meteorological applications. Research is ongoing at Technische Universität München to characterize and then minimize these discontinuities. Steps forward were made in a bachelor's thesis by Gauges (Gauges 2014), who, in studying day–

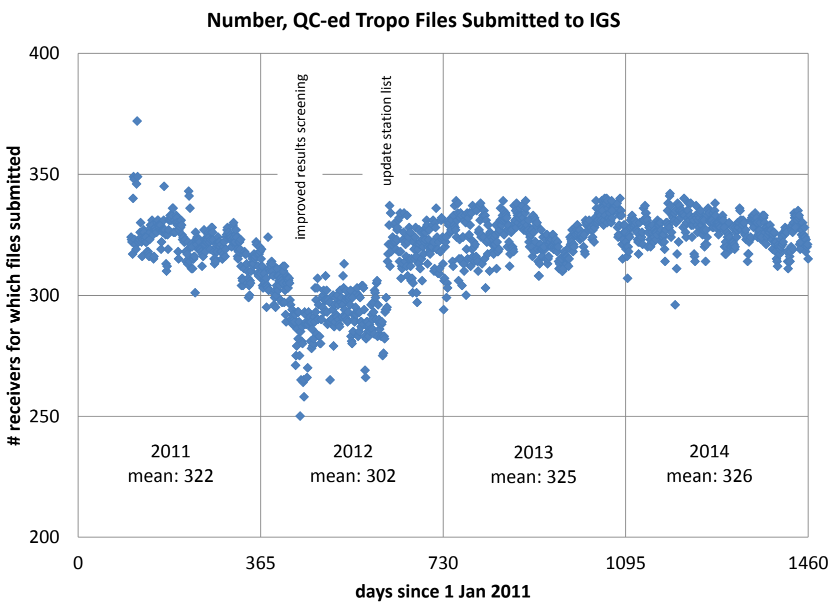

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011–4. (Estimates were produced by Jet Propulsion Laboratory up through mid–April 2011.)

boundary discontinuities at 30 locations, observed that the RMS discontinuity size at a given location was ultimately linked to the size of the zenith troposphere delay itself. A procedure to minimize the discontinuities is under development.

3 IGS Troposphere Working Group Activities 2014

The goal of the IGS Troposphere Working Group is to improve the accuracy and usability of GNSS–derived troposphere estimates. It works toward this goal by coordinating (a) technical sessions at the IGS Analysis Workshop and (b) working–group projects.

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 with the biennial 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.

In this section, we first summarize TWG–coordinated technical and splinter sessions which took place at the 2014 IGS Workshop. We then report on the status of current TWG projects. We then summarize the Fall AGU 2014 TWG splinter–group meeting.

2014 IGS Workshop technical/splinter sessions coordinated by the IGS TWG

The IGS Workshop took place 23–27 June 2014 in Pasadena, CA. The IGS TWG coordinated three sessions: an oral plenary session in which speakers presented large–scale projects related to estimation or application of GNSS–based troposphere estimates, a poster session in which maximum participation was sought in order to foster technical exchange, and an IGS TWG splinter meeting.

Plenary Session PY09A, GNSS–Derived Troposphere Delays, 26 June 2014, featured the following presentations (speaker's name bolded) which also can be accessed at http://igs.org/workshop/plenary:

- On the COST Action GNSS4SWEC[1] project, which uses GNSS–derived troposphere estimates for severe–weather forecasting:

  Advanced Global Navigation Satellite Systems Tropospheric Products for Monitor-

[1] European Cooperation in Science and Technology (COST) Advanced Global Navigation Satellite Systems Tropospheric Products for Monitoring Severe Weather Events and Climate: http://www.cost.eu/COST_Actions/essem/Actions/ES1206

ing Severe Weather Events and Climate (GNSS4SWEC), G. Guerova[2], J. Jones, J. Douša, G. Dick, S. de Haan, E. Pottiaux, O. Bock, R. Pacione, G. Elgered, and H. Vedel

