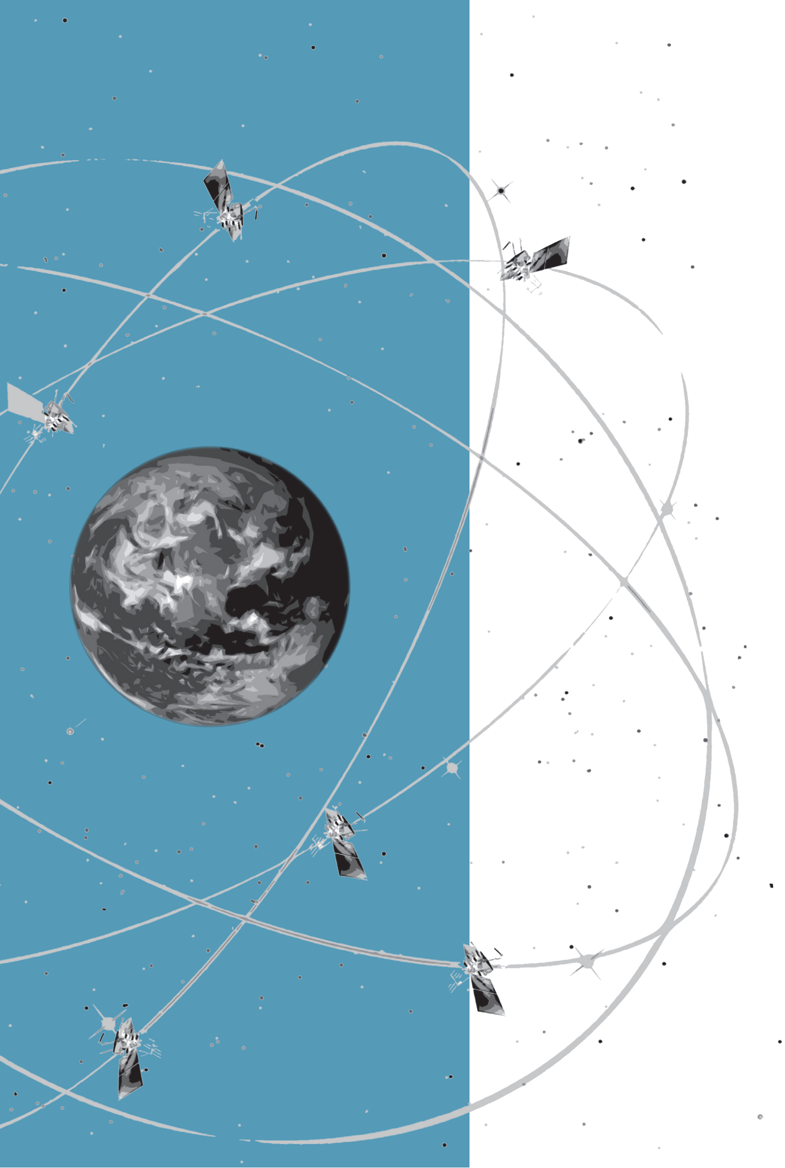
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2016



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Technical Report 2016

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 voluntary federation of government agencies, universities and research institutions, combines GNSS resources and expertise to provide the highest–quality GNSS data, products, and services in order to support high–precision applications for GNSS–related research and engineering activities.
This *IGS Technical Report 2016* 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 2016.

This report is available in electronic version at
ftp://igs.org/pub/resource/pubs/2016_techreport.pdf.

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

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G. Johnston

Geoscience Australia

1 Introduction

In 2016, the IGS has continued with a very exciting work program and list of achievements from the IGS participants. This year we have for the first time had an Analysis Centre Coordinator (ACC) distributed across two centers, Geoscience Australia and MIT, in two continents hemispheres apart, using combination software operating on Cloud computing services (Amazon Web Services).

Delivery of core reference frame, orbit, clock and atmospheric products continues strongly. 2016 has also seen further refinement of the Real Time Service with considerable efforts being targeted towards development of Standards. The transition to multi GNSS also continues apace within the IGS, with additional Galileo and Beidou satellite launches bringing those constellations closer to operational status.

In 2016, the IGS had its first workshop to be held outside of North America or Europe, with the Sydney Workshop being held in February 2016 at the University of New South Wales. This workshop, the first in South East Asia, signaled the stronger involvement of Beidou and QZSS into the IGS's GNSS futures.

The review of the Strategic plan which commenced in 2015 continued throughout 2016, with a revised version ready for publication in early 2017. The revised plan aims to recognize the extensive contribution of the IGS participants, and to encourage strong engagement with a broader stakeholder set that now rely implicitly on IGS products and services. The Call for Proposals for participation in the IGS / ICG joint Monitoring and Assessment project is a pragmatic example of the IGS being flexible enough to respond to stakeholder requirements. That project aims to utilize existing skills within the IGS family to service a new user community as an extension to our current role of providing world class GNSS expertise. The Call for participation had a strong response including a proposal from ESA to undertake the Monitoring and Assessment ACC function. Importantly this new joint project ensures the IGS continues to have strong influence with GNSS system providers. This strong relationship has been developed over many years by IGS participation in the International Committee on GNSS.

Of course the IGS functions as a service of the International Association of Geodesy (IAG), and a contributor to the Global Geodetic Observing System (GGOS). Accordingly a number of the Governing Board members continue to participate in IAG and GGOS governance, bureaus, commissions and working groups. Importantly, GB members also participate in the United Nations Global Geospatial Information Management (UN GGIM) efforts on Geodesy, which aims to enhance the sustainability of the global geodetic reference frame through intergovernmental advocacy for geodesy. GB members (Neilan, Ziebart, Enderle, and former GB member Gerhard Beutler) also gave presentations at the US PNT Advisory Board, influencing at the highest levels in the US government.

By working within the science community through (IAG/IUGG/ICSU) and the Intergovernmental community through ICG / UN GGIM / US PNT AB and others, the IGS GB is ensuring the IGS retains its strong level of relevance and impact, and therefore sustainability.

2 The IGS at a Glance

A glance of the IGS is given in Figure 1.

3 IGS Highlights in 2016

3.1 IGS 2016 Workshop – Sydney, Australia

The 2016 IGS workshop was hosted at the University of New South Wales in Sydney, Australia by Geoscience Australia, Land Information New Zealand, and the University of New South Wales. The workshop had the theme of GNSS Futures, and featured keynote presentations from Todd Humphreys (University of Texas at Austin), Jan Weiss (UCAR), and John Church (CSIRO), as well as over 50 plenary presentations and 57 posters. Keynotes, presentations, and posters may be viewed on the IGS website: http://www.igs.org/presents/workshop2016. The 2016 workshop was the first to be held outside of North America and Europe. It aimed to recognize Australia's long contribution to the IGS, but also encourage stronger participation by other South East Asian contributors.

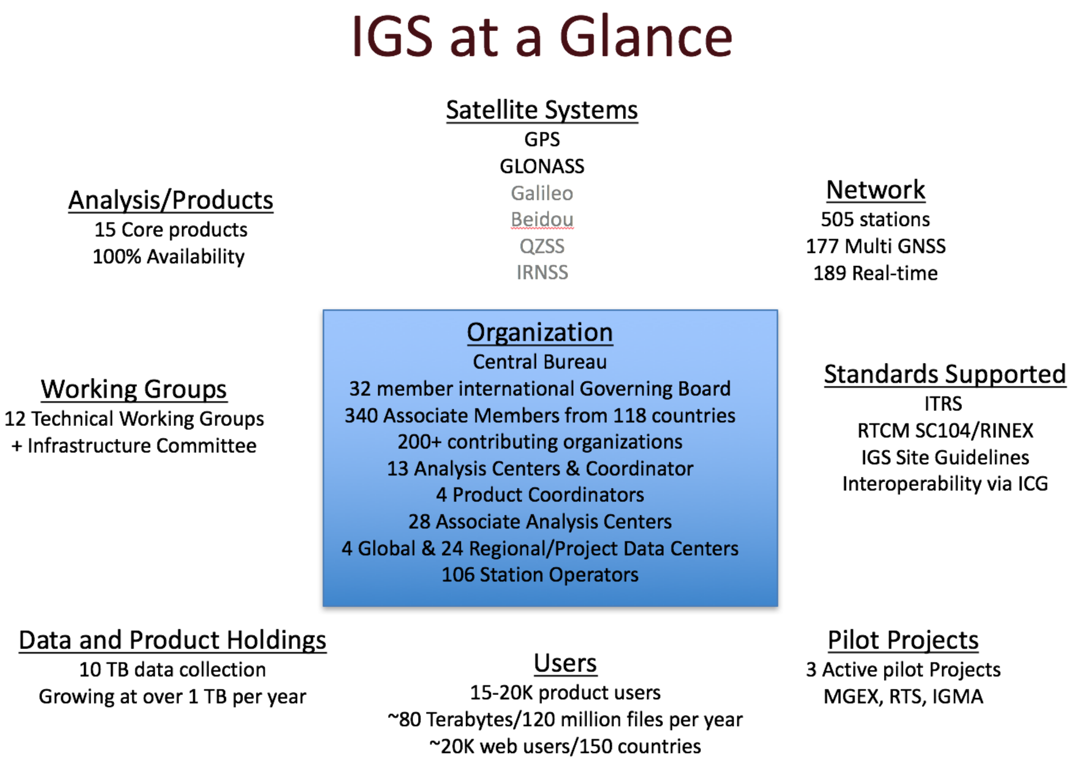

Figure 1: The IGS at a Glance.

3.2 Planning for Future IGS Workshops

At the Sydney workshop, it was decided to move the workshops to an 18-month cycle, due to the wealth of topics and quickening pace of technological development in GNSS. It was agreed that the next workshop would be hosted by IGN in Paris, France in July 2017. Planning for this workshop is actively underway, and a full summary will be included in the 2017 report.

At the December 2016 Governing Board meeting, representatives from Wuhan University presented a well-received proposal to host the 2018 workshop in China. The board agreed that this would be an excellent location for this workshop, and accepted the proposal. As a means to inform future workshop organizers, it was also decided that a representative from the next hosting organization will have a seat on the previous workshop's Scientific Organizing Committee. By doing this, each SOC will have a representative from the previous and future workshop, as well as representatives from the current workshop. Early planning is also underway for the 2019 workshop which is likely to be held in Boulder, USA, pending a proposal from UNAVCO.

4 Membership Growth and Internal Engagement

In 2016, IGS membership reached 337 Associate Members, representing 118 countries. The 32-member IGS Governing Board guides the coordination of over 200 contributing organizations participating within IGS, including 106 operators of GNSS network tracking stations, 4 global data centers, 13 analysis centers, and 4 product coordinators, 28 associate analysis centers, 23 regional/project data centers, 12 technical working groups, two active pilot projects (i.e., Multi-GNSS and Real-time), and the Central Bureau.

In order to better engage with its membership and the greater community, the IGS developed and conducted extensive stakeholder surveys throughout the year. This contributed to the development of the next IGS Strategic Plan, as well as the first Associate Member meeting, held immediately before the 47th Governing Board meeting in San Francisco, California, USA this past December.

5 ICG Monitoring and Assessment

Participation in the United Nations International Committee on GNSS (UN ICG) was a key external engagement of the IGS in 2016. Governing Board member Zuheir Altamimi (IGN, France), as co-chair of ICG Working Group on Reference Frames, Timing and Applications led the discussions and collated resulting recommendations at the November 2016 meeting in Sochi, Russia.

Governing Board members also played a central role in developing the GNSS Performance Monitoring Joint Trial Project with the UN-ICG International GNSS Monitoring and Assessment Task Force, which will be implemented to develop a credible, cooperative approach to monitoring the performance of the different GNSS.

6 IGS Operational Activities

6.1 Network Growth

The IGS network added 15 stations in 2016, bringing the total number of stations to 505. Development of the 166-station Multi-GNSS subnetwork, within the IGS network, has been driven by the MGEX Project, which develops the IGS capacity to operate with multiple GNSSs. Similarly, 187 IGS stations are now capable of real-time data streaming in support of the IGS Real-time Project.

6.2 Product Generation and Performance

ACC transition is now managed jointly by Michael Moore of Geoscience Australia and Tom Herring of the Massachusetts Institute of Technology. Operations are based at Geoscience Australia in Canberra, Australia. Responsibility for producing the IGS combined products officially transitioned from NOAA/NGS to Geoscience Australia on 1st January 2016. The combination software has been moved from a dedicated server to redundant cloud based servers located in Australia and Europe, and coordination of the IGS product generation is now done by personnel distributed between GA and MIT.

As an important measure of overall performance, the IGS keeps track of its product availability, expressed as the percentage of time that the IGS delivers products at the targeted level. The IGS has had a perfect 100% availability of its core products for each of the last four years since IGS began tracking this metric.

6.3 Data Management

The IGS data centers manage an approximately 10 Terabyte collection (over 100 million files) of GNSS and related data for IGS, which is growing at almost 2 Terabytes per year. These are maintained online for open access by all users.

Each of the four IGS global data centers is typically accessed by around 10,000 regular users who consume 70-80 Terabytes (about 120 million files) of IGS data and products per year. There are approximately 20,000 monthly users of the IGS website and related resources.

6.4 Standards Development Support

The IGS continues to contribute to the development of international standards related to GNSS, principally through participation within the RTCM (Radio Technical Commission for Maritime Service), where IGS leads the RINEX working group, as well as participating within the standards activities related to real time systems.

7 IGS Governing Board Meetings in 2016

The Governing Board discusses the activities and plans of various IGS components, sets policies, and monitors the progress with respect to the agreed strategic plan and annual implementation plan. It is customary to hold two GB meetings during any IGS Workshop – the second of which typically focusing on workshop recommendations and other debriefing from the week's activity.

7 February 2016	46th Governing Board Meeting (1 of 2 sessions), held prior to the 2016 IGS Workshop	Sydney, Australia
12 February 2016	46th Governing Board Meeting (2 of 2 sessions), held immediately after the 2016 IGS Workshop	Sydney, Australia
17 April 2016	Governing Board Business Meeting, held prior to the 2016 European Geosciences Union meeting	Vienna, Austria
11 December 2016	47th Governing Board Meeting, held prior to the 2016 American Geophysical Union meeting	San Francisco, California, United States

8 IGS Advocacy, and External Engagement

8.1 United Nations GGIM Sub-Committee on Geodesy

IGS remains active in engaging with diverse organizations that have an interest in geodetic applications of GNSS. Notably, the IGS has supported the development of the Global Geodetic Reference Frame (GGRF) resolution, roadmap, and upcoming implementation plan within the United Nations (UN) Global Geospatial Information Management (GGIM) Committee of Experts (http://ggim.un.org). In 2016, the UN further recognized the importance of a globally-coordinated approach to geodesy by forming a permanent Sub-Committee on Geodesy.

8.2 United States PNT Advisory Board

IGS actively engages and participates in the United States National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board (http://www.gps.gov/governance/advisory/). Both Central Bureau Director Ruth Neilan (NASA JPL, United States) and former Governing Board member Gerhard Beutler (AIUB, Switzerland) are members of this board, which provides advice to the US Government Executive Committee, chaired by the United States Deputy Secretary of Defense and Deputy Secretary of Transportation.

Beutler gave presentations focusing on Multi-GNSS at both May and December 2016 PNT meetings. IGS Governing Board members are often invited guests of the PNT, presenting on key contemporary issues as well as reflecting on decades of work. Marek Ziebart (University College London, United Kingdom) addressed the May PNT meeting on the topic of orbit dynamics, modeling, and timing; and GB member Werner Enderle (European Space Agency/ESOC, Germany) presented on ESA activities related to GNSS space service volume. IGS collaborators Gerald Bawden (NASA Headquarters, United States) and John LaBrecque (University of Texas at Austin, United States) also presented on real-time GNSS for earthquake and tsunami early warning at the December meeting.

8.3 International Association of Geodesy Executive Participation

The IGS is represented in a variety of roles throughout the geodetic community. Board member and Central Bureau Director Ruth Neilan and GB member Richard Gross serve as members of the International Association of Geodesy (IAG) Executive Committee, and participated in the April 2016 IAG Strategic Planning Retreat at GeoForschungsZentrum (GFZ) in Potsdam, Germany.

IGS Governing Board Members served on the Coordinating Board, Executive Committee, Consortium, and Science Panel of the IAG Global Geodetic Observing System (GGOS). Several of these members participated in the annual GGOS Days series of meetings, held at the Harvard Smithsonian Center for Astrophysics in Cambridge, Massachusetts, United States.

8.4 Communications Development and Guidance

Communications, advocacy, and public information activities were developed in 2016, including a communications interest and development session held 17 April prior to the EGU in Vienna, and a pilot associate member and working group open meeting held 11 December prior to the AGU in San Francisco.

Governing Board members, supported by the Central Bureau, played an active role in the development and distribution of two extensive strategic planning surveys. Responses from these surveys, provided by IGS members as well as external stakeholders, helped shape the upcoming Strategic Plan and provided insight as to pathways for better member engagement.

Web and printed content continue to be developed and refreshed. A new “IGS Spotlight” campaign was developed by the Central Bureau in collaboration with Governing Board members. This “Spotlight” news campaign features news pieces and articles of varying length and topic, and are meant to illustrate how an organization uniquely benefits from participating in, and contributing to, the IGS. It is also an opportunity for IGS contributing organizations to celebrate accomplishments made possible by their work with the IGS.

9 Outlook 2017

In 2017 the momentum will continue to build for the IGS towards the Paris Workshop whose theme will be “Pathways towards Improved Precision”. The workshop will be a great opportunity to bring the IGS community together in beautiful Paris, and to work through the many achievements and emerging challenges of the IGS working groups. With the Workshop being in Europe a focus on Galileo development will feature as well. The

IGS will continue to be challenged by the growing stakeholder expectations for improved product timeliness, fidelity and diversity. Continued efforts by the GB to enhance advocacy for the IGS are needed. Accordingly presentations at a variety of forums including EGU, China Satellite Navigation Conference (CSMC), IAG–IASPI Joint Scientific Assembly, and AGU just to mention few will be delivered by GB members. Strong participation in the ICG and UN GGIM will also ensure recognition of the important role the IGS plays in modern society is achieved.

Lastly, 2017 will see several working groups change their chairs as terms end or people move on. The GB thanks all participants within the IGS for the efforts, with particular thanks going to those chairs ending their current terms. Without the contributions of all the IGS could not have achieved the significant outcomes detailed in this report.

Central Bureau Technical Report 2016

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[2] UNAVCO
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1 Introduction

The mission of the IGS Central Bureau (CB) is to provide continuous management and technology in order to sustain the multifaceted efforts of the IGS in perpetuity. It functions as the executive office of the service and responds to the directives and decisions of the IGS Governing Board. The CB coordinates the IGS tracking network and operates the Central Bureau Information System (CBIS), the principal information portal where the IGS web, ftp and mail services are hosted.

The CB also represents the outward face of IGS to a diverse global user community, as well as the general public. The CB office is hosted at the California Institute of Technology/Jet Propulsion Laboratory, Pasadena, California, USA. It is funded principally by the United States National Aeronautics and Space Administration (NASA), which generously contributes significant staff, resources, and coordination to advance the IGS and its mission. The following report highlights progress made by the Central Bureau in 2016.

2 Executive Management and Governing Board Participation

Governing Board (GB) meetings were held in February (Sydney), April (Vienna), and December (San Francisco) 2016. The Executive Committee (EC) met additionally by teleconference approximately every other month. Staff of the Central Bureau, as part of its work program to carry out the business needs of the IGS, implemented actions defined by the Governing Board throughout the year. In 2016, this included a thorough analysis and refresh of the IGS Terms of Reference, which may be viewed with other guiding documents on the knowledge base section of the IGS website: `http://kb.igs.org/hc/en-us/sections/200369273-Guiding-Documents`.

The CB supported the ongoing collection of Associate Member applications and nominations, ultimately resulting in the GB decision to form a standing associate member committee, to be chaired by S. Fisher. The IGS Associate Members form the body of voters who elect the Governing Board, and play a vital role in the ongoing success and sustainability of the service. Associate Member and Governing Board Member lists are maintained by the CB and viewable on the IGS website: `http://igs.org/about/organization`.

The CB also continues to play an active role in supporting the organization of regular IGS Workshops, participating in and guiding preliminary meetings of both local and scientific organizing committee members for the 2017 Paris workshop. These meetings took place in person in April (Vienna) and December (San Francisco) as well as via email and teleconference throughout the year.

3 Network Coordination

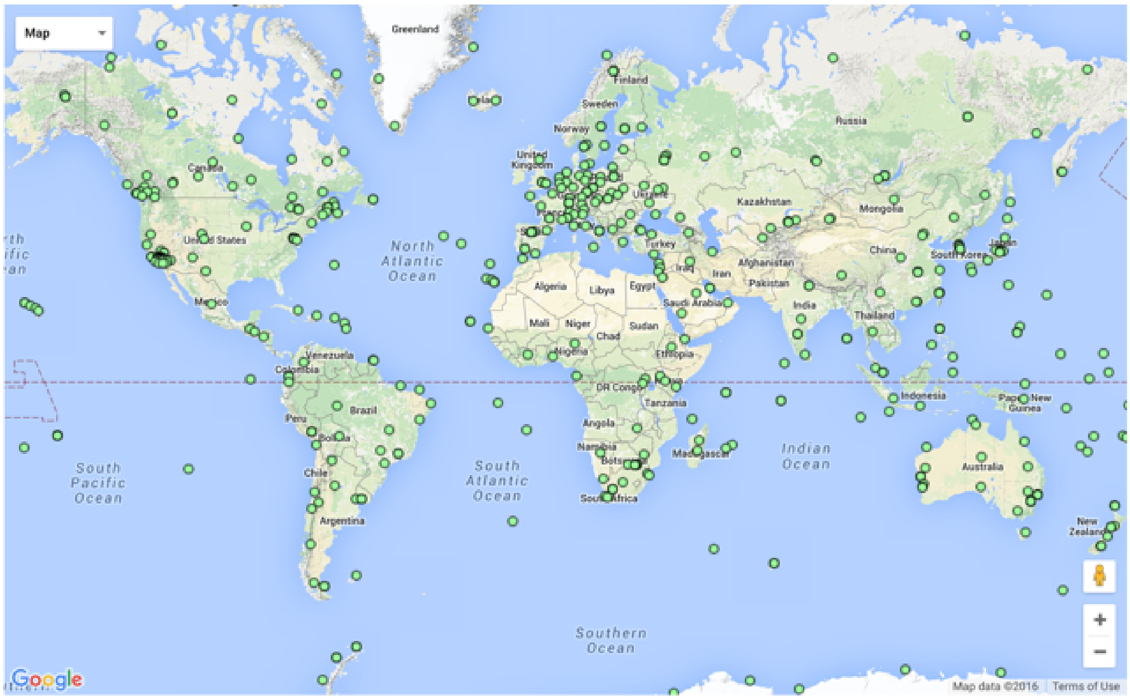

Figure 1: IGS Network, 505 Stations (igs.org/network).

There are 505 stations tracking stations participating in the IGS network. The development of a multi-GNSS sub-network with the greater IGS network is led by the MGEX project, which develops the IGS's capability to operate with multiple GNSS constellations, and has 177 multi-GNSS capable (GPS+GLONASS+one other) stations. Within the network, 189 IGS stations are now capable of real-time data streaming in support of the IGS Real-Time Service.