- On the World Meteorological Observation GRUAN[3] project, which (among other things) uses GNSS–derived troposphere values to study climate change:

  Global Precipitable Water Trend and its Diurnal Asymmetry Based on GPS, Radiosonde and Microwave Satellite Measurements, J. Wang[4], A. Dai, and C. Mears

- On the (IGS–coordinated) development of a database/website automating the comparison of troposphere estimates derived from independent techniques (e.g., GNSS, VLBI, radiosondes, and weather models):

  Development Towards Inter–Technique Troposphere Parameter Comparisons and Their Exploitation, J. Douša[5], S. Byram, G. Gyori, O. Böhm, C. Hackman, and F. Zus

Poster Session PS05, Estimation and Application of GNSS–Based Troposphere Delay (25 June, 2014) featured 18 contributions, which can be viewed at http://igs.org/workshop/posters.

The splinter meeting (25 June 2014; simulcast via gotomeeting.com) featured the following presentations on current WG projects, plus discussion of past/future directions:

- *IGS Troposphere Working Group Meeting*, C. Hackman
- *Status of Developments for Tropospheric Parameter Comparisons*, J. Douša, S. Byram, G. Gyori, O. Böhm, C. Hackman, and F. Zus
- *Draft Proposal for Tropospheric Format Update*, R. Pacione[6] and J. Douša

These presentations were distributed via the IGS TWG email list (message IGS–TWG–102) and can also be obtained by contacting this report's author.

IGS Troposphere Working Group Projects

As mentioned previously, the goal of the IGS Troposphere Working group is to improve the accuracy and usability of GNSS–derived troposphere estimates. One way to assess the accuracy of GNSS–derived troposphere estimates is to compare these estimates to those obtained for the same time/location using independent measurement techniques,

[2] Sofia University (Bulgaria)
[3] GCOS (Global Climate Observing System) Reference Upper Air Network: http://www.gruan.org
[4] University at Albany, SUNY; National Center for Atmospheric Research (both USA)
[5] Geodetic Observatory Pecný (Czech Republic)
[6] e–GEOS SpA, ASI/CGS, Matera, Italy

e.g., VLBI (Very Long Baseline Interferometry), DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), radiosondes, or from numerical weather models.

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 Gyori 2013; Gyori and Douša 2015), with contributions from other scientists at GOP and at GeoForschungsZentrum (GFZ; Germany). This database is nearly complete: it already can (and does) download and compare troposphere values from a wide variety of sources, compensating for horizontal and vertical separation of measurement locations. Development of the website by which users can view/access the values is underway as well, with USNO augmenting initial GOP efforts. USNO has also begun contributing to database development, as well as the sourcing of auxiliary databases/servers.

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 2–14 Nov 2014. Such short, focused co–work visits enable large steps forward, e.g., the installation of a second database at USNO, familiarization of USNO staff with database features, and USNO–GOP joint work on designing interface structure.

Fig. 2 illustrates how the user interface to the website/database might appear. Completion of this project is expected in 2016. This system has received interest from climatologists/meteorologists, e.g., those associated with the GRUAN and COST Action GNSS4SWEC projects, as it will simplify quality–comparison and perhaps acquisition of data used as input to their studies.

The IGS Troposphere Working group is also supporting a project to standardize the *tropo_sinex* format in which troposphere delay values are disseminated and exchanged. 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. To take one simple and relatively benign example, text strings *STDEV* and *STDDEV* are used to denote standard deviation in the GNSS and VLBI communities respectively. Such file–format inconsistencies hamper inter–technique comparisons.