In 2016, 24 stations were added and 12 were decommissioned. During the course of the year 59 equipment models were added to the rcvr_ant.tab file. The Site Log manager is currently supporting over 90 users. In 2016 the network coordinator supported 447 site metadata updates.

4 Strategic Planning and Progress

Throughout mid-2016, the Central Bureau led the development and distribution of strategic planning-themed surveys to both the IGS community as well as the broader IGS stakeholder community. Feedback was collected and analyzed by the CB and GB during the Strategic Plan development process, and used to shape the goals and objectives of the 2017-2020 Strategic Plan.

The 2017-2020 strategic plan development built upon the momentum of the 2015 December Governing Board Meeting, where a preliminary work plan and timeline for writing the new strategic plan was developed. Meetings dedicated to strategic planning took place in February (Sydney), April (Vienna), August (New York) and again after the 2016 Governing Board meeting in December (San Francisco). Feedback from GB members was requested and received throughout the year – to the great benefit of the planning process.

A preliminary draft of the new strategic plan was distributed prior to the December meetings, and is in final development phase. It is anticipated that the plan will be officially published in time for the 2017 IGS Workshop in Paris.

Formal benchmarking of progress made in advancing the IGS mission has continued since 2012. Metrics indicating performance on defined objectives are tracked annually by the CB and published on the IGS website: http://kb.igs.org/hc/en-us/sections/200623533. The IGS has continued through 2016 to exceed targeted product availability (the IGS's most important measure of success), including through the transition of Analysis Coordination responsibilities from NOAA/NGS to Geoscience Australia (GA) where availability was unaffected.

5 Web Development and Information Technology Support

In addition to administration and general support of CBIS operation, the Central Bureau has continued moving IT services to external cloud hosted servers, in order to facilitate global access. This year, web, mail, and ftp, as well as an archived copy of the IGSCB website, were all moved to cloud servers. ACC combination software was also moved from a dedicated server to redundant cloud-based servers located in Australia and Europe, with coordination of the IGS products generation carried out by personnel at Geoscience Australia (GA) and the Massachusetts Institute of Technology (MIT).

The IGS website, http://IGS.org, has been enhanced to include working group subdomains, which enable working group membership to manage their own content in addition to working with CB development and communications staff. IGS Contributing Organizations will also be provided with editable pages in IGS.org so that they may take an active role in best communicating their individual contributions to, and benefit from, the service. All other references to the old IGSCB website have been redirected to or reestablished on IGS.org or the IGS Knowledge Base.

Content and resources in the IGS Knowledge Base, http://kb.igs.org, continue to be enhanced and expanded. The Knowledge Base also serves as a task tracking and ticketing platform for Central Bureau projects and work, as well as user feedback and requests. Comments, suggestions, and other feedback are now welcomed through standardized "contact us" and "feedback" forms, whose links are available at the food of each page on IGS.org. The Real-Time Service account application has also been updated to a similar form, and automated to expedite user access.

IGS social media has also been integrated throughout the website, to facilitate sharable content and optimize engagement with IGS stakeholders. IGS audio-visual resources, made available through IGS Presents, were upgraded to include media plug integration. Workshop resources, including images, posters, presentation slides, and videos, also continue to be made available on IGS Presents.

6 Communications, Advocacy, and Public Information

The Central Bureau continued to develop communications, advocacy, and public information initiatives on behalf of the Governing Board. Pilot sessions for a number of member engagement activities were held in 2016, including communications interest and development sessions as well as enhanced associate member outreach and a dedicated associate member meeting.

An open communications interest session was held prior to the April Governing Board business meeting in Vienna, and was attended by GB members, the Global Geodetic Observing System (GGOS) Coordinating Office, and associate members. The next session is scheduled to be held as a formal splinter session at the 2017 IGS Workshop.

In response to feedback from the strategic planning survey, an inaugural IGS Associate Member and Working Group Meeting was held the morning prior to the December Governing Board meeting in San Francisco. The meeting was open to all associate members and observers, and featured presentations by working group chairs and other IGS components. Future such sessions, targeted at engaging the associate membership, will be planned in conjunction with major conferences, such as AGU, EGU, and IAG symposia, among others.

The Central Bureau actively works with other IAG components to promote communications and outreach, including the IAG Communications and Outreach Branch and GGOS Coordinating Office. As representatives of the IAG, IGS CB members also participate actively in the United Nations Initiative on Global Geospatial Information Management (GGIM) Sub-Committee on Geodesy, Focus Group on Outreach and Communications.

Social media has been actively maintained by CB staff and grew significantly in 2016, due in part by establishing links to IGS Contributing Organization communications representatives and increased frequency of posting, as well as enhanced content. Increased cross-linking with IGS website and knowledge base content, as well as promoting video resources available at IGS/presents, will continue in 2017.

7 Project Support, Committee and Working Group Participation

The Central Bureau participated within the IGS Working Groups and Projects through 2016 by:

- helping to fold in the MGEX stations within IGS the IGS network which now has 177 stations with GPS, GLONASS and at least one other GNSS
- preparing site metadata systems for RINEX 3 adoption, and supported MultiGNSS station operators with transition to RINEX3
- maintaiing a Real-time caster and supporting the Real-time Service transition to full capability, coordinated with UCAR/COSMIC to host a new caster
- handling specific information technology needs during the ACC transfer to Geoscience Australia,
- developing the IGMA activity within ICG and IGS
- and supporting related working group web content.

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

8 IGS User Support

The Central Bureau continues to devote considerable effort to the IGS community and users of its products. As measure of this, the CB tracks email traffic through the CB mail list. This traffic has increased by 54% in 2016 to about 6100 messages, though much of the increase is from notification emails from various CBIS processes that do not require response.

User support and other community inquiries have been received through a support trouble ticketing system, which also now receives and automatically creates support tickets from emails sent to cb@igs.org. Because of this, the number of tickets increased to approximately 1800, though this includes notifications and updates that are sent to the CB email address. The IGS Knowledge Base has also been continually developed and enhanced for user support, based on user feedback as well as the regular addition of content and resources.

9 External Participation

The Central Bureau participates in, and interacts with, many IGS stakeholder organizations. A continuing highlight is the CB staff activity within the United Nations GGIM Sub-Committee on Geodesy (formerly Global Geodetic Reference Frame Working Group). At the most recent session of the GGIM in New York (August 2016), the working group was established as a permanent sub-committee on geodesy, to provide stability and long-term planning for the Global Geodetic Reference Frame (GGRF). The Committee of Experts also endorsed the GGRF Roadmap, which addresses each of the key areas of action described in the operational paragraphs of the 2015 UN General Assembly resolution, at this session. These efforts are anticipated to open additional avenues for international cooperation for the IGS and geodesy in general. For more information, please visit the UN-GGIM website: http://ggim.un.org/UN_GGIM_wg1.html.

Significant progress was also made in supporting the development of a cooperative plan with the United Nations Office for Outer Space Affairs (UNOOSA), International Committee on Global Navigation Satellite Systems (ICG) to monitor performance and interoperability metrics between the different GNSSs, which is now embodied by a joint IGS-ICG working group on monitoring and assessment.

The CB Director and staff members have continued to represent the IGS the within IAG service committees and boards, including R. Neilan, the Vice-Chair of the Global Geodetic Observing System, who serves on the GGOS Executive Committee, as well as on the GGOS Coordinating Board as IAG Service Representative.

The CB Director also ensured ongoing IGS engagement and participation in the US Federal Advisory Board for Space-based Position, Navigation and Timing, where she serves as the appointed NASA representative. Other IGS representatives presenting at the PNT Advisory Board meetings in 2016 include Professsors Gerhard Beutler (University of Bern, Switzerland) and Marek Ziebart (University College London, UK), Werner Enderle (ESA/ESOC, Germany), as well as Gerald Bawden and John LaBrecque (NASA, USA). To view presentations made at PNT Advisory Board meetings, please visit: http://www.gps.gov/governance/advisory/. Table 1 provides a listing of the principal external meetings attended by CB staff during 2016.

10 Publications

IGS 2015 Technical Report section, IGS website

NASA SGP/ICPO annual progress report, NASA internal publication

GGOS Bureau of Networks and Operations Report

GGOS Days IGS Update Report

Table 1: Principal meetings attended by CB staff and role/outcomes

Meeting	Month	Location	Purpose
NASA HQ Programmatic Interactions	Jan.	Washington, DC	Programmatic meetings at NASA HQ
IGS Workshop	Feb.	Sydney, NSW, AUS	Coordinate and support the regular assembly of the global IGS community
UCAR/UNAVCO meetings	Mar.	Boulder, CO	Programmatic meetings at UNAVCO and UCAR in support of partner efforts at each organization
IGS Governing Board and	Apr.	Vienna, AUT	Support of ongoing essential IGS other meetings business items, strategic planning, and and organizational management
UNOOSA committee meetings	Apr.	Vienna, AUT	Participate in working group meetings for GGRF
PNT Advisory Board	May	Washington, DC	Participate as the NASA respresentative to the advisory board
ICG Working Group S meeting	Jun.	Vienna, AUS	Represent IGS on working group and IGMA activities
UCAR/UNAVCO meetings	Jul.	Boulder, CO	Programmatic meetings at UNAVCO and UCAR in support of partner efforts at each organization
United Nations GGIM Committee of Experts	Aug.	New York, NY	Participate as US and IAG delegate to the UN GGIM CoE, participate in GGRF WG meetings
University College London	Aug.	London, UK	Meet with representatives of UCL regarding agreements and future support of the IGS
Bundesamt für Eich- und Vermessungswesen (Austrian Federal Agency for Metrology and Surveying)	Aug.	Vienna, AUT	Meet with the new GGOS Coordinating Office staff to facilitate progress in their new role, lead web redevelopment efforts, and guide other communications and organizational development work. Coordinate with representatives from the German Federal Agency for Cartography and Geodesy.
GGOS Days Meetings	Oct.	Boston, MA	Participate in GGOS Consortium, Coordinating Board, and Focus Area meetings on behalf of the IGS
PNT Advisory Board	Dec.	Redondo Beach, CA	Participate as the NASA respresentative to the advisory board, support local organization of the meeting and additional activities.
IERS DB Meeting	Dec.	San Francisco	In lieu of participating, coordinated with AC and RF coordinators to participate in meeting for IGS
IGS Governing Board, Associate Member, and splinter meetings	Dec.	San Francisco	Coordinate and support meetings of the IGS Governing Board, Associate Members, Workshop Planning Committees, and Strategic Planning
GGOS Bureau of Networks and Observations	Dec.	San Francisco	Represent IGS, support IGS Chair in participation throughout the meeting.

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2016

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1 Introduction

Since January 2016 Geoscience Australia and MIT have taken over the role of the Analysis Centre Coordinator (ACC). The ACC provides an oversight on the products that contribute to the IGS combined solution, by controlling which centres are weighted in the combination.

2 ACC activities in 2016

For the first time the service of combining the IGS products was placed into the Amazon Web Service cloud environment. The system is designed to run in two potential regions Frankfurt and Sydney. Moving the system to the cloud reduces the potential for disruptions of service due IT infrastructure issues commonly experienced at institutional organisations.

An effort was made to begin converting the combination code from one which was reliant on the Lahey fortran compiler to a code base that could be compiled by a generic compiler such as gfortran. Upon successful completion, this will allow access to more advanced cloud features currently not utilized, and hopefully an easier development path. This project has not been completed, the results obtained using a different compiler did not agree close enough to the results obtained from the Lahey compilation. The main issue that needs to be resolved is within the code used to compute the clock combination. This is of concern to us and will need to be revisited. We need to determine if there is an underlying issue, or if there is an error made in the the adaptation of the code to be compilable by gfortran. The operational code used to compute the clock combination is still based on the original code base compiled with Lahey, with minor adaptations for IGS14. On Tuesday December

13 th an IGS Analysis meeting was held in parallel to the AGU conference. During this meeting Jake Griffiths presented the results from the combination of the products from second reprocessing effort. The repro2 orbit and clock combinations was completed by Jake Griffiths. These products are available from CDDIS under:

ftp://cddis.gsfc.nasa.gov/gps/products/WWWW/repro2

The recommendation is to not use the combined IGS clock solution for long term PPP analysis, as the quality of the product appears to have degraded compared to repro1. For more details see Jake Griffith's poster presented at AGU (http://acc.igs.org/repro2/griffiths_ig2.pdf).

Earlier in the week the IERS had meet, and endorsed a transition to IGS14. Following this endorsement, the IGS analysis centres agreed upon a transition date to ITRF2014 to be in line with products generated for GPS week 1934 and onwards.

3 Product Quality and Reliability

For 2016, with the exception of a few unusual delays, delivery of all IGS products was generally uninterrupted.

3.1 Combined orbit quality

Inter–AC agreement of the Final orbit products remains within 5 mm with precision ranges 3-4 mm (1D error). At the individual analysis centre level, ESA agreement improved after their box wing modelling was removed from the block IIF satellites (as well as the solar radiation pressure and earth albedo for the box) at week 1892 (see pink line of Figure 1). Since the implementation of IGS14 (see pink line of Figure 2), ESA now has markedly improved it agreement with the IGS final combination scale. Since the implementation of IGS14 JPL has requested their solution to be used for comparison only. Subsequently the solutions from JPL and EMR are not agreeing as closely to the final IGS combination. Once JPL have completed a reprocessed time series consistent with IGS14, then we will look at re-weighting their solutions into the combination. As EMR are basing their final solution on Gipsy, we will likely see a closer agreement of JPL and EMR to the final combined solutions.

Wuhan's rapid solution, since week 1928, now closely agrees with the IGS combined solutions (see grey line of Figure 3). If this performance is maintained we will look at weight Wuhan's contribution for the rapid products.

There have been a few issues with the clock alignment with UTC, on two occasions this has exceeded 20 ps (see Figure 4). There is an increase in the standard deviation with the alignment, and a tendency to drift since 2016. We are currently investigation on how this can be improved with Michael Coleman.

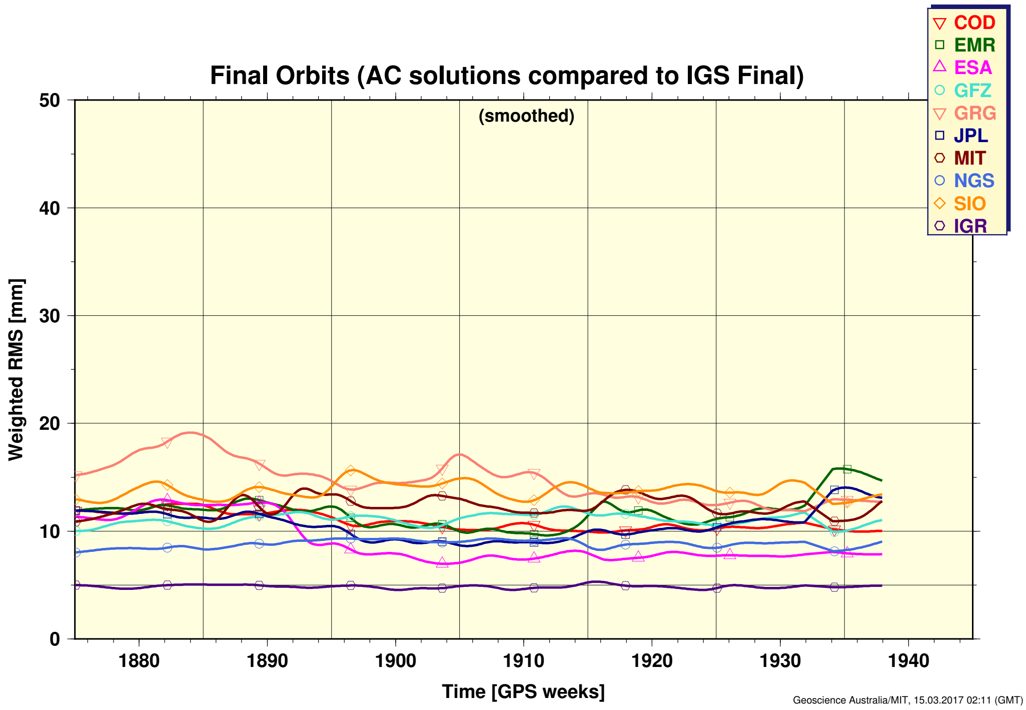

Figure 1: Smoothed WRMS of Final orbits

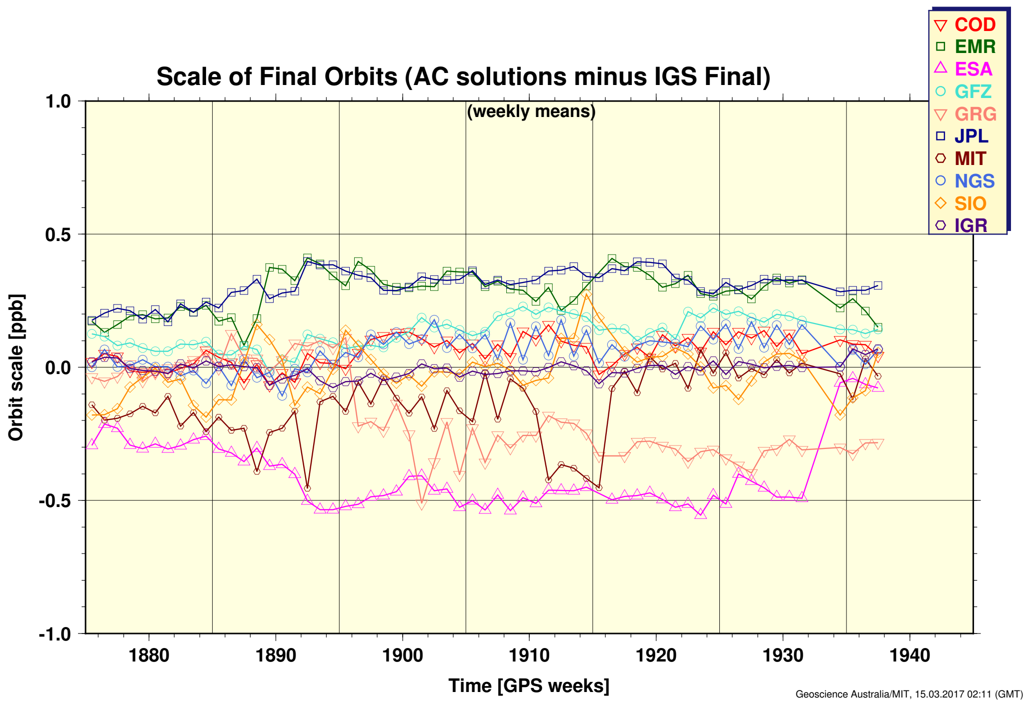

Figure 2: Scale of AC solutions wrt to Final combination

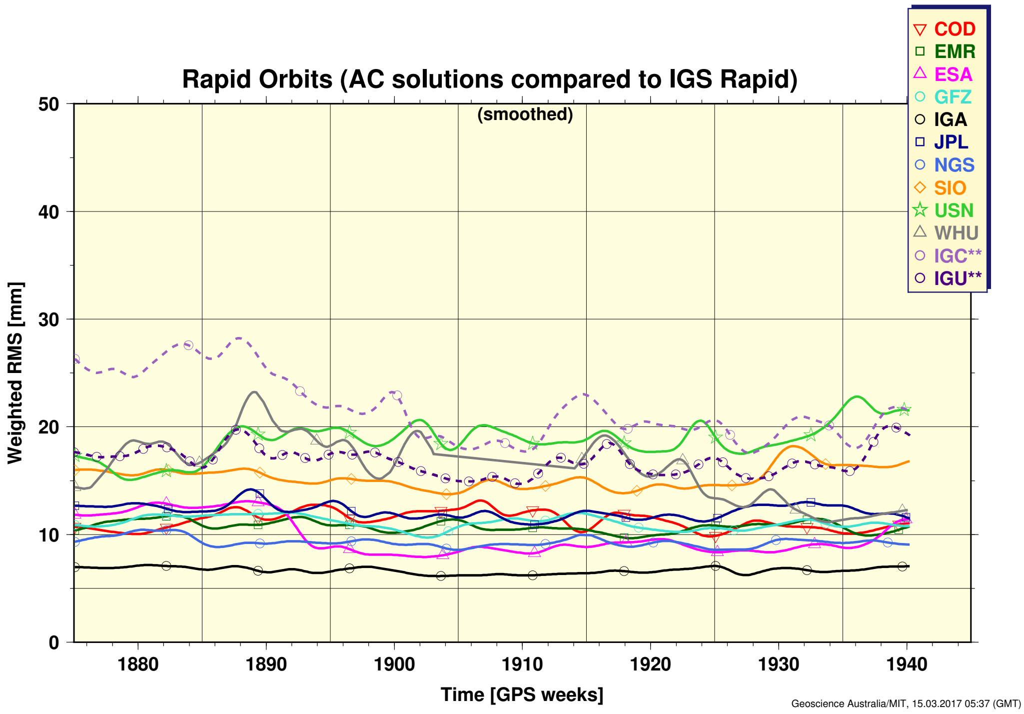

Figure 3: Smoothed WRMS of Rapid orbits

3.2 Events Impacting Product Quality and Reliability

- Number of core IGS stations exceeded 200 causing rapid product failure, and the combination software had to be re-dimensioned to accommodate a larger network.
- Clock alignment issues exceeding 20 ps.
- Ultra rapid failure associated with a problem parsing a priori ERP values
- Corrupt orbit weight file delayed the submission of an IGS final product
- Sporadic errors in the GPS and GLONASS broadcast files have caused delays in the Final GLONASS products, and delayed rapid products.

Starting from the implementation of IGS14, the procedure in Bernese used to compute the long arcs to generate the orbit statistics has been changed. The procedure now estimates twice and four times per revolution in D, with stochastic impulses at 2 hour intervals for all satellites. This has allowed the modelling a greater degree of freedom to fit the submitted ACs orbit models. The statistics have changed from an rms at the 3 cm level, to an rms fit of below 1 cm.

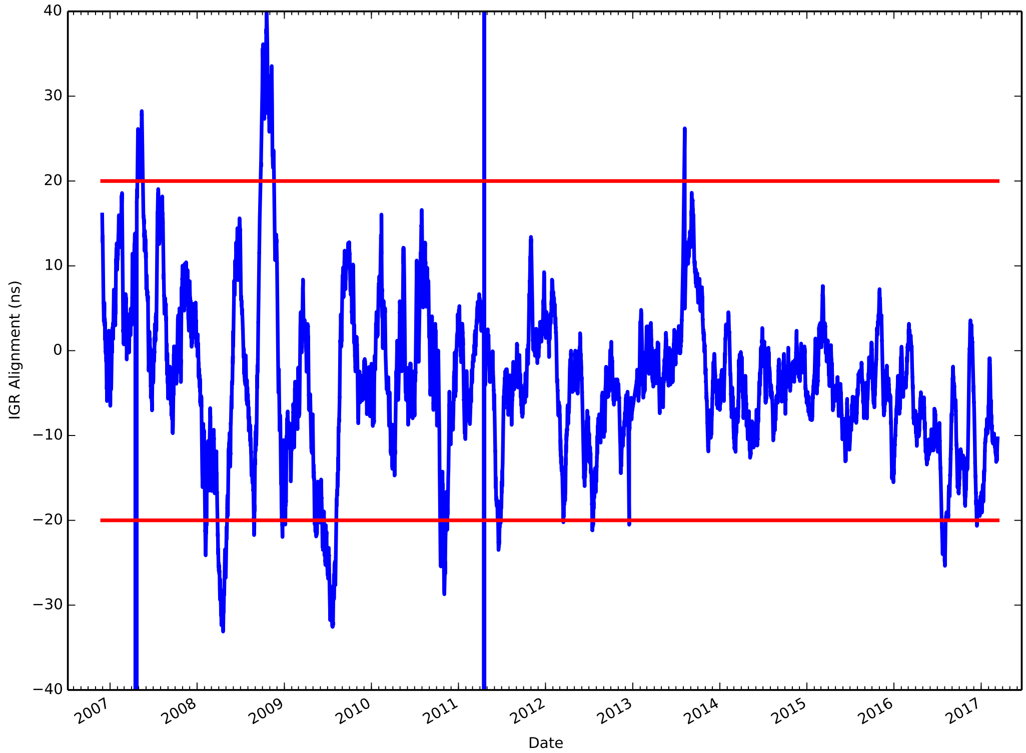

Figure 4: Rapid clock alignment with UTC

4 Activities planned for 2017

- Investigate the current modelling applied by ACs.
- Determine if a common attitude model should be applied, or a method to report the attitude estimates from each AC should be used.
- Encourage further investigation into orbit modelling issues, particularly for Block IIF satellites.
- Review the IGV products to see if these can be moved closer to production status.
- Review the clock combination procedure currently implemented.
- Confirm/adapt the combination software to handle SP3-D format.
- Increase statistical plots available from ACC website:
  - Plot statistics for each satellite
  - Plot weight of AC contributions through time
  - Plot clock statistics from clock combination and alignment

Center for Orbit Determination in Europe (CODE) Technical Report 2016

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

D. Arnold[1], *E. Orliac*[1], *L. Prange*[1], *S. Sidorov*[1], *A. Sušnik*[1], *A. Villiger*[1], *L. Mervart*[a], *A. Jäggi*[1], *G. Beutler*[1],

E. Brockmann[2], *D. Ineichen*[2], *S. Lutz*[2], *A. Wiget*[2],

A. Rülke[3], *D. Thaller*[3], *W. Söhne*[3], *J. Ihde*[3], *J. Bouman*[3],

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Frankfurt a. M., Germany
[4] Institut für Astronomische und Physikalische Geodäsie,
Technische Universität München, Munich, Germany

1 The CODE consortium

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

- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland
- Federal Office of Topography swisstopo, Wabern, Switzerland
- Federal Agency 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. 2015).

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

2 CODE products available to the public

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

Within the table the following abbreviations are used:

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

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 Table 2.

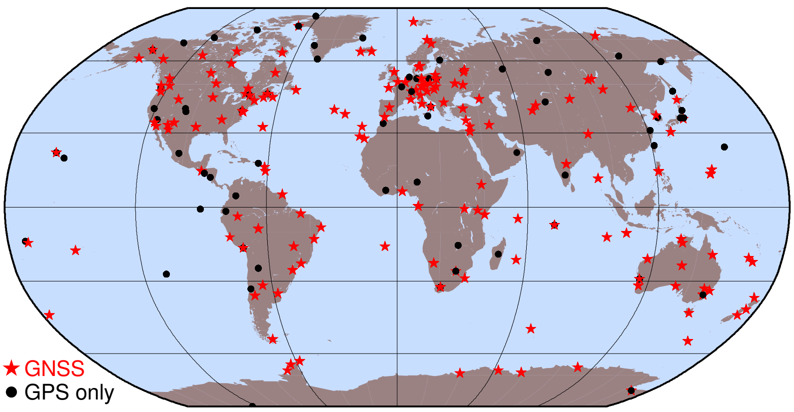

Figure 1: Network used for the GNSS final processing at CODE by the end of 2016.

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

Referencing of the products

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

- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE ultra-rapid product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75676.1 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE rapid product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75854.1 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Sušnik,

Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE final product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75876.2 .

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

Table 1: CODE products available through anonymous ftp.

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

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

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

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

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

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

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

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

Files generated from three–day long–arc solutions:

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

Files generated from pure one–day solutions:

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

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

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

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

CODGddd0.yyI.Z	GNSS 2-hour global ionosphere maps in IONEX format, including satellite and receiver P1−P2 code bias values
CKMGddd0.yyI.Z	GNSS daily Klobuchar-style ionospheric (alpha and beta) coefficients in IONEX format
GPSGddd0.yyI.Z	Klobuchar-style ionospheric (alpha and beta) coefficients from GPS navigation messages represented in IONEX format

versity of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2013; DOI: 10.7892/boris.75680 .

3 Changes in the daily processing for the IGS

The CODE processing scheme for daily IGS analyses is constantly subject to updates and improvements. The last technical report was published in Dach et al. (2016).

In Sect. 3.1 we give an overview of important development steps in the year 2016. Section 3.2 describes the introduction of the advanced handling of GNSS biases in the processing scheme of CODE .

3.1 Overview of changes in the processing scheme in 2016

Table 3 gives an overview of the major changes implemented during year 2016. Details on the analysis strategy can be found in the IGS analysis questionnaire at the IGS Central Bureau (ftp://igscb.jpl.nasa.gov/igscb/center/analysis/code.acn).

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

3.2 Introducing the Advanced Bias Handling

Since May 2016, CODE changed its code bias handling completely, from a differential to a pseudo–absolute bias setup. The code bias estimation is crucial for GNSS data processing when not only phase data, but also code measurements are used, such as for clock analysis or ambiguity resolution strategies relying on code measurements. The differential code biases (DCB) (and the corresponding inter–system biases (ISB) for multi–GNSS clock

Table 3: Selected modifications of the CODE processing over 2016.

Date	DoY/Year	Description
28-Jan-2016	028/2016	Ensure consistency between the clock RINEX and Bernese formatted satellite clock files regarding the used reference clock in the final processing scheme (both files are publicly available at AIUB's FTP server)
28-Feb-2016	059/2016	Precise orbit files include also 24 UT epoch (for internal purposes only!)
17-Mar-2016	077/2016	SVN 49 is excluded from clock processing.
27-Mar-2016	087/2016	Renaming of two GLONASS-M satellites (SVN 754→854 and SVN 755→855). See: IGSMAIL #7252 and BSWMAIL #0351.
10-May-2016	131/2016	Adjust the settings for supporting weakly observed satellites (at this time G04 and R26) by additional redundant baselines.
17-May-2016	138/2016	Start with enabeling the new bias handling scheme into the operation processing. This software change should have no effect on the products.
25-Jun-2016	177/2016	Solve potential issues if the wavelength factor is not given in the input RINEX file
26-Jun-2016	178/2016	Based on the new bias handling principle new types of biases are monitored: • GLONASS-like bias monitoring for all non-GLONASS systems • Bias Multiplier estimation. • BIACAL/IONGEN/MULGEN processes are not station-specific.
26-Jun-2016	178/2016	Also stations from CODE-MGEX solution are added to the internal PPP processing
03-Jul-2016	185/2016	For monitoring purposes currently inter-GNSS translation and troposphere biases are setup (see Dach et al. (2012)). These set of biases are now extended to troposphere gradient bias parameters.
03-Jul-2016	185/2016	Use satellite as reference clock for the clock estimation in order to guarantee a complete clock product with the smalles possible numbers of missing epochs. The reference clock is changed after the processing and before the submission to a station clock.
24-Jul-2016	206/2016	Satellite attitude modelling according to Kouba (2009) for GPS- and Dilssner et al. (2011) for GLONASS-satellites
21-Aug-2016	234/2016	When introducing the new bias handling scheme in May 2016 unintentionally the receiver and satellite biases are stacked over three days in the final ionosphere product generation whereas they are treaded as daily independent parameters in the rapid ionosphere procedure. The setup was adjusted that receiver biases are estimated independently day by day whereas the satellite biases are stacked over three days in both, the final and rapid ionosphere product generation procedures.
22-Sep-2016	235/2016	Preparation the processing for PSD-handling (post-seismic deformations) as requested for the ITRF2014/IGS14 reference frame. Establishing the parallel processing scheme including the usage of RINEX 3 data (as far as available) and updating the station list for the final processing.
16-Oct-2016	290/2016	Introducing priority list when processing RINEX 3.0x data (at this point only in the internal PPP process): 1. RINEX 3 files with long names generated in the receiver 2. RINEX 3 files with short names 3. RINEX 2 files 4. RINEX 3 files with long names generated from a stream 5. RINEX 3 files from unknown sources
30-Oct-2016	304/2016	Additional verification step to check the observation quality by a station-by-station and baseline-by-baseline processing.

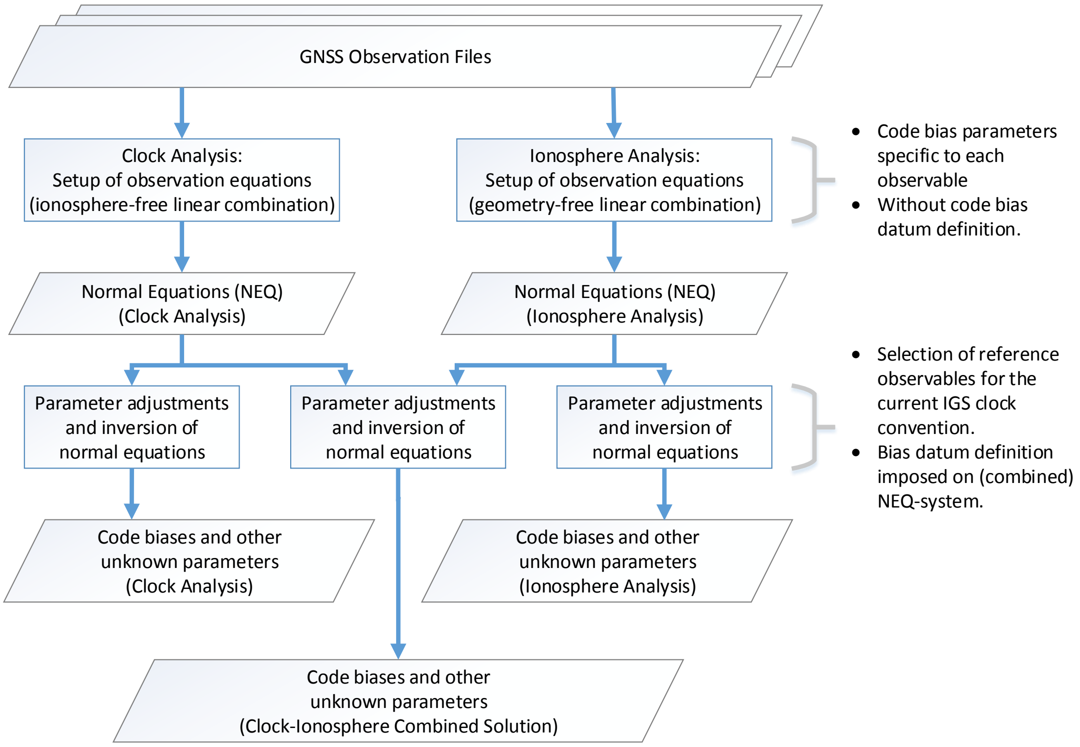

Figure 2: New workflow for code bias estimation at CODE.

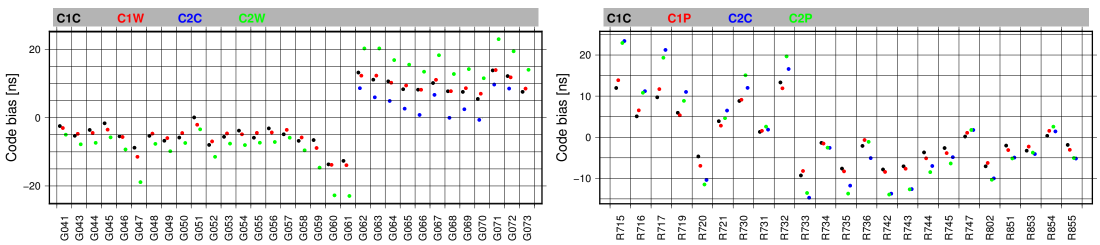

Figure 3: GPS (left) and GLONASS (right) observable specific code biases from 30-day average (February 2017).

analysis) have been replaced by observable–specific code biases (OSB) which assigns each observable type its own bias. The new implementation has major advantages for multi–GNSS processing and allows to distinguish between different observable types according to their description in the RINEX V3 format. The OSB parameters are introduced into the observation equations and can be later combined on the normal equation (NEQ) level. This can be done either to produce a multi–day solution or to combine bias parameters from different sources, e.g. to combine biases from clock and ionosphere analysis to retrieve one common set of OSBs, which can be later used for all purposes.

With the changed bias handling, the processing scheme for the bias determination has been revised using the advantage of combining bias NEQs from different sources. Figure 2 shows the updated workflow of CODE's processing scheme for the determination of the code biases. Our main bias products are extracted from the combination of normal equations (NEQ) of bias estimations of clock and ionosphere analysis. The estimated OSBs can be used for any application by simply correcting each observation according to the estimated biases value.

The OSB implementations lead to a revised processing strategy for the 30-day code bias products CODE.DCB and CODE_FULL.DCB (`ftp://ftp.unibe.ch/aiub/CODE/CODE.DCB` and `ftp://ftp.unibe.ch/aiub/CODE/CODE_FULL.DCB`). The combination of the 30-day average DCBs are generated combining OSBs of the last 30 days on the normal equation level based on the clock-ionosphere combined solution. The resulting OSB values are converted into DCBs and P1–C1 bias tables for cctononcc (`ftp://ftp.unibe.ch/aiub/bcwg/cc2noncc/p1c1bias.hist`) and published on our ftp server. The OSBs for GPS and GLONASS satellites are shown in Figure 3. The new OSB estimations will be made publicly available in 2017 using the upcoming BIAS-SINEX V1.00.

3.3 Changing the Satellite Attitude Handling

Starting from GPS week 1907 GNSS yaw attitude models for the GPS and GLONASS-M satellites were introduced for the routine GNSS analysis at CODE. The models are applied during eclipse seasons when the satellites do not follow the nominal yaw attitude behavior, in particular, during noon and midnight orbit manoeuvres. Description of the attitude behaviour during these periods is discussed in Kouba (2009) for the GPS Block IIA and Block IIR satellites, in Dilssner (2010) for the GPS Block IIF and in Dilssner et al. (2011) for the GLONASS-M satellites.

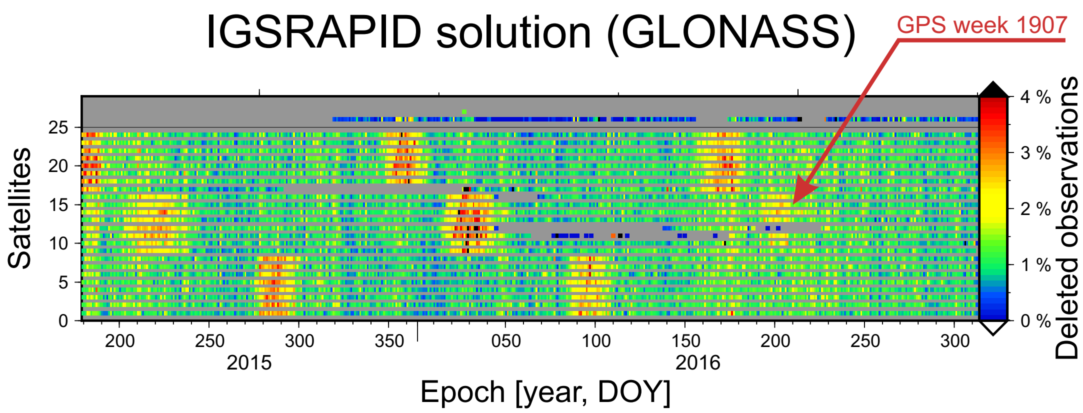

Figure 4: Overview of deleted observations after residual screening during Rapid orbits estimation of GLONASS satellites.

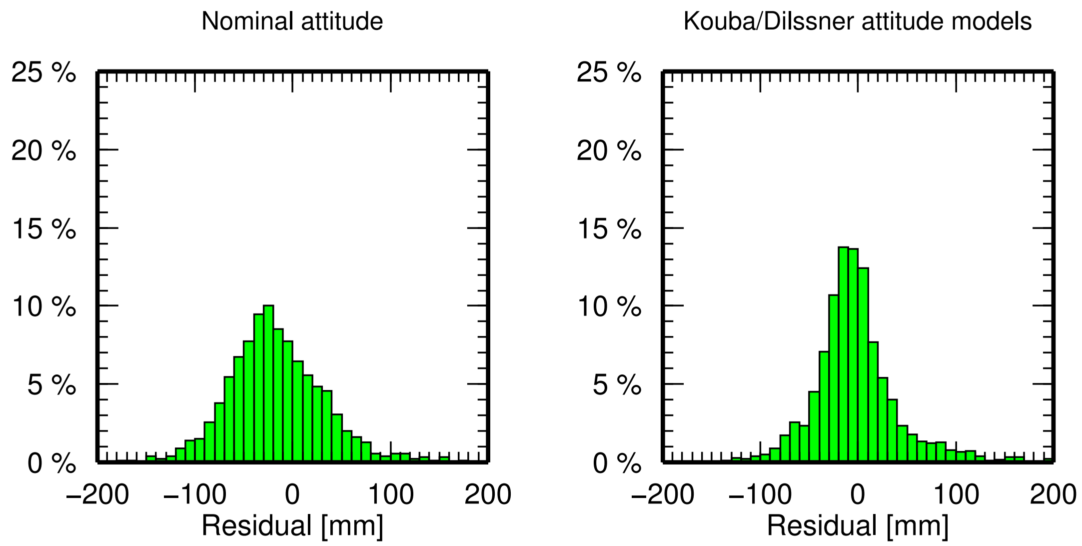

Figure 5: SLR residuals of eclipsed GLONASS satellites computed with nominal (left) and Kouba/Dilssner (right) attitude models over 02-29 October 2015.

As the GPS Block IIA, IIF and GLONASS-M satellites have non-zero horizontal phase center eccentricity with respect to the z-axis in the body-fixed reference frame, deviations from the nominal yaw attitude directly affect the satellite-station geometry. For other satellite types the incorrect yaw attitude modelling is primarily absorbed in satellite clocks and, thus, results in their biased estimates. The introduction of the attitude models had an impact on the number of rejected observations in the routine IGS analyses at CODE. Thus, prior to GPS week 1907 the use of only nominal attitude for GLONASS satellites resulted in repeating reductions of accepted observations during eclipse seasons in, e.g., our Rapid solutions, Figure 4. With the introduction of the aforementioned attitude models the number of observations during eclipse seasons is no longer reduced.

The impact of the yaw attitude modelling can also be observed in the accuracy of the computed orbits. In particular, Figure 5 shows SLR residuals of GLONASS satellites during 02-29 October 2015 when one plane of the constellation was in eclipse. With the use of the yaw attitude models the bias between the microwave and SLR orbits is reduced from $-15 \pm 61\,\text{mm}$ to $-2 \pm 44\,\text{mm}$.

4 CODE contribution to the IGS–MGEX campaign

Since 2012 CODE contributes to the IGS Multi-GNSS EXperiment (MGEX) aiming on the integration of new GNSS into existing processing chains (Prange et al. 2016a). The product is generated using the latest development version of the Bernese GNSS Software package and is derived from a rigorously combined five system solution considering GPS,

Table 4: CODE MGEX products available through anonymous ftp

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

GLONASS, Galileo, BeiDou (MEO and IGSO), and QZSS satellites. Even if the focus is on the satellite orbits and satellite clock corrections, also other parameters need to be estimated: diverse biases for the receivers, ERPs, station coordinates, and troposphere parameters. Since the beginning of 2016 the CODE MGEX (COM) products are not only submitted to the CDDIS, but also provided via the anonymous ftp server of the AIUB (`ftp://ftp.unibe.ch/aiub/CODE_MGEX/CODE`). The list of products is given in Table 4.

Based on the MGEX solution, CODE has contributed to the comparison and validation of estimated satellite antenna phase center offsets for Galileo satellites (Steigenberger et al. 2016). Some effort has been put to the adaptation to the long RINEX3 file name convention and data management. The main focus of CODE's MGEX activity in 2016 was, however, on the critical review of the results achieved so far and on the definition of the most important topics for research and technical improvements in the next time. The results of this analysis are discussed in Prange et al. 2017b. If the new GNSS shall contribute to future IGS solutions in the same extent as GPS and GLONASS, improvements are necessary in the following fields:

- Receiver and transmitter antenna PCO and PCV
- Handling of observation types and biases
- Earth radiation pressure model
- Transmitter antenna thrust model
- Orbit normal attitude and related SRP models (for BDS, QZSS)
- Integer ambiguity resolution

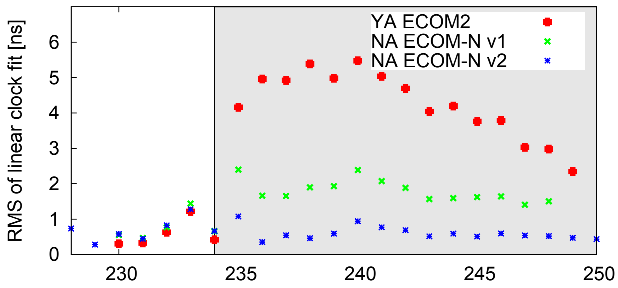

Figure 6: RMS of daily linear fit through epoch-wise satellite clocks of QZS-1 between DOY 228 and 250/2015. Gray background: Satellite is in orbit normal mode. YA: Yaw attitude law applied. NA: Normal attitude law applied. ECOMx: SRP model version.

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

NRCan Analysis Center Technical Report 2016

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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 2016 (products labelled 'em*'). Additionally, changes to the stations operated by NRCan are briefly described. Readers are referred to the Analysis Coordinator web site at http://acc.igs.org for historical combination statistics of the NRCan–AC products.

2 NRCan Core Products

The Rapid and Ultra–Rapid products continued to be generated using the Bernese GNSS Software version 5.2 (Dach et al. 2015).

Since summer 2016, 15–min GNSS data files, normally available within a few minutes at CDDIS (USA), BKG (Federal Agency for Cartography and Geodesy, Germany) and Geoscience Australia, are downloaded for use in our Ultra–Rapid Products generation. Hourly files are downloaded whenever 15–min files are missing.

A revision of available GNSS hourly/daily stations was performed at the end of summer 2016. Improved spatial distribution and density of GLONASS tracking network resulted in minimal (ps) improvement to GLONASS clock RMS and improved GLONASS orbits RMS by an order of 5–10 mm, when compared to IGS Final (IGL).

The Final GPS products continued to be estimated with JPL's GIPSY–OASIS software in 2016. Starting February 1, 2016 the software was upgraded to version 6.4.

The products available from the NRCan–AC are summarized in Table 1. 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 continued to be generated internally. The impact of ionospheric products from NRCan and selected IGS AC's on single frequency PPP was reported in Ghoddousi-Fard and Lahaye (2016). Starting November 28, 2016, NRCan's global daily total electron content maps (emrg[ddd]0.[yy]i) use GLONASS observations from about 220 of the 350 contributing stations. Estimated GPS and GLONASS satellite and station DCBs are reported in the header of daily IONEX files.