This project, spearheaded by IGS Troposphere WG members R. Pacione and J. Douša, is being conducted within the COST Action GNSS4SWEC Working Group 3. This COST WG consists of representatives from a variety of IAG (International Association of Geodesy) organizations and other communities; its work is further supported by the EU-

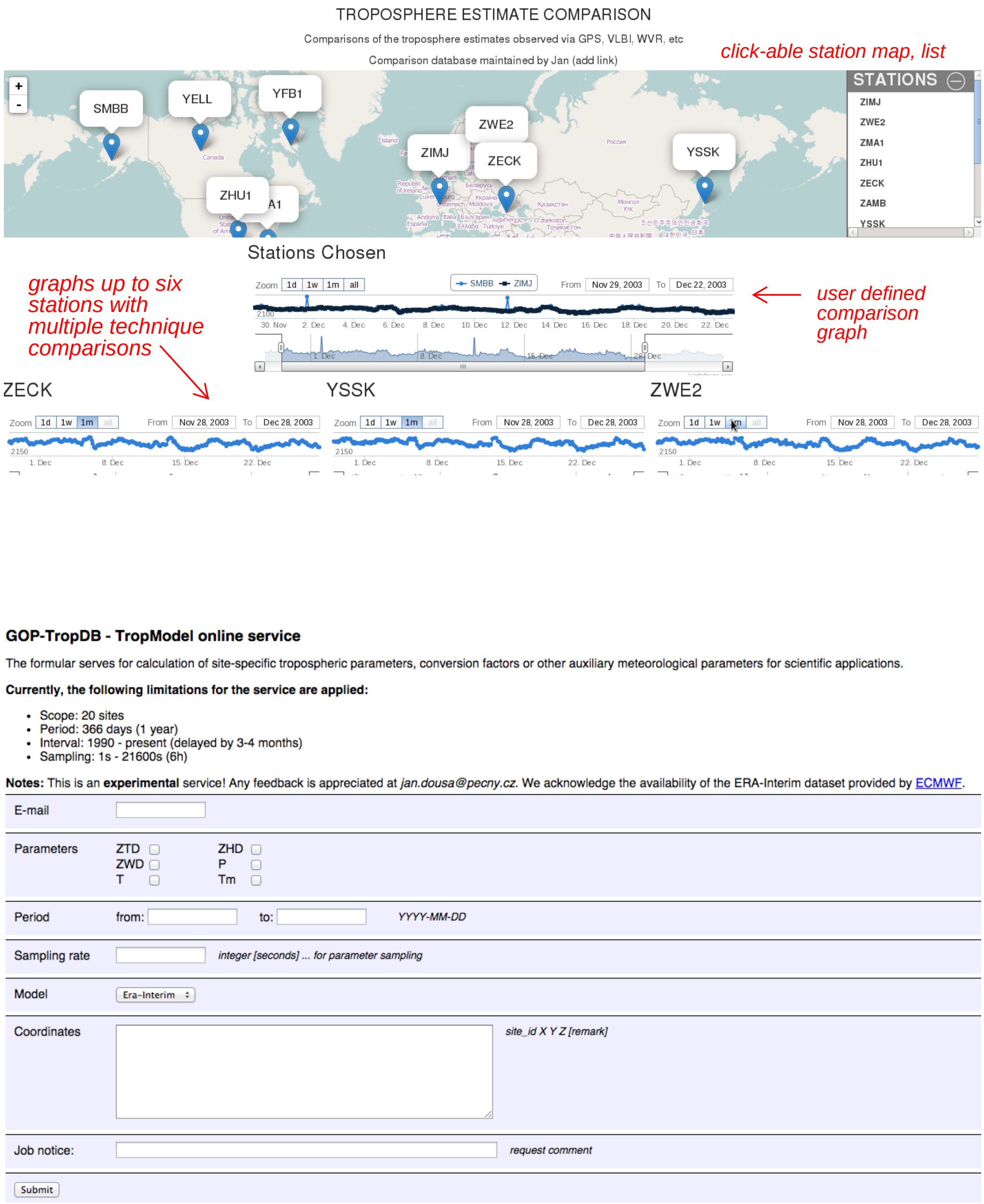

Figure 2: Early drafts: two parts of user (website) interface to troposphere–comparison database. (Top) User can choose locations and sources for which s/he would like to compare values. (Bottom) User can request measurement files.