Ionospheric irregularities as sensed by GPS phase rate derived indices from real–time IGS network continued to be monitored in near–real–time and archived for long–term analysis. These, together with high rate GPS and GLONASS observations from other regional networks, are processed for targeted periods with complementary sensors to study space weather storms and characterize ionospheric irregularities at high latitudes (see e.g. Ghoddousi-Fard et al. (2016a, b); Prikryl et al. (2016)).

4 Operational NRCan stations

In addition to routinely generating all core IGS products, NRCan is also providing public access to GPS/GNSS data for more than 80 Canadian stations. This includes 40 stations currently contributing to the IGS network through the Canadian Geodetic Survey's Canadian Active Control System (CGS–CACS), the CGS Regional Active Control System (CGS–RACS), and the Geological Survey of Canada's Western Canada Deformation Array (GSC–WCDA). The NRCan contribution to the IGS network includes 25 GNSS plus 15 GPS only stations. Since December 7, 2016, NRCan has been contributing RINEX v3.03 data for 30 GNSS stations from the CGS–CACS network. Several upgrades/changes to the CGS–CACS were completed in 2016 and these are listed in Table 2. Figure 1 shows a map of the NRCan GPS/GNSS network as of January 2017. Further details about NRCan stations and access to NRCan public GPS/GNSS data and site logs can be found at `https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php` or from the following anonymous ftp site: `ftp://rtopsdata1.geod.nrcan.gc.ca/gps/`.

5 Acknowledgement

ESS Contribution number / Numéro de contribution du SST: 20160354

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Table 1: NRCan-AC products

Product	Description
Repro2	
em2wwwwd.sp3 em2wwwwd.clk em2wwwwd.snx em2wwww7.erp	GPS only • Time Span 1994–Nov–02 to 2014–Mar–29 • Use of JPL's GIPSY–OASIS IIv6.3 • 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 v6.4 from 2016–Feb–01 • Daily orbits, ERP and SINEX • 30–sec clocks • Weekly submission for IGS Final combination
	GPS+GLONASS • Since 2011–Sep–11 and ongoing • Use of Bernese 5.0 until 2015–Jan–31 • Use of Bernese 5.2 since 2015–Feb–01 • Daily orbits and ERP • 30–sec clocks • Weekly submission for IGLOS Final combination • Station XYZ are constrained, similar to our Rapid solutions
Rapid (daily)	
emrwwwwd.sp3 emrwwwwd.clk emrwwwwd.erp	GPS only • From July 1996 to 2011–05–21 • Use of JPL's GIPSY–OASIS (various versions) • Orbits, 5–min clocks and ERP (30–sec clocks from 2006–Aug–27) • Daily submission for IGR combination
	GPS+GLONASS • Since 2011–Sep–06 and ongoing • Use of Bernese 5.0 until 2015–Feb–11 • Use of Bernese 5.2 from 2015–Feb–12 • Daily orbits and ERP • 30–sec GNSS clocks

Ultra–Rapid(hourly)	
emuwwwwd_hh.sp3 emuwwwwd_hh.clk emuwwwwd_hh.erp	GPS only • From early 2000 to 2013–09–13, hour 06 • Use of Bernese 5.0 • Orbits, 30–sec clocks and ERP (hourly) • Submission for IGU combination (4 times daily)
	GPS+GLONASS • Since 2013–09–13, hour 12 • Use of Bernese 5.0 until 2015–Feb–12 • Use of Bernese 5.2 since 2015–Feb–13 • Orbits and ERP (hourly) • 30–sec GNSS clocks (every 3 hours) • 30–sec GPS–only clocks (every other hours) • Submission for IGU/IGV combination (4 times daily)
Real–Time	
	GPS only • Since 2011–11–10 • In–house software (HPGPS.C) • RTCM messages: – orbits and clocks:1060 (at Antenna Reference Point) – pseudorange biases: 1059 – Interval: 5 sec

Table 2: NRCan Station Upgrades in 2016

Station	Date	Remarks
albh	2016–06–09	Station receiver switched to TPS NET–G3A
albh	2016–06–09	External H–MASER installed
algo	2016–06–29	Station receiver switched to JAVAD TRE_G3TH DELTA
baie	2016–07–11	Station receiver upgraded to GNSS TPS NET–G3A
baie	2016–07–11	Antenna switched to TPSCR.G3 NONE
chur	2016–07–21	NOVS dome installed
drao	2016–06–08	New antenna cable
drao	2016–06–08	External H–MASER installed
frdn	2016–08–11	Damaged antenna replaced with same model TPSCR.G3 NONE
kuuj	2016–02–02	Damaged receiver replaced with same model TPS NET–G3A
prds	2016–06–10	Station receiver switched to JAVAD TRE_G3TH DELTA
sask	2016–08–18	Station receiver switched to JAVAD TRE_G3TH DELTA

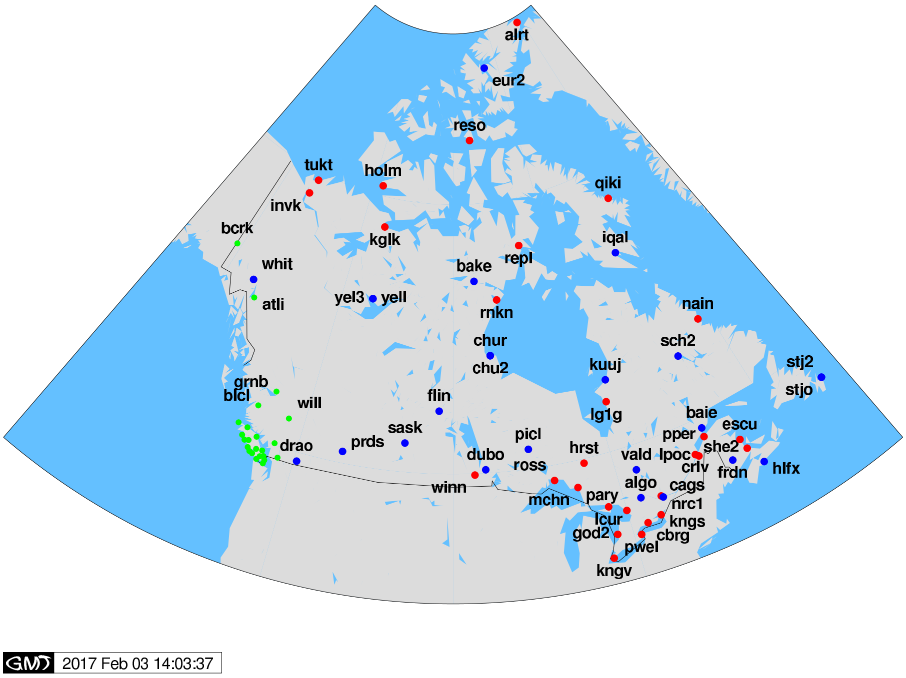

Figure 1: NRCan Public GPS/GNSS Stations (CGS–CACS in blue, CGS–RACS in red and GSC–WCDA in green).

The ESA/ESOC IGS Analysis Centre Technical Report 2016

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1 Introduction

The IGS Analysis Centre of the European Space Agency (ESA) is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The ESA/ESOC Analysis Centre has been involved in the IGS since its very beginning in 1992. In this report we give a summary of the IGS related activities at ESOC in 2016.

2 Overview

2.1 Routine Products

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

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

  - Provided daily for the previous day
  - Available within 3 hours after the end of the observation day
  - Based on 24hour solutions using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, Ionosphere, and EOPs
  - Rapid SINEX coordinates and EOPs available as well
- Ultra-Rapid GNSS (GPS+GLONASS) products
  - Provided 4 times per day covering a 48 hour interval; 24 hours of estimated plus 24 hours of predicted products
  - Available within 3 hours after the end of the observation interval which start at 0, 6, 12, and 18 hours UTC
  - Based on 24 hours of observations using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting out of Orbits, Clocks, and EOPs
  - Separate Ionosphere estimates and predictions
- Real-Time GNSS services
  - Generation of two independent real-time solution streams
  - Analysis Centre Coordination
  - Generation and dissemination of the IGS Real Time Combined product stream
- GNSS Sensor Stations
  - A set of 10 globally distributed GNSS sensor stations
  - Station data available in real-time with 1 second data sampling

Besides these core products ESA is very active in different working groups, e.g., the Real-Time Service where besides being one of the analysis centres we are also responsible for the analysis centre coordination, infrastructure committee (committee chairmanship), MGEX, antenna calibarations, and satellite orbit modeling working groups.

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

2.2 Product Changes

The main changes in our processing in 2016 were the following:

- Switch to new NAPEOS version 4.0
- Turned off box-wing model for GPS Block IIF satellites as it was having a negative effect on the products
- Preparation of ITRF2014 and other changes including:
  - Switch to ITRF2014 including PSD functions (done on GPSweek 1934)
  - Include Power Thrust for GPS and GLONASS
  - Correct Infrared (IR) properties in our box-wing models (GPSweek 1935)
  - Investigate and tune GPS Block IIF box-wing model properties (on-going)

2.3 Product Highlights

The main highlight of the ESA/ESOC Analysis Centre products is that they are one of the best products available from the individual IGS analysis centres. Furthermore, the ESA products are one of the most complete GNSS products. In fact ESA/ESOC was the first IGS analysis centre to provide a consistent set of GNSS orbit *and* clock products. Our GNSS products constituted the very first products that could, and are, used for true GNSS precise point positioning. In particular for this purpose, the sampling rate of our final GPS+GLONASS clock products is 30 seconds. Another special feature of the ESA products is that they are based on completely independent 24 hour solutions. Although this does not necessarily lead to the best products, as in the real world the orbits and EOPs are continuous, it does provide a very interesting set of products for scientific investigations as there is no aliasing and no smoothing between subsequent solutions. An other unique feature is that our rapid products are, besides being one of the best, also one of the most timely available products. Normally our GNSS rapid products are available within 2 hours after the end of the observation day whereas the official GPS-only IGS products become available only 17 hours after the end of the observation day, a very significant difference.

Another important feature of the ESA products is that we use a box-wing model for the GNSS satellites to a priori model the Solar- and Earth Albedo radiation pressure. The GNSS block type specific models were tested thoroughly in the scope of our IGS reprocessing and the results were presented at the IGS workshop in 2014,Springer et. al. (2014). Significant improvements were observed for most, if not all, estimated parameters. Last but not least it is wortwhile to mention that besides being an analysis center in the IGS ESA/ESOC is also an analysis center in the IDS and the ILRS. This represents a rather unique achievement in that one single software version, NAPEOS Springer et. al. (2009), contributes to the products and solutions of three different space geodetic techniques. Work is in progress to also add VLBI to our processing capabilities.

3 GNSS Sensor Station Upgrade

ESA/ESOC continues to provide worldwide data for all GNSS constellations to the IGS via its 10 public stations, and to expand its proprietary station network. This expansion is accomplished by focusing on the establishment of collaborations with third parties to install new stations at various locations around the world such as in South Africa, Brasil, Russia, Canada, etc. The ESOC GNSS Reference Station network is also present at all ESA Deep Space sites and other locations where ESA have satellite tracking assets around the world (see map below).

The entire ESA GNSS network now operates Septentrio PolarRx4 receivers with SEPCHOKE antennas, with the exception of MGUE, MAL2, MAS1 and FAA1 where the Leica AR25.R4 antennas are installed. The station network has been expanded in recent times with installations in Awarua (New Zealand), Dubai (U.A.E), Malaysia, Tsukuba (Japan), Bishkek (Kyrgyzstan), Darmstadt (Germany), and plans are on-going for up to 9 more stations in the next 18 months. No data is publicly available for the time being for any of the newly installed stations.

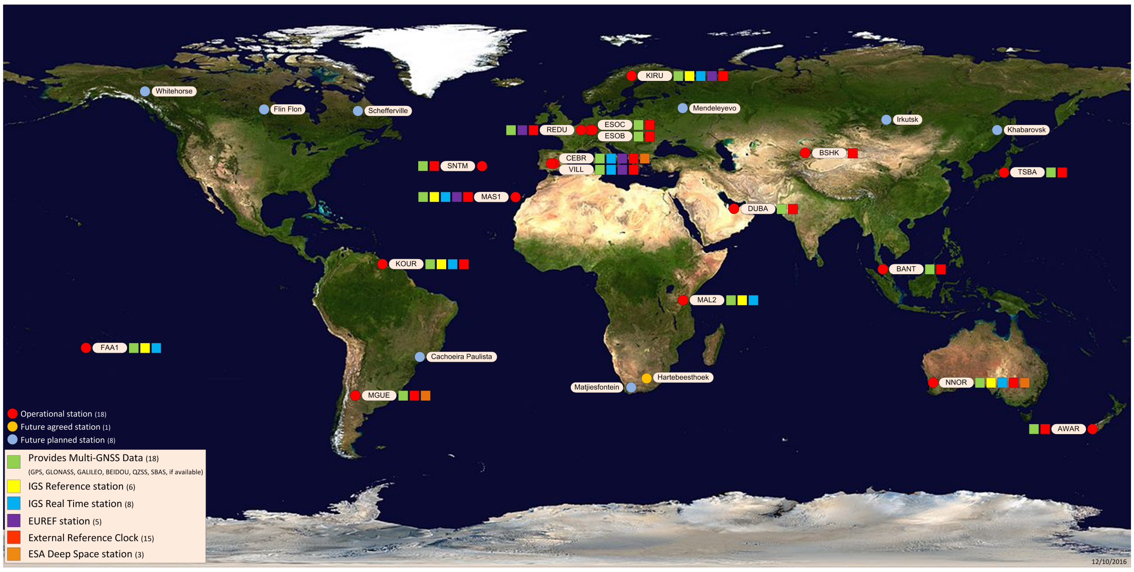

Figure 1: ESA/ESOC GNSS Station Network

The Septentrio PolaRX4 receivers have proven to be very capable at our stations and they provide all phase and pseudo-range measurements for the GNSS constellations as available: GPS, GLONASS, Galileo, QZSS, Compass, SBAS, EGNOS, etc, last year ESA/ESOC has started contributing with long name daily, hourly and high-rate multi-GNSS RINEX 3 data to the IGS for the 10 ESA/ESOC public stations. ESA/ESOC continues to provide the NBS (NavBits) data from GPS L1 in support of LEO Precise Orbit Determination for EUMETSAT.

For 2017/2018 worldwide coverage is planned to be enhanced considerably with the ongoing negotiations with third parties in Brasil, South Africa, Russia and Canada ongoing. The station map shows a projection of the impact on the global coverage for the inclusion of the 9 planned future ESA/ESOC stations, enhancing worldwide GNSS satellite coverage, aiming to provide full triple station coverage for al GNSS satellites at all times.

4 Ionosphere Modeling Activities

ESA/ESOC contributes with IONEX products to the IGS Ionosphere Working Group since its inception in 1998. Up to now, ionosphere products for the IGS are still based on a single-layer approach, where the vertical TEC is represented by spherical harmonics, in combination with an estimation of daily receiver and satellite DCBs. ESA IONEX files are delivered in final (2h time resolution) and in rapid (2h and 1h time resolution) mode to the IGS, and they are based on processing both GPS and GLONASS observations. In addition, predicted products are delivered. ESOC employs the Ionosphere Monitoring Facility (IONMON) for its ionosphere processing, which in 2013 became and integral part of ESOC's NAPEOS software.

5 Multi-GNSS (MGEX)

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

- Strong azimuthal dependent pattern in the GALILEO carrier phase residuals, clearly an azimuthal ANTEX pattern needed
- Severe inconsistency between the three GPS phase signals (L1, L2, and L5); a periodic effect with an amplitude of 50 mm clearly visible
- Severe challenges to model the QZSS satellite during the orbit normal mode phase ($|\beta| < 20^0$)
- Strong elevation dependent pattern in the BEIDOU pseudo range residuals for the MEO satellites
- Severe challenges to model the BeiDou GEO satellite due to orbit normal mode attitude
- Significant challenges to model the BeiDou MEO and IGSO satellites during the orbit normal mode phase ($|\beta| < 4^0$)

In 2016 our prime focus has been to improve our understanding and modelling of the Galileo satellites to such a level that they can be included in our core IGS products (final, rapid, ultra-rapid, and ionosphere) as soon as possible. We are confinced that we have now achieved this goal and that the quality of our Galileo orbit estimates is significantly better then that of our GLONASS orbit estimates and is getting close to the quality of the GPS orbit estimates.

6 Summary

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

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

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GFZ Analysis Center Technical Report 2016

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1 Summary

During 2016, the standard IGS product generation was continued with minor changes in the processing software EPOS-8. The GNSS observation modeling still conforms to the GFZ repro-2 (2nd IGS Reprocessing campaign) settings for the IGS Final product generation. The multi-GNSS processing was continued routinely during 2016 including GPS, GLONASS, BeiDou, Galileo, and QZSS with only few exceptions from a regular submission.

At the end of October 2016, Dr. Mathias Fritsche left GFZ and, therefore, 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 great commitment but also for his collegial spirit over the past three years.

2 Products

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

3 Operational Data Processing and Latest Changes

Our EPOS-8 processing software is following the IERS Conventions 2010 (Petit and Luzum 2010). For the IGS Final, Rapid and Ultra-rapid chains approximately 200, 130, and 95

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

IGS Final	(GLONASS since week 1579)
gfzWWWWD.sp3	Daily orbits for GPS/GLONASS satellites
gfzWWWWD.sp3	Daily orbits for GPS/GLONASS satellites
gfzWWWWD.clk	5-min clocks for stations and 30-sec clocks for GPS/GLONASS satellites
gfzWWWWD.snx	Daily SINEX files
gfzWWWW7.erp	Earth rotation parameters
gfzWWWW7.sum	Summary file including Inter-Frequency Code Biases (IFB) for GLONASS
gfzWWWWD.tro	1-hour tropospheric Zenith Path Delay (ZPD) estimates
IGS Rapid	(GLONASS since week 1579)
gfzWWWWD.sp3	Daily orbits for GPS/GLONASS satellites
gfzWWWWD.clk	5-min clocks for stations and GPS/GLONASS satellites
gfzWWWWD.erp	Daily Earth rotation parameters
IGS Ultra-Rapid	(every 3 hours; provided to IGS every 6 hours; GLONASS since week 1603)
gfuWWWWD_HH.sp3	Adjusted and predicted orbits for GPS/GLONASS satellites
gfzWWWWD_HH.erp	Earth rotation parameters
MGEX Rapid	
gbmWWWWD.sp3	Daily satellite orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
gbmWWWWD.clk	30 sec (since GPS-week 1843) receiver and satellite clocks
gbmWWWWD.erp	Daily Earth rotation parameters
MGEX Ultra-Rapid	(since week 1869)
gbuWWWWD_HH.sp3	Adjusted and predicted orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
gbuWWWWD_HH.erp	Earth rotation parameters

sites are used, respectively. Recent changes in the processing strategy are listed in Table 2. Only minor changes have been applied for the observation modeling in order to keep the consistency with respect to the repro-2 processing strategy. In preparation for the reference frame switch from IGS2008 to IGS2014 an additional processing chain, without product submission, was running between GPS week 1924 (November 20th, 2016) and 1933 (January 28, 2017).

4 Multi-GNSS data processing

The IGR-like and the ultra-rapid like style multi-GNSS processing was continued in 2016 (Deng 2016). The GFZ multi-GNSS solution covers 5 different systems, namely GPS,

Table 2: Recent processing changes

Date	**IGS**	**IGR/IGU**	Change
2016-02-02	w1881	-	Switch from meteo model NOM to GPT2 and from GMF to VMF in the processing of 30 s clock corrections in order to be consistent with 300 s clock processing
2016-03-01	w1886	w1886.4	Skip bad satellites from constellation mean calculation
2016-05-25	w1896	w1898.4	Inclusion of RINEX 3 data

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

Satellite System	**# Satellites**	**Observation Types**
GPS	31	L1/L2
GLONASS	23	L1/L2
Galileo	11	E1/E5a
BeiDou	13	B1/B2
QZSS	1	L1/L2

GLONASS, Galileo, BeiDou and QZSS. Figure 1 shows the total number of satellites per GNSS included in the `gbm` MGEX solution. Table 3 shows the corresponding observation type selection made for the individual GNSS. The ultra-rapid like products are identified with the `gbu` acronym (cf. Table 1).

Since November 1st, 2016 both product types, `gbm` and `gbu`, are available at `ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/` with an artificial latency of 3 days. Registered users (registration is possible by sending an e-mail to mgnss@gfz-potsdam.de) have access to the products via dedicated download pathes without any latency.

5 Reprocessing activities

The GFZ Analysis Center is contributing to the TIGA Reprocessing Campaign as a TIGA Analysis Center. In order to continue our activities described in Deng et al. (2016), we reprocessed the GPS data of the global TIGA tracking network for the time span from begin of 2013 until end of 2015 (GPS weeks 1721 to 1877). The number of processed GPS stations is provided as time series in Figure 2.

Since the number of daily processed TIGA stations exceeds the number of 600 stations (Figure 2) and our EPOS-8 software can process up to 250 stations in a single job, the TIGA stations are splitted into several sub-networks. One of the sub-networks consists of the IGS tracking stations, whereas the TIGA-only stations are divided into 2 sub-

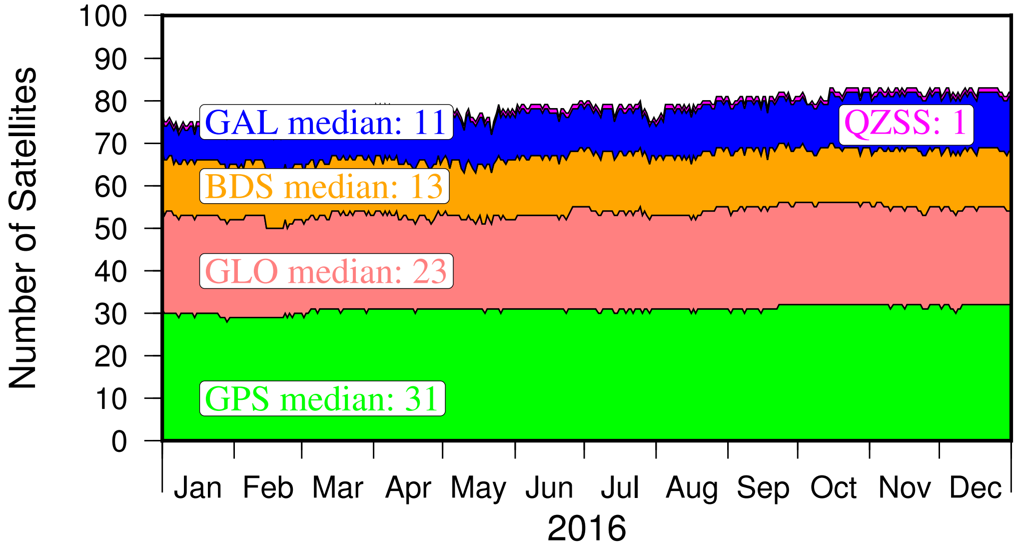

Figure 1: Total number of satellite per GNSS included in the daily MGEX processing

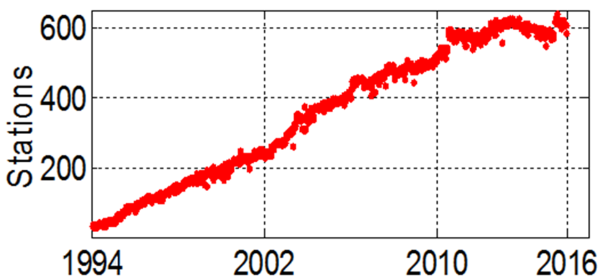

Figure 2: Number of GPS stations in GFZ's TIGA re-processing

networks. The final TIGA solution is the result of a normal equation stacking of all sub-networks. In order to connect the sub-networks 30 globally distributed IGS repro-2 stations are selected and processed together with the TIGA-only sub-networks. The group of connecting stations is different for each sub-network and variates slightly from day to day as they are selected automatically regarding station distribution and a posteriori fits. The derived daily normal equations were submitted to the TIGA Combination Center by mid of December 2016.

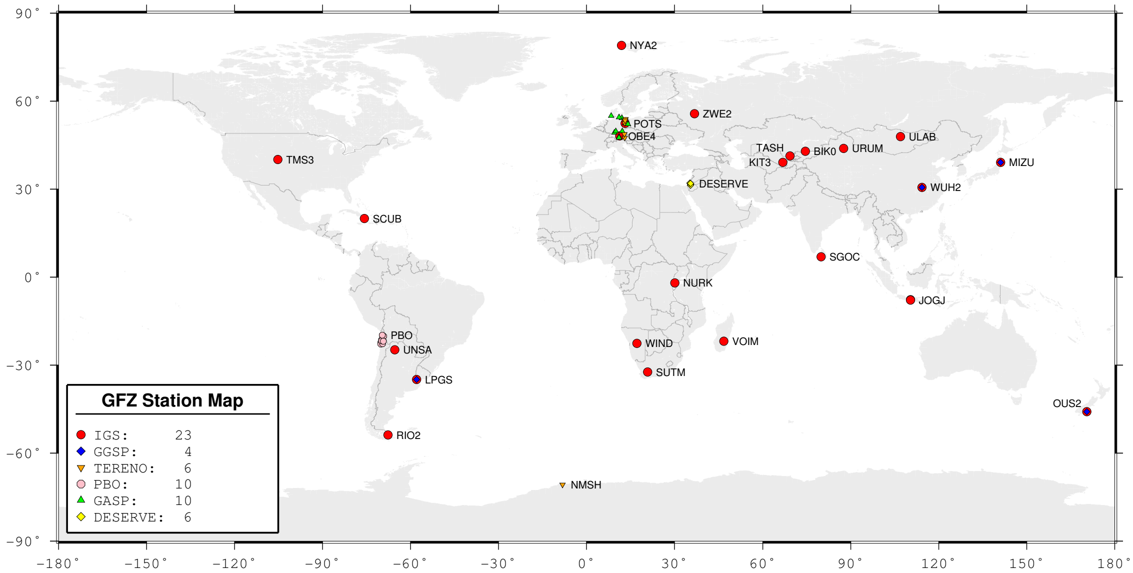

Figure 3: GNSS stations operated by GFZ

6 Operational GFZ Stations

The GFZ operated global GNSS station network comprises currently 23 GNSS stations participating in the IGS tracking network. Figure 3 shows the globally distribution of these stations. Within the 2016, the station La Plata (LPGS) was complete renewed after a long series of unexplained height variations. The station is now equipped with a Javad TRE_3 DELTA receiver and a Javad RINGANT_G5T antenna. In addition, the station Santiago de Cuba (SCUB) was updated to a tracking rate of 1 Hz.

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CNES–CLS Analysis Center Technical Report 2016

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1 Introduction

In 2016, the CNES-CLS Analysis Center continued its contribution through the weekly delivery of final GPS-GLONASS-Galileo products using the GINS software package. The major evolutions in terms of models and parametrization are the following:

- Implementation of a new SRP model
- Software bug correction related to station PCV corrections
- Multi-GNSS satellite clock product alignment strategy

2 Implementation of a new SRP model

As described in the previous reports, our dynamic parameters estimation strategy was based on the idea of not estimating once per revolution terms in the sun D direction for GPS block II-A satellites in order to reduce the correlations with the LOD parameter (and because the estimation of these parameters was not needed for those satellites). This approach was necessarily temporary as the number of block II-A satellites was diminishing. The last one stopped transmitting signals during week 1881 which started impacting the quality of our LOD solutions (Figure 1). An alternative parametrization based on the ECOM2 approach has been implemented since week 1896 for all constellations. If the impact on the orbits was limited (centimeter biases and slight degradation during eclipses)

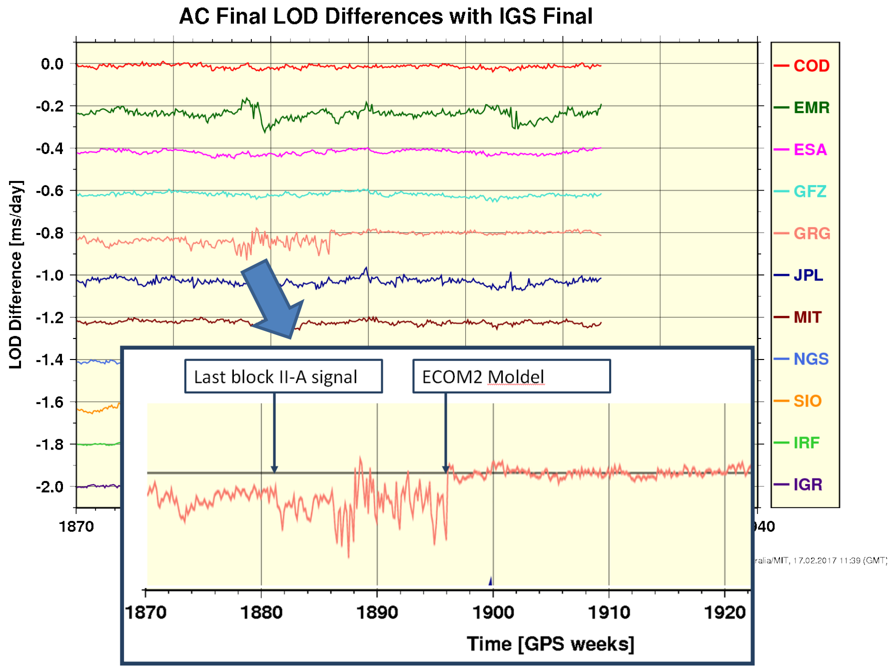

Figure 1: Impact of the new SRP parameterization (starting week 1896) on GRG LOD products.

the LOD solution was drastically improved (Figure 1) mainly because once per revolution terms in the sun direction are no longer estimated.

Table 1: Empirical dynamic parameters estimation strategy

Axis	Old Stategy	New Strategy
D	• Scale factor	• Scale factor
	• 1/rev cos+sin except Block II-A	• 2/rev cos+sin
Y	• 1 bias per arc	• 1 bias per arc
X	• 1/rev cos+sin	• 1 bias per arc
		• 1/rev cos+sin

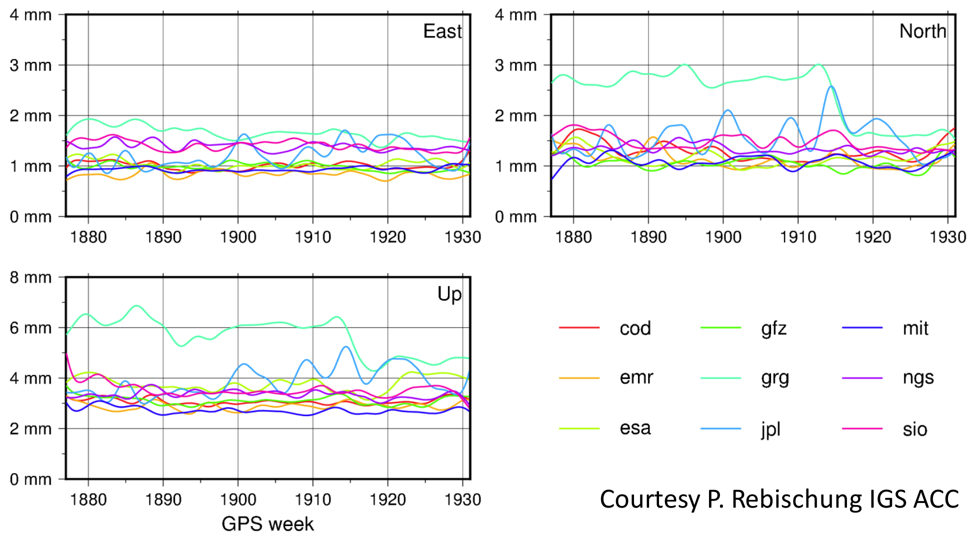

Figure 2: Improvement of GRG station coordinate products since week 1915 after applying correct station antenna PCV maps.

3 Software bug correction related to station PCV corrections

A software bug has been detected and corrected since week 1915. In cases where GLONASS PCV information are available in addition to GPS in the ANTEX files only the last block read en was used (i.e. GLONASS instead of GPS) in the processing. If the impact of using the correct GPS station PCV data on the orbit products was not obviousvery limited, a clear improvement could be detected during the network combination by the ACC as shown in Figure 2.

4 4. Multi-GNSS satellite clock product alignment strategy

First, we modified our strategy in estimating inter-system bias when producing the orbit/clock solutions from simultaneous GPS+GLONASS+Galileo data processing. We

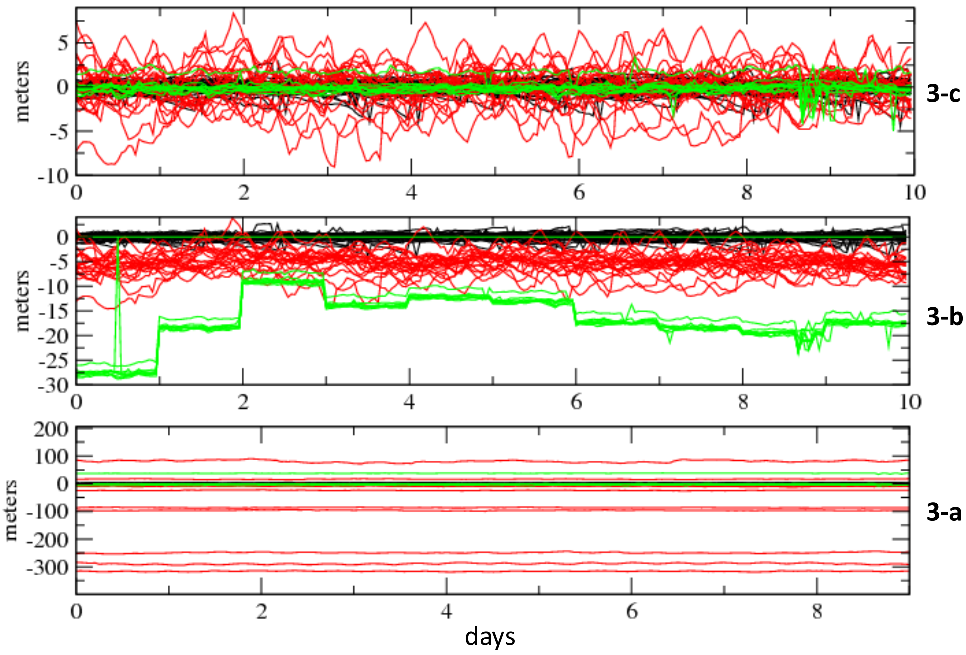

Figure 3: GRG clock solution comparison with BRDM products (GPS in black, GLONASS in red and Galileo in green). Initial products (3-a), products after alignment of GPS clocks to BRDC ephemerides (3-b) and products after alignment of GLONASS and Galileo clocks to BRDM ephemerides (3-c). All clocks expressed in meters.

moved from one inter system bias per satellite-station couple to one per station for Galileo and one per frequency for GLONASS. The level of the correlations was drastically reduced and the impact on the clock solution can be seen on Figure 3-b. Second, we included in our clock "alignment" procedure an additional step consisting in applying 1 constant bias (per daily solution) for GLONASS and Galileo solutions using BRDM MGEX broadcast information. These additional constraints make possible the use of these GRG products for timing as it was already the case for GPS clocks. The corresponding solutions are represented in Figure 3-c.

For more results concerning GRG Multi-GNSS products please refer to the MGEX section of this document.

5 Perspectives

The originality of the CNES-CLS AC processing strategy is to be based on a zero-difference approach including the so-called "Integer Recovery Clock Model" for GPS products. Using GRG orbits and clocks with the associated and provided satellite biases enables ambiguity fixing for single receiver PPP. Our plan is to extend this property to Galileo products. In addition investigations on the spurious signals affecting GR2 REPRO2 products have to be finalized in order to be prepared for REPRO3.

JPL IGS Analysis Center Technical Report 2016

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1 Introduction

In 2016, the Jet Propulsion Laboratory (JPL) continued to serve as an Analysis Center (AC) for the International GNSS Service (IGS). We contributed operational orbit and clock solutions for the GPS satellites; position, clock and troposphere solutions for the ground stations used to determine the satellite orbit and clock states; and estimates of Earth rotation parameters (length-of-day, polar motion, and polar motion rates). This report summarizes the activities at the JPL IGS AC in 2016.

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

Table 1 summarizes our contributions to the IGS Rapid and Final products. All of our contributions are based upon daily solutions centered at noon and spanning 30-hours. Each of our daily solutions is determined independently from neighboring solutions, namely without applying any constraints between solutions. High-rate (30-second) Final GPS clock products are available from 2001 onwards.

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

ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/readme.txt.

2 Processing Software and Standards

During 2016, the JPL AC used version 6.4 of the GIPSY/OASIS software package to generate our contributions to the IGS. This is the latest GIPSY version and supersedes version 6.3 which was used for our IGS repro2 contribution. In our operations, we have adopted the data processing approach used for our repro2 reprocessing which had the following improvements from our previous data processing strategy:

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

A complete description of our current operational processing approach, also used for repro2, can be found at:

ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/readme.txt

We continue to use empirical GPS solar radiation pressure models developed at JPL instead of the DYB-based strategies that are commonly used by other IGS analysis centers. This choice is based upon an extensive evaluation of various internal and external metrics after testing both approaches with the GIPSY/OASIS software (Sibthorpe et al. 2011).

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

1. Improved geophysical models:
    a) Second-order ionosphere correction: tweaks to use of IGRF, IRI, IONEX models.
    b) GPT model: finer 1° resolution and GPT2w a-priori wet delay calculation.
    c) Time-varying gravity (including ICGEM format to GIPSY format converter).
2. Improved attitude modeling of GPS block IIF at noon and midnight turns (Kuang et al. (2013)).
3. Improved reference frame handling with support for large ITRF2014 covariance files.
4. Software upgrades to ninja editor and gd2p PPP tool, several new utilities, bug fixes.

Note that no further release or development in GIPSY is anticipated.

3 GipsyX Overview

For several years we have been developing a replacement to GIPSY called GipsyX which has the following features:

1. GipsyX is the C++/Python3 replacement for both GIPSY and Real-Time GIPSY (RTG).
2. Driven by need to support both post-processing and real-time processing of multiple GNSS constellations.
3. Can already process data from GPS, GLONASS, Beidou, and Galileo.
4. Can be easily extended to support DORIS and SLR data processing.
5. Multi-processor and multi-threaded capability.
6. Single executable replaces multiple GIPSY executables: model/oi, filter. smoother, ambiguity resolution.
7. Versatile PPP tool (gd2e) to replace GIPSY's gd2p.
8. Similar but not identical file formats to current GIPSY.
9. Runs under Linux and Mac OS.
10. GipsyX beta-version released to the GIPSY user community in December 2016.

In parallel with the GipsyX development we have also been developing new Python3 operational software to generate both the rapid and final products that we deliver to the IGS using GipsyX instead of GIPSY as well as generating our ultra-rapid products that are available on our ftp site.

4 Testing of GipsyX Operations

We have run extensive tests of our new 'modern' operational software that uses GipsyX shadowing our current legacy rapid and final operational processes for over 10 months and then comparing our results with both IGS and our legacy GIPSY products. As shown in Figure 1 and Figure 2 we also ask undertook a longer 2.5 year comparison of the IGS final products with both our current legacy system (that uses GIPSY) and our new replacement 'modern' system (that uses GipsyX). The median of daily 3D RMS median differences over 24 hours is 25.5 mm for legacy vs IGS and 25.4 mm for modern vs IGS while the median of daily RMS differences across the constellation over 24 hours is 38.6 mm for legacy vs. IGS and 38.7 mm for modern vs IGS. Thus, we expect our switch to using GipsyX to create our IGS products to be fully transparent to IGS users and furthermore that GipsyX-generated products are at least as good as GIPSY-generated products.

5 Future Work

At the start of GPS week 1934 (29-Jan-17) we will switch to creating all the products we deliver to the IGS using our new GipsyX-based operational system[1]. Also, we are developing an improved solar radiation model for the block IIF GPS satellites as well as making other enhancements to our data processing, some of which are described in more detail in our presentations at the IGS 2016 workshop in Sydney. Our longer term goal is to generate other GNSS constellation orbit and clock products using this new software as well as adding the capability to process other non-GNSS geodetic data.

6 Acknowledgments

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

[1]Note: This switch has be made.

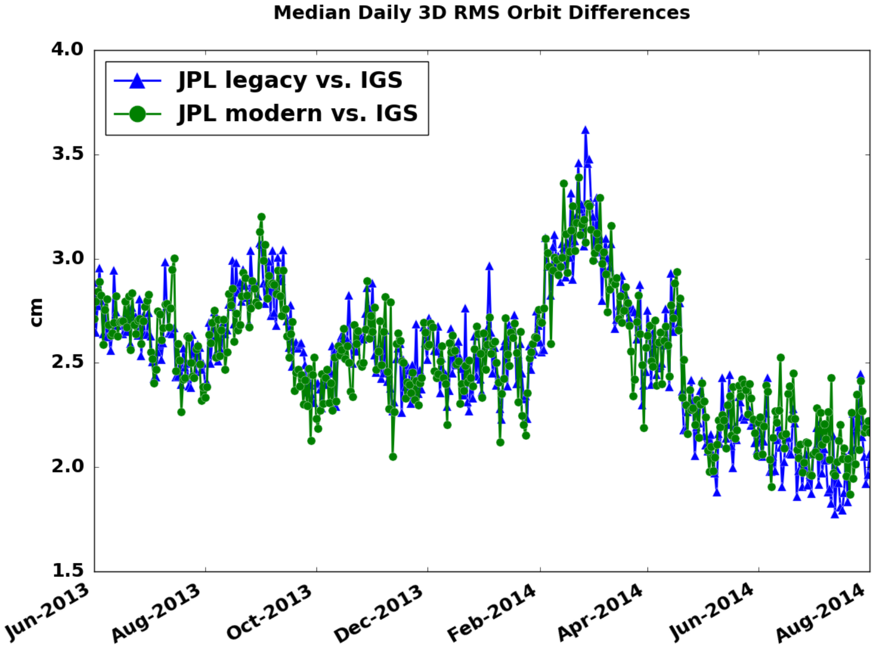

Figure 1: Median daily 3D RMS orbit differences. Blue line is JPL GIPSY-based legacy system versus IGS and green line is JPL GipsyX-based modern system versus IGS.

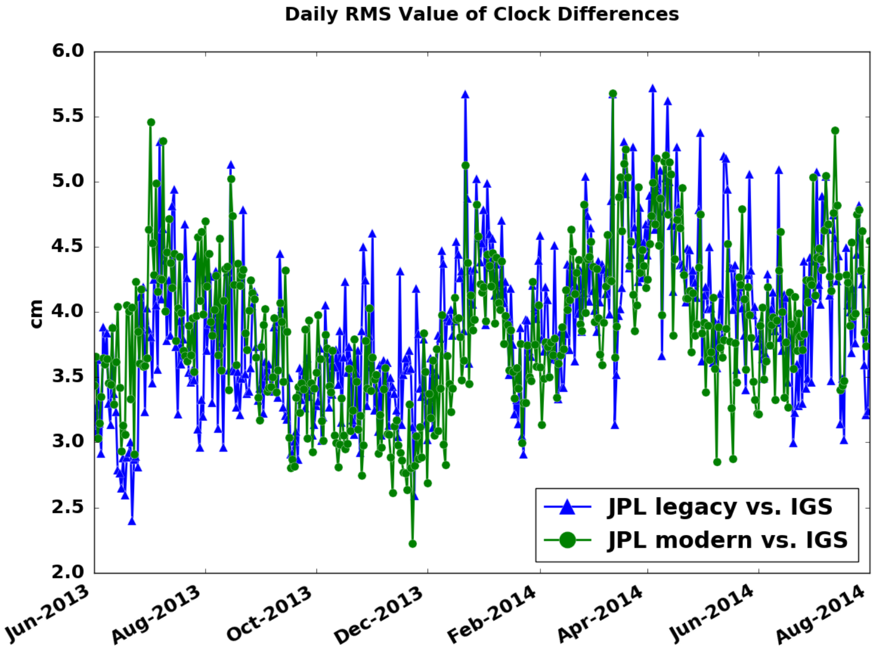

Figure 2: Daily RMS of clock differences. Blue line is JPL GIPSY-based legacy system versus IGS and green line is JPL GipsyX-based modern system versus IGS.

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MIT Analysis Center Technical Report 2016

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1 Introduction

In this report, we discuss results generated by the MIT analysis center (AC) both for submissions of weekly final IGS solutions and our weekly combination of SINEX files from MIT and the other eight IGS analysis centers that submit final SINEX files. We present here analysis of the networks we process, comparison between our position estimates and those from other IGS analysis centers, and estimates of GPS satellite phase center offsets (PCO) from our repro2 results.

2 Overview of MIT processing

The MIT analysis for IGS final orbits, clocks and terrestrial reference frame uses the GAMIT/GLOBK software versions 10.60.003 and 5.29 (Herring et al. 2015). The GAMIT software uses a double–difference estimator. In order to efficiently process a large global network sub–networks are used. Each day, 350 stations are included in the combined network which is composed of seven individual networks each with 50 stations and pairs of stations that couple each sub–network to every other sub–network. These networks are generated independently each day and depend of the data that is available in the IGS and other data archives. We search CDDIS, UNAVCO, SOPAC, Geosciences Australia and BKG for RINEX data. Each network is seeded with four distant sites (not all sites need to be available) and the seven networks are sequentially filled, first from a list of 378 IGS sites and then from other sites around the world that will fill in regions not covered by the IGS sites. Sites are added one–at–time to each network rather than making one complete network before moving the next. The sequential approach makes each network as globally distributed as possible. Pairs of overlap stations are selected from the stations

Table 1: MIT products submitted for weekly finals analysis

File	Description
mitWWWW7.sum.Z	Summary file.WWWW is GPS week number.
mitWWWW7.erp.Z	Earth rotation parameters for 9–days, IGS format
mitWWWWn.sp3.Z	Daily GPS satellite orbits (n=0–6)
mitWWWWn.clk.Z	Daily GPS satellite clocks (n=0–6)
mitWWWW.snx.Z	Daily GPS coordinate and EOP SINEX file.