REF 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.

IGS Troposphere Working Group Meeting, 16 December 2014, San Francisco, CA (simulcast via `gotomeeting.com`)

This meeting featured status reports on WG projects, a report from the GNSS4SWEC team, research–paper contributions by groups unable to attend, and a discussion of troposphere–estimate day–boundary discontinuities.

The presentations and papers were distributed via the IGS TWG email list (message IGS–TWG–115), and can also be obtained by contacting this report's author.

- Presentations:
  - *IGS Troposphere Working Group Meeting*, C. Hackman
  - *GNSS4SWEC Update* – G. Guerova and the GNSS4SWEC team
- Discussion: cause & amelioration of day–boundary discontinuities in IGS Final Troposphere Estimates, based partly on results presented in Gauges 2014.
- Publications contributed to the meeting:
  - J. Böhm, G. Möller, M. Schindelegger, G. Pain, and R. Weber. "Development of an improved empirical model for slant delays in the troposphere (GPT2w)," *GPS Solutions*, DOI 10.1007/s10291–014–0403–7, 2014. (MATLAB source code here: `http://ggosatm.hg.tuwien.ac.at/DELAY/SOURCE/GPT2w`)
  - B. Federici, I. Ferrando, and D. Sguerso. "GM24P: GNSS monitoring to predict potential precipitation," Community Protection Expo, 9–11 December 2014, Genoa IT, 2014. `domenico.sguerso@unige.it`
  - L. Morel, E. Pottiaux, F. Durand, F. Fund, K. Boniface, P. Sergio de Oliveira Junior, and J. Van Baelan. "Validity and behaviour of tropospheric gradients estimated by GPS in Corsica," *Advances in Space Research*, 55:135–149, 2015. `http://dx/doi/org/10.1016/j.asr.2014.10.004`

[7] `http://www.euref.eu/euref_twg.html`
[8] EUMETNET EIG GNSS Water Vapour Programme; `http://egvap.dmi.dk`

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 or Dr. Christine Hackman, christine.hackman@usno.navy.mil.
- To learn more about the IGS Troposphere Working Group, you may:
  - contact Dr. Christine Hackman at christine.hackman@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

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Appendix A. IGS Troposphere Working Group Members

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Bock	Olivier	IGN–LAREG	France
Boehm	Johannes	TU Wien	Austria
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
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Cao	Wei	Univ. New Brunswick	Canada
Chen	Junping	Shanghai Astronomical Observatory	China
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Crespi	Mattia	Univ. Roma, La Sapienza	Italy
Deng	Zhiguo	GFZ	Germany
Dick	Galina	GFZ	Germany
Douša	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
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Jones	Jonathan	Met Office UK	UK
Langley	Richard	Univ. New Brunswick	Canada
Leandro	Rodrigo	Hemisphere GNSS	USA
Leighton	Jon	3vGeomatics	Canada/UK
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Melachroinos	Stavros	Geoscience Australia	Australia
Moeller	Gregor	TU Wien	Austria

Moore	Angelyn	JPL	USA
Negusini	Monia	Inst. Radioastronomy (IRA); Nat'l. Inst. Astrophysics (INAF)	Italy
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
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Prikryl	Paul	Communications Research Centre, Canada	Canada
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Sguerso	Domenico	Lab. Geodesy, Geomatics, GIS; Univ. Genoa	Italy
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Tracey	Jeffrey	USNO	USA
van der Marel	Hans	TU Delft	Netherlands
Wang	Junhong	UCAR/NCAR	USA
Willis	Pascal	Inst. de Physique du Globe de Paris	France
Xu	Zong–qiu	Liaoning TU	China
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Appendix B. IGS Troposphere Working Group Charter

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.

  o Confer with outside agencies interested in the use of IGS products.

  o 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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