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

File	Description
migWWWWn.snx	Combined sinex file from all available analysis centers (n=0–6, WWWW GPS week number)
migWWWWn.sum	Name of this summary file (n=0–6)
migWWWWn.res	File of the individual AC position estimates residuals to the combined solution for the week. (n=0–6)

in each network to join the networks together. No station is used more than twice in this approach. The network solutions and parameterized orbit models are combined with the GLOBK software. The GAMIT solutions estimate parameters for the full Bernese Empirical Code Orbit model (ECOM) (Beutler et al. 1994): 6 initial conditions, 3 constant radiation parameters and 3 pairs of once–per–revolution (OPR) radiation parameters. In the GLOBK combination stage, we often force the OPR terms for all but the B–axis to zero. The treatment of the OPR terms is based on overlaps between trial solutions with different parameterizations and the estimates and standard deviations of the OPR terms. Random walk process noise is also assigned to the OPR terms based on the daily solution variability of the estimated OPR terms. The GAMIT clock solutions, which have not been used in the IGS clock estimates since mid–2015, are based on un–differenced data analysis using the MIT orbit, station positions, and Earth orientation parameter estimates. The clock estimates are generated in a post–processing step using the GAMIT phase cleaning program.

In addition to weekly final processing, we also generate combined SINEX processing from the combination of all eight IGS ACs contributing to the IGS finals. We do this in our role as an associate analysis center (AAC). All stations submitted by the ACs are included in MIG combined SINEX file. Covariance matrices or inverted normal equations are scaled based the root–mean–square (RMS) differences of IGb08 reference frame stations between each AC solution and the combination all other AC solutions. In Tabular 1 and 2 we list the products submitted by MIT in our AC and AAC roles.

The network of stations processed by MIT in 2016 is shown in Figure 1. The figure shows the weighted root–mean–square (WRMS) scatter of the horizontal coordinates of nearly all of the stations included in the MIT finals processing. Stations that were used just a few times (15 stations in all) are not included in the plot. Only linear trends were removed from the time series. Figure 2 shows histograms of the WRMS in all three topocentric coordinates after the removal of linear trends from the time series. The median WRMS scatters of the 450 sites included in the statistics are 1.5 mm in North and East and 5.9 mm in height. No annual signals were removed.

3 Position repeatability and comparison to other ACs

We can also compare the MIT daily position estimates with those of other analysis centers based on the AAC combinations performed at MIT. The MIG combined solution is used for comparison with the official IGS combination preformed at IGN and generally matches the IGN solution at the level of $0.1-0.2$ mm in north and east (NE) and $0.7-1.0$ mm in height (U). The two analyses use different methods to determine AC weighting and different selection of sites. In Figure 3, we show the WRMS scatter of the daily fits to 60–70 IGb08 reference frame sites from each of the IGS ACs and the combined SINEX solution with the weights assigned to each AC consistent with the fit of the AC to combination of the other ACs. There is good consistency between the ACs with the exception of the early part of the GRC solution which deviates from the other ACs. For the final third of 2016, the match of the GRC solution improved considerably. While the AC results look similar, there are differences in the mean of the RMS differences. Table 3 gives the mean RMS differences for each AC with respect IGb08 and respect to the combination. This table shows that on average the MIT solution provides a very good match to the combined solution with sub–millimeter horizontal WRMS and 3.3 mm WRMS in height. We also compute the chi–squared per degree of the fits and all AC's have similar chi–squared values indicaring that no one center dominates the combination.

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4 Satellite antenna offset estimates from MIT repro2 processing

For the rrepo2 reanalysis, MIT estimated the phase center offsets (PCO) values for all satellites processed. We have analyzed a new method for estimating the average of value of the PCOs for different satellite vehicle numbers. The current IGS14 estimates of satellite PCOs are based on time series analysis of daily estimates of the PCO values with the terrestrial frame fixed at the coordinates given in ITRF2014 after accounting for changes in coordinates of specific stations where new antenna calibrations are used in IGS14. In our approach, we directly estimate the mean PCO values by combining the MIT loosely

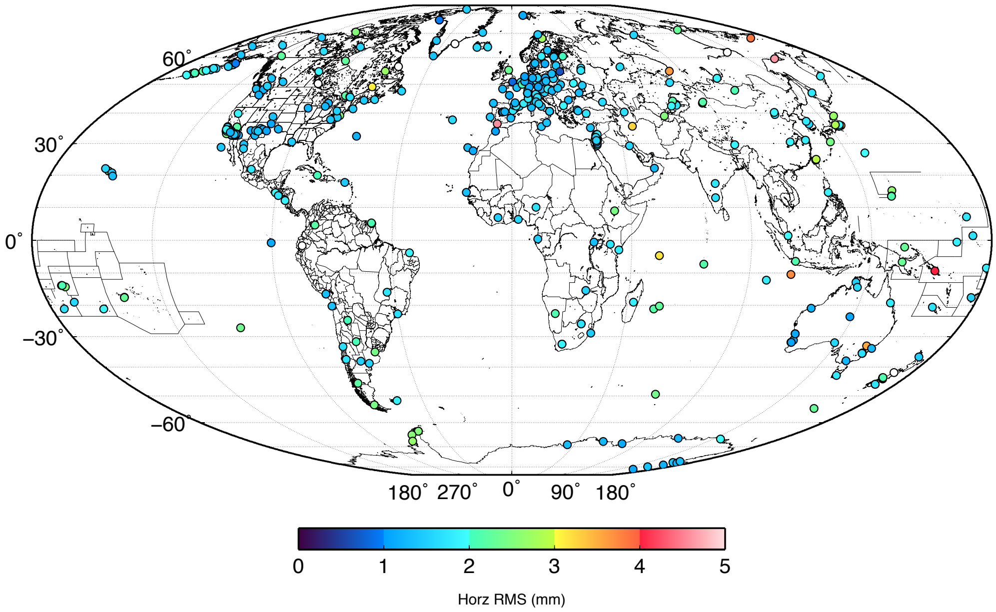

Figure 1: RMS scatter of the horizontal position estimates from the network of 435 stations processed by MIT in 2016. Each daily network has 350 station and the networks evolve with time depending on data availability and geometry.

constrained SINEX files (actually the GLOBK binary equivalent of these files) in GLOBK. (We use the original MIT analysis files before the satellite PCO values are constrained to ±1mm for submission of the repro2 SINEX files to avoid any additional computational noise from removing the PCO constraints). Most importantly, in the SINEX combination we do not constrain the ground station site coordinates or any of the satellite initial conditions or the radiation parameters of the ECOM orbit model. The correlations between the PCO estimates, satellite clocks and ground station coordinates are high, they are not unity and provided the nadir dependence of satellite phase center variations are held fixed (possibly a big assumption) and the ground antenna calibrations are also held fixed, this type of solution is possible. However, the high correlations make this solution prone to systematic errors and time series of the daily estimates do show large, non–white noise variations. These types of systematics are present even when the terrestrial reference frame is held fixed.

The results from our estimates are shown in Figure 4 and Table 4. The data analyzed spanned 1994/01/01 to 2015/08/23 and in all the PCO values for 63 satellites were estimated. In some cases, multiple PRNs have been assigned to the same vehicle and, in these cases, we have multiple estimates for the same vehicle. Figure 4 shows the differences between our estimates and the IGb08 and IGS14 values adopted by the IGS. Table 4 shows the values averaged over each block type. The overall average difference from the IGb08 values is −37 mm with an RMS scatter of 33 mm while for IGS14 the average difference

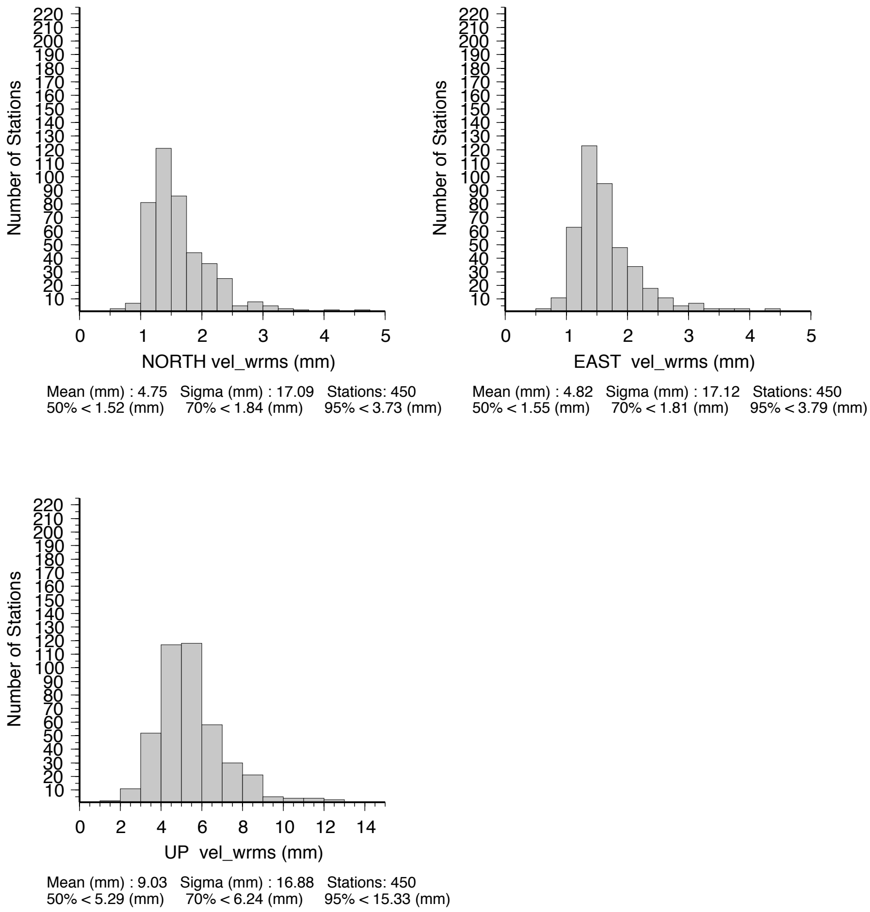

Figure 2: Histogram of the weighted root–mean–square (WRMS) scatter of daily position estimates for 2016 after removal linear trends and elimination of gross outliers (5 times WRMS scatter.

Table 3: Comparison of the fits to the IGb08 reference frame (RF) and daily combined solutions for RF sites in the MIT and other AC daily final SINEX files. Typically, 65–70 sites are used in the comparison

Center		IGb08			Combined	
	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
MIT	3.78	4.41	11.15	0.92	0.95	3.25
COF	3.85	4.47	10.14	1.21	1.05	3.66
EMR	4.47	4.29	10.45	1.06	0.80	2.86
ESA	4.56	4.96	9.42	1.06	0.94	3.81
GFZ	4.24	5.03	10.98	1.01	1.05	3.14
GRG	6.47	5.81	13.05	2.52	1.55	6.12
JPL	4.56	4.38	11.40	0.95	0.83	3.40
NGS	3.99	4.12	10.97	1.27	1.43	3.76
SIO	3.87	4.18	10.93	1.39	1.53	4.13

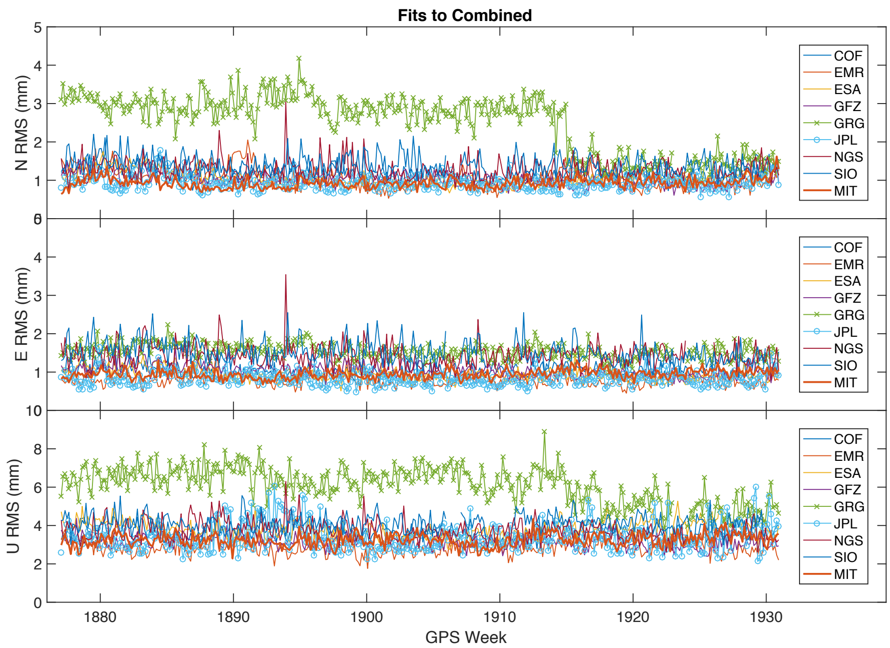

Figure 3: RMS scatters of the fits of the different IGS ACs to the MIG combined solution for 2016.

is 20 mm with a smaller RMS of 20 mm.

The implications of our results are we expect a 0.29 ppb scale change from IGb08 (based on the Zhu et al. (2003)empirical relation of –0.94 ppb for average 121 mm change in satellite PCO Z–values) and –0.15 ppb scale change from IGS14. This scale change from IGS14

Table 4: Block mean estimates of the satellite antenna Z–offset estimates. All units are mm. The values of individual satellites are shown in Figure 4. The mean over all blocks (71 satellites) is –36.9 mm, RMS 33 mm for IGb08 and 19.7 mm RMS 20 mm for IGS14. The standard deviations of the estimates (± column) are white noise estimates from combining the SINEX files

Type	#	IGb08	IGS14	±	WRMS IGb08	WRMS IGS14
BLOCK I	3	–152.50	–62.90	6.40	8.20	19.00
BLOCK II	9	–52.40	12.10	0.40	15.70	13.70
BLOCK IIA	29	–54.40	4.80	0.20	14.50	9.70
BLOCK IIR–A	8	7.90	46.10	0.30	11.10	7.70
BLOCK IIR–B	4	–17.50	29.80	0.50	12.60	12.10
BLOCK IIR–M	10	–21.80	32.20	0.40	15.80	12.30
BLOCK IIF	9	–87.60	8.20	0.50	42.20	16.90

would bring the scale inferred from our estimates close to the ITRF2008 scale. One caveat is that all our results are (as are the IGS14 PCO estimates) generated from processing that used the IGb08 ground antenna calibration values which have been modified in IGS14 for a number of, but not all, antennas.

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Zhu, S.Y., Massmann, F.–H., Yu, Y., and Reigber, C. Satellite antenna phase center offsets and scale errors in GPS solutions. J Geod 76(11–12):668–672, 2003. doi:10.1007/s00190–002–0294–1

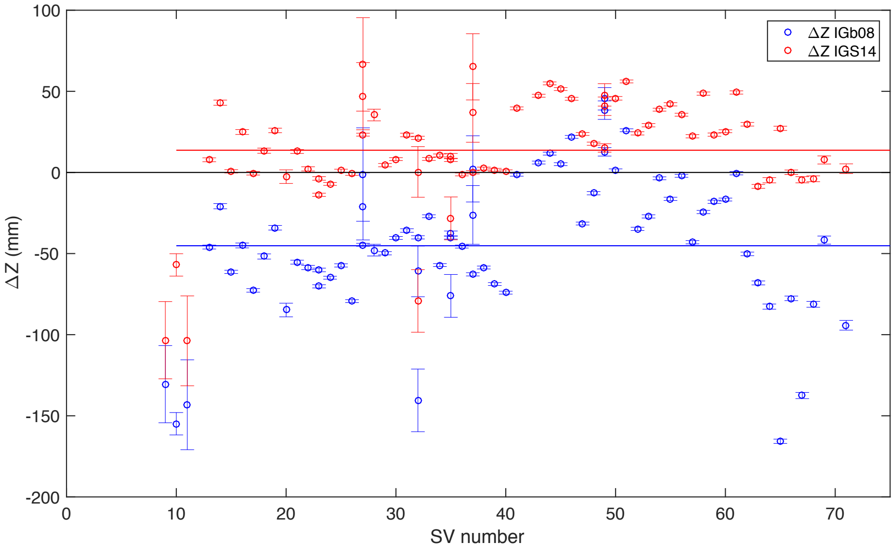

Figure 4: Estimates of the average satellite antenna Z–offset from the MIT repro2 analysis based on the combined solution discussed in the text. Multiple estimates from the same satellite vehicle number arise from re–assigned PRN numbers. Only values with standard deviations less than 50 mm are shown.

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1 Introduction

In 2016, NGS continued to serve as an IGS analysis center and a regional data center. This report summarizes the routine analysis and data center activities conducted at the National Geodetic Survey (NGS), and all significant changes that occurred during the year 2016.

2 Core Analysis Center Products

There were no changes in the NGS analysis center products (see Tabular 1) for 2016. Please refer to the Analysis Coordinator website (http://acc.igs.org) for combination statistics of the NGS analysis center products.

3 Analysis Center Processing Software and Strategies

There were no changes to the processing models or strategies for 2016. For details about the models and strategies used, please refer to the NOAA/NGS Analysis Strategy Summary (ftp://igs.org/pub/center/analysis/noaa.acn).

Table 1: NGS Analysis Center Products

Product	Description
Final (weekly)	
ngswwwwd.sp3	GPS only
ngswwwwd.snx	PAGES software suite (5.97 – 5.101)
ngswwww7.erp	Orbits, ERP and SINEX
Rapid (daily)	
ngrwwwwd.sp3	GPS only
ngrwwwwd.erp	PAGES software suite (5.97 – 5.101)
	Orbits, ERP and SINEX
	Daily submission for IGR combination
Ultra–Rapid (hourly)	
nguwwwwd.sp3	GPS only
nguwwwwd.erp	PAGES software suite (5.97 – 5.101)
	Orbits and ERP4 times a day submission for IGU combination

Changes to the processing software and strategies include:

- Week 1886 (2016–02–28).

  Minor changes for software use under both Sun and Linux OS. No effect upon products.

- Week 1913 (2016–09–04).

  Minor changes for software use under both Sun and Linux OS. No effect upon products.Week 1919 (2016–10–16)

  Changes making ITRF2014 and IGS14 acceptable options for orbit product production. No effect upon products.

Changes in staff include:

- Jacob Heck came on–board.
- Giovanni Sella, who had served as the CORS program manager at NGS, moved on to other role within NGS in January of 2017 and no longer serves as the CORS program manager.

Trial production of IGS14 orbit products began with the final products for week 1915.

4 Regional Data Center Core Products

During 2016, NGS contributed data from the following sites to the IGS Network:

Table 2: Site list of NGS contribution to the IGS Network

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

As a Regional Data Center, NGS also facilitated data flow for the following sites:

Table 3: Site list of NGS contribution as a regional data center

Site	Location	Lat.	Long.	Receiver Type	System
BJCO	Cotonou, BEN	6.38	2.45	TRIMBLE NETR5	G, R
GUAT	Guatemala City, GTM	14.59	–90.52	LEICA GRX1200GGPRO	G, R
ISBA	Baghdad, IRQ	33.34	44.44	TRIMBLE NETR5	G, R
MANA	Managua, NIC	12.15	–86.25	TRIMBLE NETR9	G
WUHN	Wuhan, CHN	30.53	114.36	TRIMBLE NETR9	G, R

Please refer to the IGS Network website (http://igs.org/network) for site logs, photos, and data statistics for the sites serviced by the NGS regional data center.

5 Acknowledgments

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

USNO Analysis Center Technical Report 2016

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1 Introduction

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

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

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

USNO AC products are computed using Bernese GNSS Software (Dach et al. 2015)[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.

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

GPSAD also generates a UT1-UTC-like value, UTGPS, five times per day. UTGPS is a GPS-based extrapolation of VLBI-based UT1-UTC measurements. The IERS[2] Rapid Combination/Prediction Service uses UTGPS to improve post-processed and predicted estimates of UT1-UTC. Mr. Tracey oversees UTGPS.

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

2 Product Performance, 2016

Figures 1-4 show the 2016 performance of USNO rapid and ultra-rapid GPS products, with summary statistics given in Table 1. USNO rapid orbits had a median weighted RMS (WRMS) of 18 mm with respect to (wrt) the IGS rapid combined orbits. The USNO ultra-rapid orbits had median WRMSs of 26 mm (24-h post-processed segment) and 41 mm (6-h predict) wrt the IGS rapid combined orbits. These values are slightly degraded compared to the 2015 values (17, 20 and 38 mm).

USNO rapid (post-processed) and ultra-rapid 6-h predicted clocks had median 152 ps and 1216 ps RMSs wrt IGS combined rapid clocks, compared to 172 ps and 1201 ps in 2015. Note the slight improvement in the rapid clock predictions.

USNO rapid polar motion estimates had (x, y) 111 and 74 microarcsec RMS differences wrt IGS rapid combined values. USNO ultra-rapid polar motion estimates differed (RMS; x, y) from IGS rapid combined values by 156 and 151 microarcsec 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 381 and 322 microarcsec. The rapid polar motion values show significant improvement towards the end of 2016.

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.

In 2016, seven-parameter Helmert transformations computed between USNO and IGS ultra-rapid GPS+GLONASS orbits had median RMSs of 30 and 60 mm for the 24-h post-processed and 6-h predict portions, respectively. Meanwhile, the USNO GPS+GLONASS ultra-rapid 24-h post-processed polar motion x and y values differed from the IGR values, RMS, by 267 and 129 microarcsec, respectively. USNO GPS+GLONASS ultra-rapid 24-h predicted polar motion x and y values differed from the IGR values, RMS, by 406 and 307 microarcsec, respectively. These data are shown in Table 2/Figures 5-6.

The USNO AC acquired Bernese 5.2 GNSS Software in 2013 and released the official rapid

[2] International Earth Rotation and Reference Systems Service

products generated using it in 2016. The GPS+GLONASS rapid and ultra-rapid solutions referenced above have been generated using Bernese 5.2 GNSS Software since December 2014.

3 USNO AC Conference Presentations/Publications

USNO AC members presentations/publications are as follows for 2016:

S. Byram and C. Hackman, "IGS Final Troposphere Product Update". 2016 IGS Workshop, Sydney, Australia, 2016.

V. Slabinski, "LAGEOS Solar Radiation Force: Contribution from Cube-Corner Retroreflection". 2016 Division on Dynamical Astronomy/AAS Meeting, Nashville, TN, 2016.

References

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

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Table 1: Precision of USNO Rapid and Ultra-Rapid Products, 2016. All statistics computed with respect to IGS Combined Rapid Products.

USNO GPS satellite orbits				USNO GPS–based polar motion estimates						USNO GPS–based clock estimates	
Statistic: median weighted RMS difference units: mm				Statistic: RMS difference units: 10^{-6} arc sec						Statistic: median RMS difference units: ps	
dates	rapid	ultra–rapid past 24 h	ultra–rapid 6-h predict	rapid x	rapid x	ultra–rapid past 24 4 x	ultra–rapid past 24 4 y	ultra–rapid 24-h predict x	ultra–rapid 24-h predict y	rapid past 24 h	ultra–rapid 6-h predict
1/1/2016–12/31/2016	18	26	41	111	74	156	151	381	322	152	1216

Table 2: Precision of USNO Ultra-Rapid GPS+GLONASS Test Products, 2016. Orbit statistics computed with respect to IGV Combined Ultra-Rapid GPS+GLONASS Products. Polar motion statistics computed with respect to IGS Rapid combined values.

USNO GLONASS satellite orbits			USNO GPS+GLONASS polar motion estimates	
Median RMS of 7-parameter Helmert transformation units: mm			RMS difference units: 10^{-6} arc sec	
dates	past 24 h	6-h predict	past 24 h	pred 6 h
1/1/2016–12/31/2016	30	60	x: 129 y: 12	x: 406 y: 307

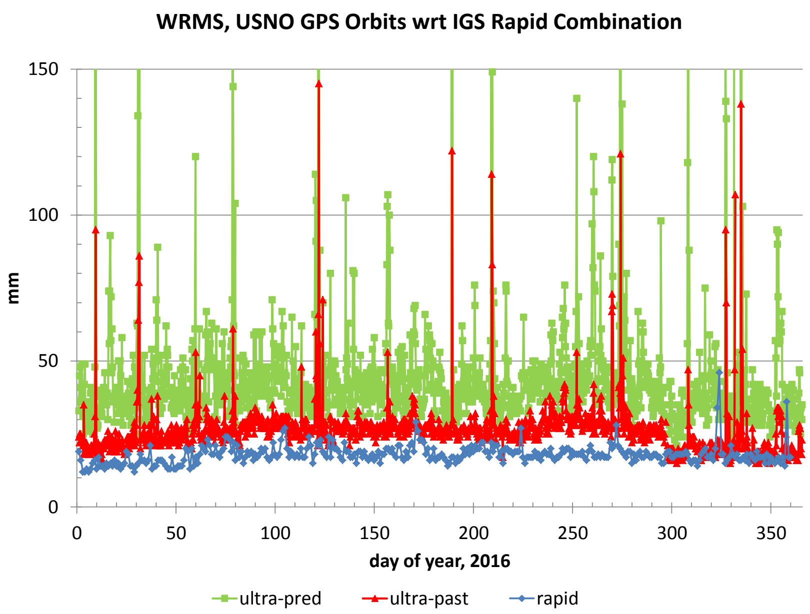

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2016. "Ultra-past" refers to 24-hour post-processed section of USNO ultra-rapid orbits. "Ultra-pred" refers to first six hours of ultra-rapid orbit prediction.

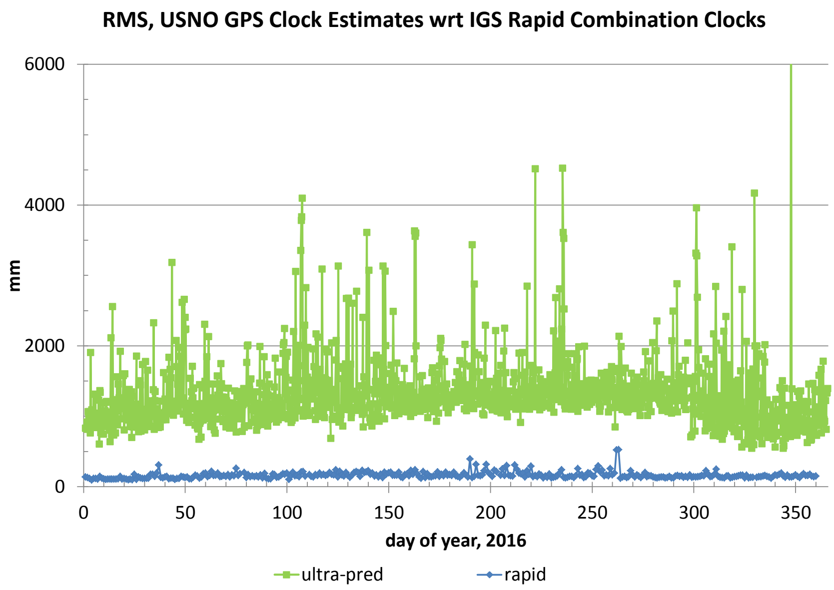

Figure 2: RMS of USNO GPS rapid clock estimates and ultra-rapid clock predictions with respect to IGS Rapid Combination, 2016.

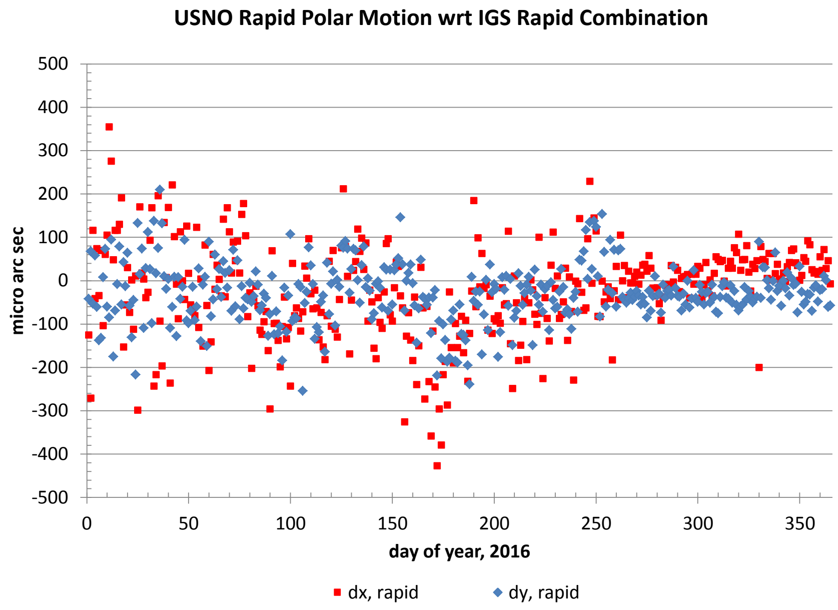

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2016.

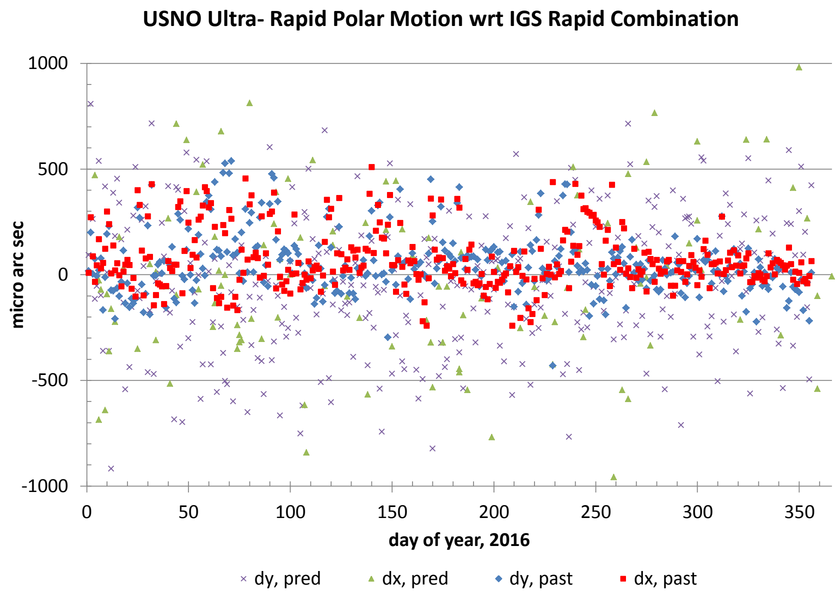

Figure 4: USNO ultra-rapid polar motion estimates minus IGS Rapid Combination values, 2016.

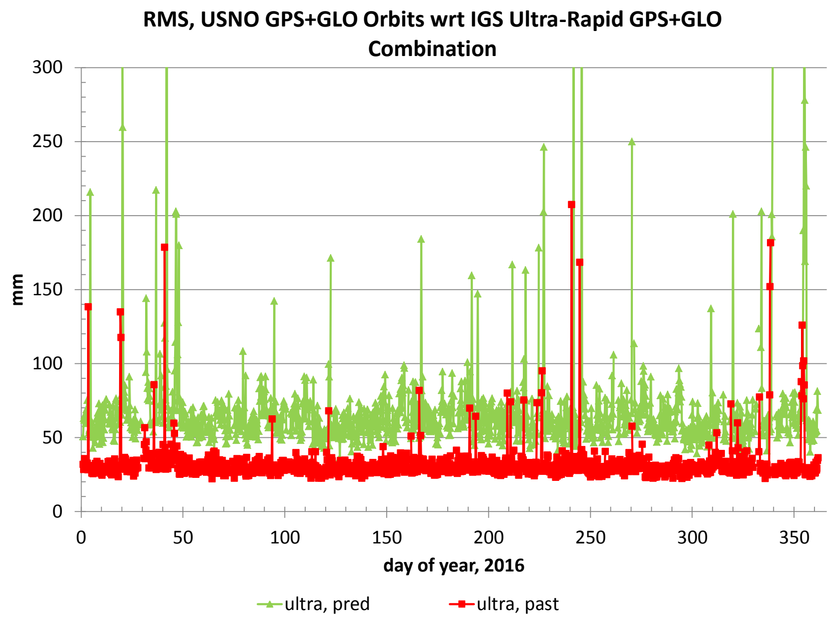

Figure 5: RMS of USNO ultra-rapid GLONASS orbit estimates with respect to IGS Combined Ultra-rapid GLONASS orbits, 2016. "Ultra, past" refers to 24-hour post-processed section of USNO ultra-rapid orbits. "Ultra, pred" refers to first six hours of ultra-rapid orbit prediction. Helmert transformations computed using Bernese 5.0 Software.

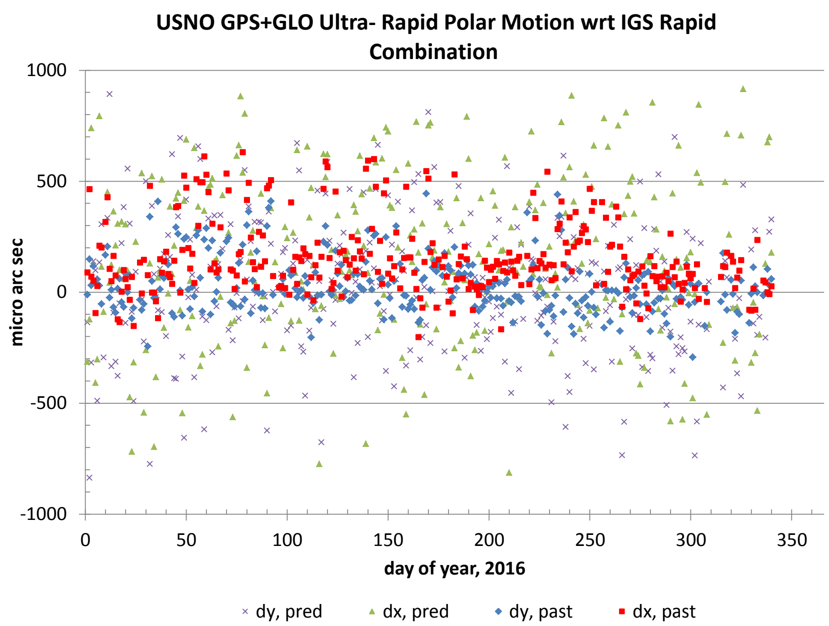

Figure 6: Difference between 24-h post-processed polar motion estimates in USNO test ultra-rapid GPS+GLONASS solution and IGS "IGU" GPS-only ultra-rapid solution, 2016.

WHU Analysis Center Technical Report 2016

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1 Introduction

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

During 2016, the standard RAPID product generation was continued with minor changes in the software PANDA, and we established a Ionosphere Analysis Center and a IGS Data Center at the GNSS Research Center, Wuhan University. In this report we give a summary of the IGS related activities at WHU during the year 2016.

2 PANDA software

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

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

3 WHU Analysis Products

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

Table 1: List of products provided by WHU.

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

4 IGS Data center from WHU

The IGS Data Center from WHU has been designed and implemented in answer to global and especially Chinese users, for both post-processing and real-time applications. The GNSS observations both IGS and MGEX from all the IGS network stations, as well as the IGS products are archived and available at WHU IGS Global Data Center. So as to have a more reliable data flow and a better availability of the service, two identical configurations with the same data structure have been setup in Alibaba cloud and Data Server of WHU University. Each configuration has:

- FTP access to the GNSS observations and products (`ftp://igs.gnsswhu.cn/`).
- access to the GNSS observations and products (`http://igs.gnsswhu.cn/`).

In order to ensure the integrity of the observation data and the product, we compare the daily data, hourly data and products with CDDIS. If a data file is missing, we will download it from CDDIS again. Figure 1 shows status of daily observation.

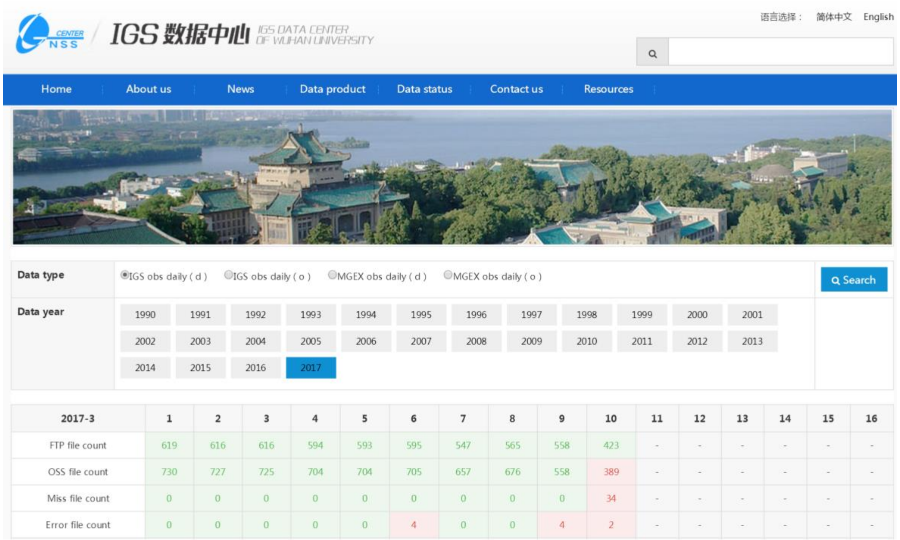

Figure 1: Status of daily observations.

5 Ionosphere Activities

WHU are making efforts to boost the ability of processing GNSS data for generating global ionosphere maps over these years. WHU joined IGS Ionosphere Working Group as an Ionosphere Associate Analysis Center in 2016, and has been providing various kinds of ionosphere products since 2016, such as rapid products, hourly products and final products. New algorithms are proposed to improve the quality of ionosphere maps. For instance, inequality-constrained least squares method is proposed to eliminate negative VTEC values in global ionosphere maps (Zhang et al. 2013). Meanwhile, WHU use IRI model to generate VTEC values where GNSS signals are not available (Wang et al. 2016). VTEC maps (from 1998 to 2016) are assessed through comparisons between IAACs' products and IGS final GIMs, as shown in Figure 1. The VTEC maps in IONEX format can be downloaded from the FTP of WHU ionosphere products: `ftp://pub.ionosphere.cn` .

A software platform is built for data processing and ionosphere analysis. This platform is comprised of function modules, including downloading global GNSS data, preprocessing and processing data, graphical visualization of TEC maps, releasing the ionosphere products, real-time delivering operating status of data processing as well as updating website. The website (`http://ionosphere.cn`) is established and maintained for the display of VTEC maps, DCB values and the other information. English version of the website will be updated soon. Besides, the efficiency of global ionospheric modeling is improved by using distributed computers with both desktops and servers in different two network

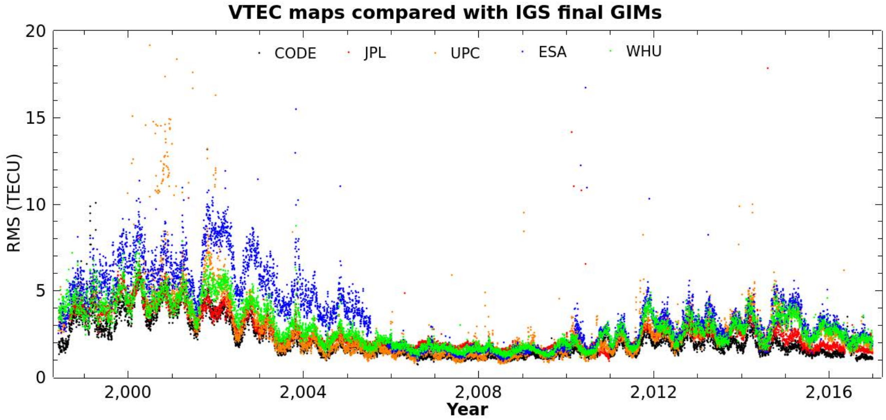

Figure 2: The RMS differences between IAACs' VTEC and GIMs from 1998 to 2016.

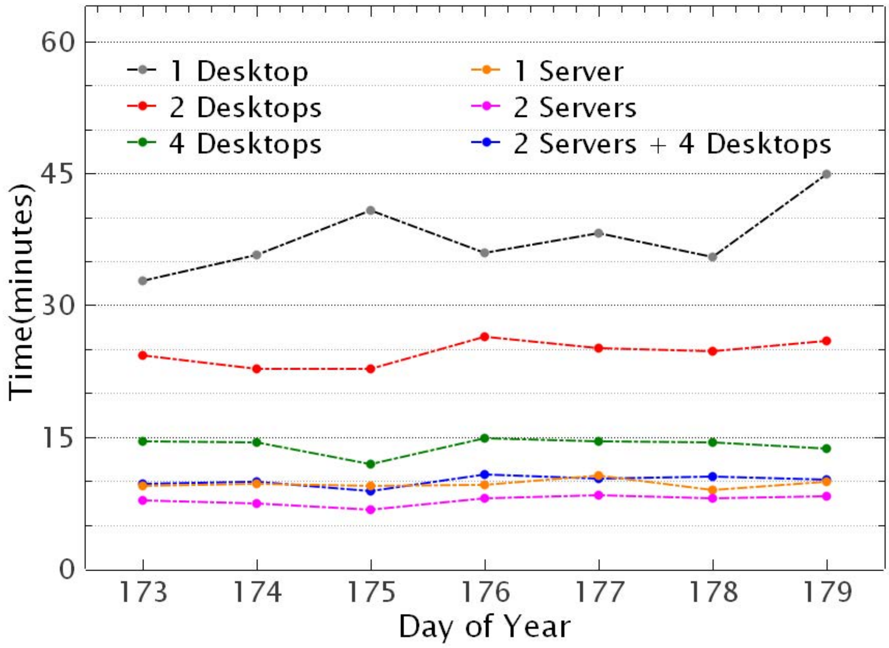

Figure 3: Test of global ionospheric modeling by using distributed computers.

segments. The time consumption of ionosphere modeling with different combination of distributed computers is presented in Figure 2. The efficiency of modeling is promoted apparently by using more computers. It's very helpful for algorithm testing of modeling, fast releasing of ionosphere products, post-time verification and prediction. However, it is better that the computers are installed in the same network segment so as to decrease the time consumption of data communication.

Recently, WHU develops software for editing the ionosphere products in IONEX format (called INX Editor). It supports Windows, Linux and Mac OS. INX Editor could edit and generate ionosphere products with customized interval, latitudes and longitudes. Moreover, it could convert the ionosphere products from IONEX format to binary format or from binary format to IONEX format. Figure 3 shows the operation instructions of INX Editor. Please consult the detailed introduction to this software by this webpage (`http://ionosphere.cn/inx.html`).

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EUREF Permanent Network Technical Report 2016

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1 Introduction

The 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). EPN observation data as well as the precise coordinates and the zenith total delay (ZTD) parameters of all EPN stations are publicly available. The EPN cooperates closely with the International GNSS Service (IGS); EUREF members are e.g. involved in the IGS Governing Board, the IGS Real–Time Working Group, the IGS Antenna Working Group, the IGS Troposphere Working Group, the IGS Infrastructure Committee, and the IGS Multi–GNSS Working Group and Experiment (MGEX). This paper gives an overview of the main changes in the EPN during the year 2016.

2 New EPN CB web site and monitoring

End of November 2016, the brand new EPN Central Bureau web site (http://epncb.eu/) was opened to the public. The improved web site has an extended station list with more station metrics, extended GNSS data quality checks (multi–GNSS) on both RINEX 2 and RINEX 3, improved station position time series, extended GNSS data availability and latency checks on both RINEX 2 and RINEX 3, full implementation of long RINEX3 station names, and extended monitoring of real–time data streams. In addition, the web site has a new responsive design to allow an improved visualization on tablets and smartphones.

Together with the metadata of the EPN densification network (see http://epncb.eu/_densification), the EPN CB now maintains and distributes centrally the metadata of 1479 European GNSS stations.

3 Tracking Network

Nineteen new stations were integrated in the EPN network in 2016 (see Table 1), bringing the total number of EPN stations to 294 (Figure 1 and Table 1) from which 32% belong to the IGS. The majority of the new EPN stations has individual antenna calibrations. End of 2016, 84% of the EPN stations provide GPS+GLONASS data and 35% provide Galileo data.

4 EUREF Working Group on "Multi–GNSS"

The EUREF Working Group on "Multi–GNSS" stimulates EUREF members to be actively involved in multi–GNSS activities. Figure 2 shows the improvement in data submissions using RINEX 3 data. Among the 332 EPN stations that delivered RINEX 2 data in December 2016, 147 also delivered RINEX 3 data. Unfortunately, the majority of RINEX meteo files are submitted using the old short file names. An example for the long file name convention of meteo RINEX 3 files was finally added to the RINEX 3 format description in November 2016.

Working Group members are also developing the GNSS software packages enabling multi–GNSS data quality checks: G–Nut/Anubis [1.2.1] (Václavovic and Dousa 2016) and BNC [2.12] (Weber et al. 2016). The results of their application can be seen on e.g. http://www.pecny.cz/GOP/index.php/gnss/data-center/eur-rnx3, http://pnac.swisstopo.admin.ch/pages/en/anubis_monitor_r3.html, and at the EPN Central Bureau http://epncb.eu/_networkdata/data_quality/.

End of July 2016, the first EPN Analysis Center (swisstopo; LPT; EUREF Mail 8644)

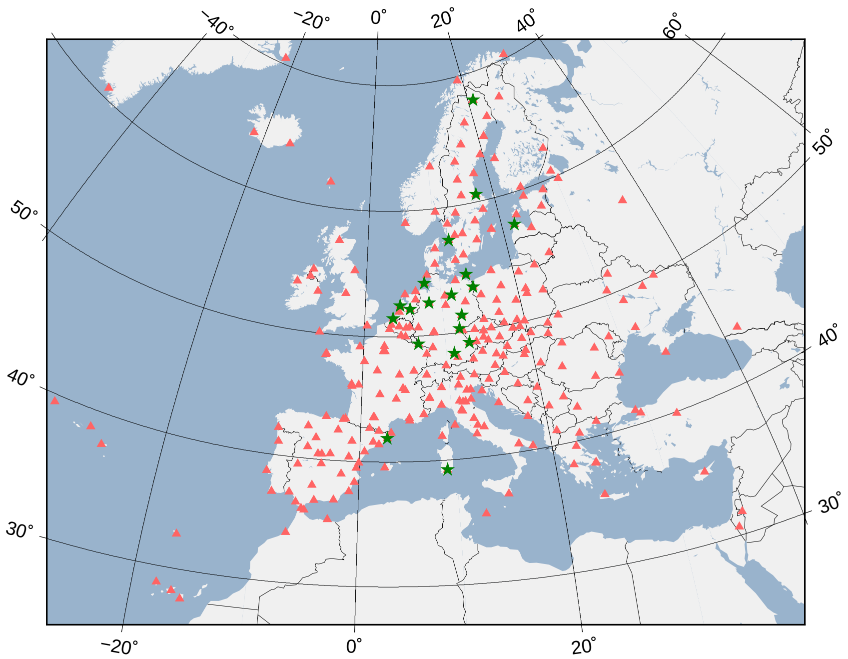

Figure 1: EPN tracking stations, status December 2016. * indicates new stations included in the network in 2016.

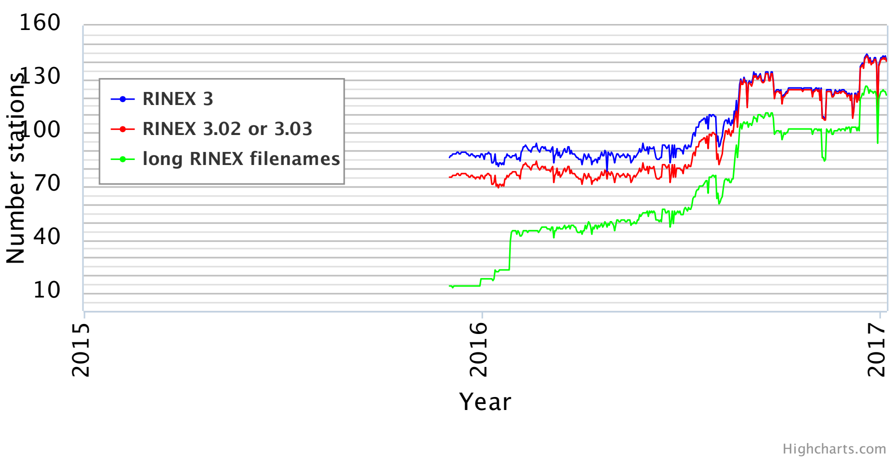

Figure 2: Number of stations providing RINEX 3 files in the EPN.

Table 1: New stations included in the EPN in 2016 (stations indicated with * also contribute to the IGS)

4–char ID	Location	Tracked Satellite Systems	Real–time	Antenna Calibration
AUBG	Augsburg, DEU	GPS GLO GAL		Individual (robot)
CAG1	Calgiary, ITA	GPS GLO GAL BDS		Type mean
CASE	Cassa de la Selva, ESP	GPS GLO GAL BDS	X	Individual (robot)
DIEP	Diepholz, DEU	GPS GLO GAL		Individual (robot)
DILL	Dillingen, DEU	GPS GLO GAL		Individual (robot)
GELL	Gellin, DEU	GPS GLO GAL		Individual (robot)
GOR2	Gorleben, DEU	GPS GLO GAL		Individual (robot)
HEL2	Helgoland Island, DEU	GPS GLO GAL		Individual (robot)
HOFJ	Hof, DEU	GPS GLO GAL		Individual (robot)
IJMU	Ijmuiden, NLD	GPS GLO	X	Individual (robot)
IRBE	Irbene, LVA	GPS GLO GAL		Type mean
KIR8*	Kiruna, SWE	GPS GLO GAL BDS	X	Individual (robot)
KOS1	Kootwijk, NLD	GPS GLO GAL BDS QZSS	X	Individual (robot)
LEIJ*	Leipzig, DEU	GPS GLO GAL BDS		Individual (robot)
MAR7*	Gavle, SWE	GPS GLO GAL BDS	X	Individual (robot)
ONS1*	Onsala, SWE	GPS GLO GAL BDS	X	Individual (robot)
SAS2	Sassnitz Island, DEU	GPS GLO GAL BDS		Individual (robot)
VLIS	Vlissingen, NLD	GPS GLO		Individual (robot)
WRLG	Bad Koetzting, DEU	GPS GLO GAL		Individual (chamber)

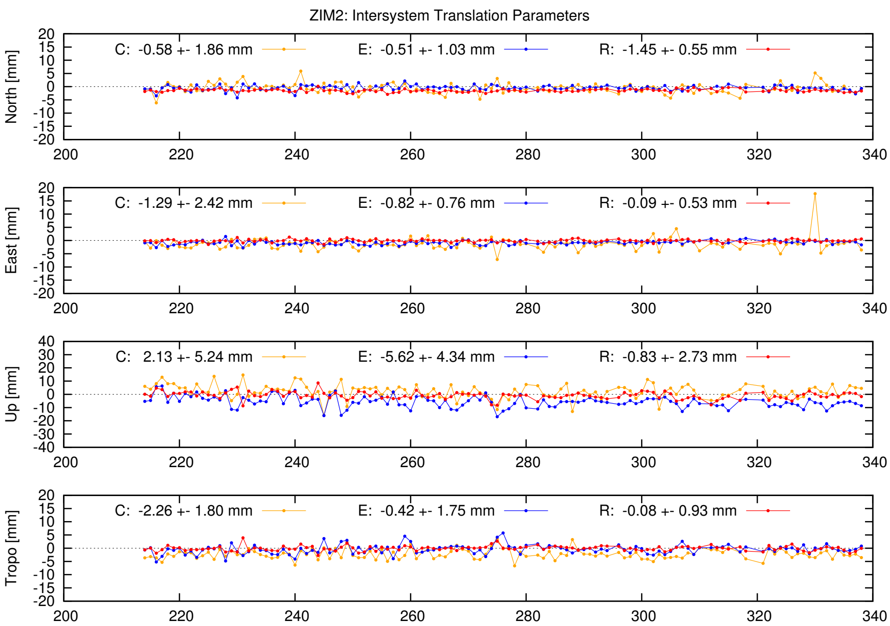

Figure 3: Daily Intersystem parameters for station ZIM2 for 125 days between August 1 and December 3 (differences of the coordinate and troposphere results of GLONASS (R), Galileo (E) and BeiDou (C) with respect to GPS (G)

started to submit solutions including Galileo and BeiDou data in addition to GPS and GLONASS using the development version Bernese GNSS Software (BSW), version 5.3. “Only” 15% additional observations are used compared to a GPS/GLO processing. The coordinate differences derived from a seven weeks parallel processing are small: Helmert standard deviation of about 0.3 mm in the horizontal and 0.7 mm in the vertical component. Figure 3 shows an example of the daily intersystem parameters for the station ZIM2. In extreme cases, usually with special antenna constructions, differences can reach several centimetres: -−35 mm vertical differences GPS–GLO for TRF2, horizontal differences GPS–GAL of more than 5 mm for OBE4, or the same magnitude for LINZ in case of horizontal coordinates GPS–BDS. Depending on the number of observations involved, a coordinate adjustment forcing estimation of a unique GPS/GLO/GAL/BDS value can therefore lead to different estimates between analysis centres using different satellite systems.

5 Data Analysis

5.1 Positions

The EPN Analysis Centres (AC) routinely process GNSS observations collected at EPN stations. In 2016, all 16 ACs (Table 2) were providing final weekly and daily coordinate solutions of their subnetworks, 10 ACs were providing also rapid daily solutions, and 3 ACs were providing ultra–rapid solutions. In 2016, LPT AC switched from a two system (GPS, GLONASS) to a four system (GPS, GLONASS, Galileo and BeiDou) processing scheme for its final products (see Section 4 for more details), and SUT AC switched the processing software from BSW version 5.0 to version 5.2. Also, IGN AC started providing final daily coordinate solutions of its subnetwork.

The Analysis Combination Centre (ACC) continued to combine the AC’s subnetwork solutions (provided in SINEX format) into official EPN solutions. In 2016, the ACC prepared new reports on final weekly and daily combinations and created new scripts for checking the correctness of receiver/antenna information given in AC SINEX files (stations with inconsistencies are excluded from the combination). Since January 2016, the reports from the weekly combinations are available on the EPN ACC website www.epnacc.wat.edu.pl), see (EPN LAC mail 2014).

At the end of 2016, the method for creating weekly combined EPN solutions was changed. Up to and including week 1924, the weekly combined solutions were created directly from the AC weekly solutions. Since week 1925 (November 27–December 4, 2016), the daily AC solutions are used for that purpose; at first the daily AC solutions are combined for each day of the week, and then the seven daily combined solutions are stacked into a weekly solution. The new approach consistently handles position outliers (for both AC and combined solutions) at the daily level, and mitigates inconsistencies between AC solutions,

Table 2: EPN Analysis Centres characteristics: provided solutions (W – final weekly, D – final daily, R – rapid daily, U – ultra–rapid), the number of analyzed GNSS stations (in brackets: stations added in 2016), used software (GOA – GIPSY–OASIS, BSW – Bernese GNSS Software), used GNSS observations (G – GPS, R – GLONASS, E – Galileo, C – BeiDou)

AC	Analysis Centre Description	Solutions	# sites	Software	GNSS
ASI	Centro di Geodesia Spaziale G. Colombo, ITA	W, D, R, U	50 (0)	GOA 6.2	G
BEK	Kommission für Erdmessung und Glaziologie, DEU	W, D, R	95 (11)	BSW 5.2	G, R
BKG	Bundesamt für Kartographie und Geodäsie, DEU	W, D, R, U	109 (15)	BSW 5.2	G, R
COE	Center for Orbit Determination in Europe, CHE	W, D	43 (0)	BSW 5.3	G, R
IGE	Instituto Geografico Nacional, ESP	W, D, R	78 (1)	BSW 5.2	G, R
IGN	Institut Geographique National, FRA	W, D, R	64 (0)	BSW 5.2	G
LPT	Federal Office of Topography swisstopo, CHE	W, D, R, U	59 (4)	BSW 5.3	G,R, E, C
MUT	Military University of Technology, POL	W, D	137 (3)	BSW 5.2	G, R
NKG	Nordic Geodetic Commission, Lantmateriet, SWE	W, D	76 (7)	BSW 5.2	G, R
OLG	Austrian Academy of Science, AUT	W, D	103 (2)	BSW 5.2	G
RGA	Republic Geodetic Authority, SRB	W, D	56 (0)	BSW 5.2	G, R
ROB	Royal Observatory of Belgium, BEL	W, D, R	84 (12)	BSW 5.2	G, R
SGO	FOMI Satellite Geodetic Observatory, HUN	W, D, R	42 (0)	BSW 5.2	G, R
SUT	Slovak University of Technology, SVK	W, D	56 (8)	BSW 5.2	G, R
UPA	University of Padova, ITA	W, D, R	49 (2)	BSW 5.2	G, R
WUT	Warsaw University of Technology, POL	W, D, R	106 (5)	BSW 5.2	G, R

which are observed when combining on a weekly level. The comparison for 70 weeks (1831–1900) showed that differences in weekly station positions between both approaches can reach in extreme cases up to 14 mm for horizontal components and up to 20 mm for vertical component. Apart from these cases, both approaches for creating weekly solutions were highly consistent: about 93% of station position residuals for horizontal components were smaller than 0.1 mm, and about 90% of vertical residuals were smaller than 0.25 mm. The weekly and daily analysis reports were updated accordingly to reflect this change in combination strategy.

The long–term combination, performed every 15 weeks, is compared to the national realizations of ETRS89 used in the different the countries. The difference plots, available under http://epncb.oma.be/_productsservices/coordinates/img/ETRF_EPN_HOR.JPG and http://epncb.oma.be/_productsservices/coordinates/img/ETRF_EPN_UP.JPG show clearly the homogeneous implementation of the various ETRS89 realizations in Europe.

5.2 Troposphere

Beside station coordinates, the 16 ACs also submit ZTD parameters on a routine basis in SINEX_TRO format. Fourteen ACs are also submitting horizontal gradients. The ZTDs and horizontal gradients are delivered with a sampling rate of 1 hour, on a weekly basis but in daily files. As regard to the troposphere mapping function, eight of the 16 ACs use the Vienna Mapping Function, and the remaining eight the Global Mapping Function.

In 2016, the ZTD estimates are provided for 280 stations by three or more ACs (compared to 260 in 2015)), for 10 stations by two, and for 6 stations just by one AC.

http://epncb.eu/_productsservices/sitezenithpathdelays/ shows the weekly mean bias (top) and the related standard deviation (bottom). They give insight into the agreement of the individual solutions with respect to the combined solution. The time series are based on EPN–Repro2 solutions (GPS week 834 until 1824) and on operational solutions afterwards.

5.3 Reprocessing

Within the Working Group "EPN Reprocessing" several strategies have been tested during the past years and finally the EPN–Repro2 reprocessing was finalized in 2016 using an analysis strategy based on agreed parameters, which were largely consistent with the strategies of the IGS. The entire EPN network was processed with BSW 5.2, GAMIT 10.5 and GIPSY 6.2 and two large subnetworks of the EPN were analyzed with BSW 5.2. Each AC provided daily coordinates and troposphere parameters for their network as well as weekly solutions for the period 1996 until spring 2013. The combination of the daily and weekly solutions, done by the ACC, has proven that the individual solutions are very homogeneous. The main difference between some of the strategies was the application of individual antenna calibration correction models or type mean corrections only. While the IGS applies only type mean corrections, the EPN considers also individual corrections when available. The impact of these different antenna models was analyzed and it has been shown that the impact on the reference frame is negligibly small for the EPN (Araszkiewicz and Völksen 2016). The SINEX files of the individual ACs and the combined products of the ACC are available from the data server at the BKG.

In parallel, a tropospheric combined solution for the period 1996–2014 has been computed (Pacione et al. 2016). For each EPN station, plots on ZTD time series, ZTD monthly mean, comparison versus Radiosonde data (if collocated), are available at the EPN Central Bureau (http://epncb.eu/_productsservices/troposphere/).

The EPN–Repro2 tropospheric products (Pacione 2016) have been evaluated against radiosonde data and European Centre for Medium–Range Weather Forecasts (ECMWF) reanalysis (ERA–Interim) data. Assessment of the EPN–Repro1 and Repro2 with respect to radiosonde data shows an improvement of approximately 3–4% in the overall standard deviation. Evaluation of the EPN–Repro1 and Repro2 with respect to the ERA–Interim re–analysis showed the 8–9% improvement of the latter over the former in both, overall standard deviation and systematic error. EPN–Repro2 will be used as a reference data set for climate monitoring over Europe in cooperation with the COST Action ES1206 'GNSS4SWEC'.

6 Densification of the IGS and EPN

Based on the EPN combined weekly SINEX solutions (back to mid–1996), a multi–year EPN position and velocity solution is maintained as the densification of the IGS realization of the ITRS in Europe. This solution is computed with the CATREF software, tied to IGb08, and is updated each 15 weeks. Following the publication of ITRF2014, a new multi–year EPN solution including EPN–Repro2 has been computed for test purposes and prepared for implementation (Kenyeres et al. 2016a)). The final computation and publication will be done, when the IGS realization of ITRF2014 will be published. The EPN multi–year product files (including a discontinuity table and associated residual position time series) are available at ftp://epncb.eu/pub/station/coord/EPN. More details can be found in http://epncb.eu/_productsservices/coordinates/.

EUREF also combines the weekly SINEX solutions provided by European countries for their dense national active GNSS networks with the weekly EPN SINEX solution. All available weekly combined solutions are stacked to obtain a consistent cumulative position/velocity solution. Both combinations (the weekly and the multi–year) are also performed using the CATREF software applying exactly the same approach and parameters as for the generation of the EPN IGb08 densification ensuring full consistency from the global to the local level. The total number of stations included in the EPN densification exceeds 3000 as of December 2016. 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 European Plate Observing System (EPOS) and the European Positioning System (EUPOS). This work is still in progress (see Kenyeres et al. (2016b)).

7 Stream and Product Dissemination

While the number of EPN stations grew also in 2016, the number of EPN stations providing real–time data could not keep the pace. Beside possible technical restrictions, the main reason seems to be related to financial or commercial restrictions.

The number of stations providing real–time observation streams in the RTCM 3.2 Multiple Signal Messages (MSM) format grew significantly. However, almost all of the streams were provided as raw data streams, so that a conversion tool has to be applied to derive RTCM messages. As of end of November 2016, 17 EPN stations were providing RTCM 3.2 data streams, the majority available from the MGEX caster of BKG, http://mgex.igs-ip.net. In addition to GPS and GLONASS, most of the streams contain Galileo, BeiDou, QZSS and SBAS.

The monitoring of the three EUREF broadcasters at the EPN Central Bureau was extended. In addition to the RTCM 2 and 3.1 format, also the RTCM 3.2 data stream content is now verified against the proposed content of the sourcetable, see http://epncb.eu/_networkdata/data_access/real_time/.

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SIRGAS Regional Network Associate Analysis Centre Technical Report 2016

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1 Introduction

The SIRGAS Reference Frame is currently composed of 411 continuously operating GNSS stations (Figure 1). It comprises two hierarchy levels (Brunini et al. 2012): a core network (SIRGAS-C, Sánchez et al. (2015a)) providing the primary link to the global ITRF; and national reference networks (SIRGAS-N) improving the geographical density of the reference stations to ensure the accessibility to the reference frame at national and local levels. The SIRGAS reference stations are processed by 10 SIRGAS processing centres (Cioce et al. 2016a):

- Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (Germany), Sánchez (2016)
- CEPGE: Centro de Procesamiento de Datos GNSS del Ecuador, Instituto Geográfico Militar (Ecuador)
- CNPDG-UNA: Centro Nacional de Procesamiento de Datos GNSS, Universidad Nacional (Costa Rica), Moya et al. (2016)
- CPAGS-LUZ: Centro de Procesamiento y Análisis GNSS SIRGAS de la Universidad del Zulia (Venezuela), Cioce et al. (2016b)
- IBGE: Instituto Brasileiro de Geografia e Estatistica (Brazil)
- IGAC: Instituto Geográfico Agustń Codazzi (Colombia)
- IGM-Cl: Instituto Geográfico Militar (Chile), Parra (2016)

- IGN-Ar: Instituto Geográfico Nacional (Argentina)
- INEGI: Instituto Nacional de Estadística y Geografía (Mexico)
- SGM: Servicio Geográfico Militar (Uruguay), Suárez (2016)

2 Routine processing of the SIRGAS reference frame

The SIRGAS processing centres follow unified standards for the computation of loosely constrained weekly solutions for the station positions. These standards are generally based on the conventions outlined by the IERS and the GNSS-specific guidelines defined by the IGS; with the exception that in the individual SIRGAS solutions the satellite orbits and clocks as well as the Earth orientation parameters (EOP) are fixed to the final weekly IGS, and positions for all stations are constrained to ± 1 m (to generate the loosely constrained solutions in the SINEX format). INEGI (Mexico) and IGN-Ar (Argentina) employ the software GAMIT/GLOBK (Herring et al. 2010); the other local processing centres use the Bernese GPS Software V. 5.2 (Dach et al. 2015). The processing standards applied at present are described in (Sánchez and Drewes 2016). The individual solutions are combined by the SIRGAS combination centres operated by the DGFI-TUM (Sánchez et al. 2012; Sánchez 2016) and the IBGE (Costa et al. 2012). In charge of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS), DGFI-TUM processed the entire SIRGAS reference network from June 1996 until August 2008 (Brunini et al. 2012; Sánchez et al. 2012). Now, it is responsible for

- processing the SIRGAS-C core network (Figure 1), Sánchez (2016)
- combining the core network with the national reference networks (Figure 2 and 3), Sánchez (2016);
- ensuring that the SIRGAS processing strategy meets the IERS standards and IGS guidelines;
- developing strategies to guarantee the reliability of the reference frame over time, this includes the estimation of the reference frame kinematics (Figure 4) and modelling crustal deformation in the SIRGAS region (Figure 5), Sánchez and Drewes (2016);
- making available the SIRGAS products via `www.sirgas.org` and `ftp.sirgas.org`.

At present, the SIRGAS efforts are concentrated on the second reprocessing of the reference network backwards until January 1997 using the IGS14 as the reference frame.

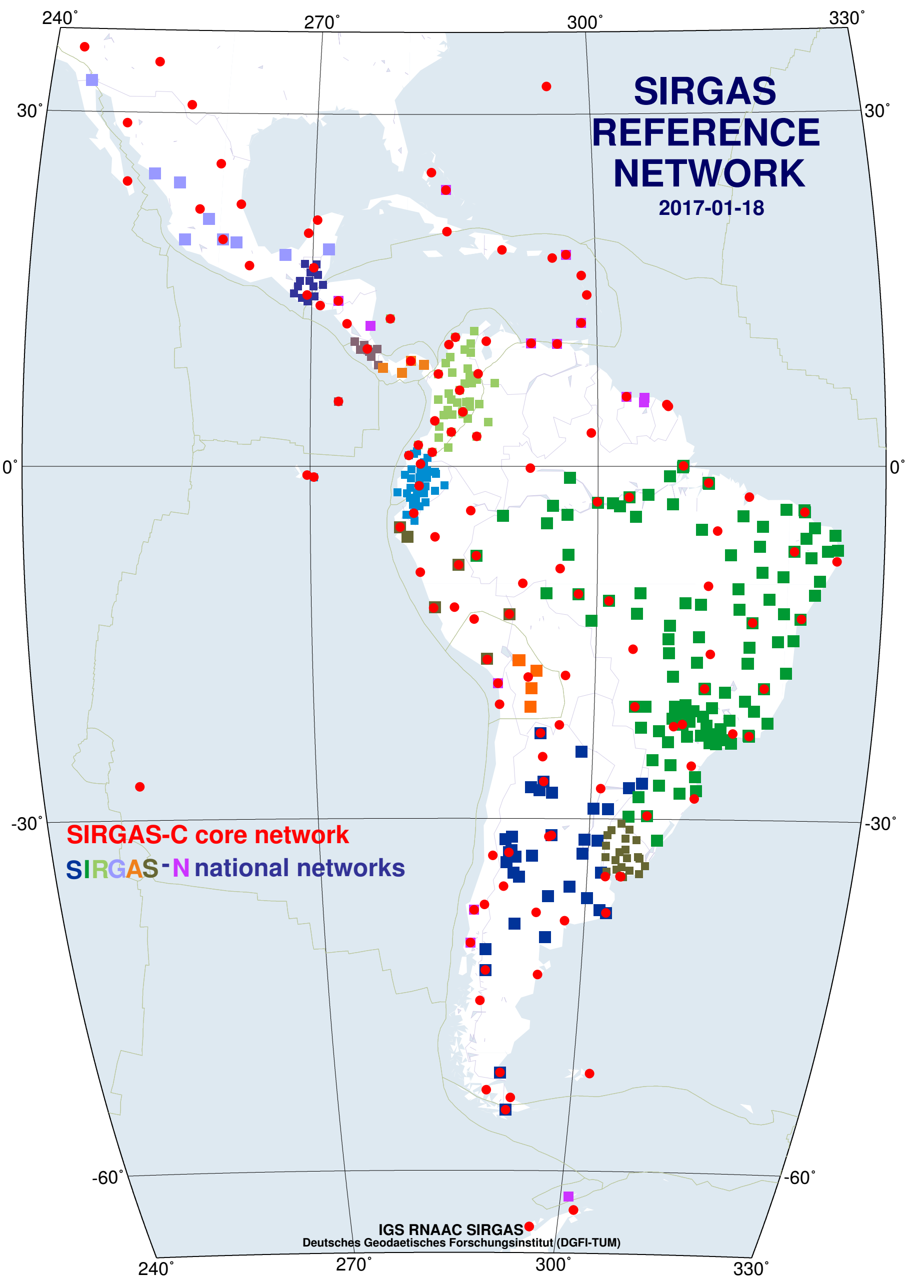


Figure 1: Core and national networks within the SIRGAS Reference Frame (January 2017)

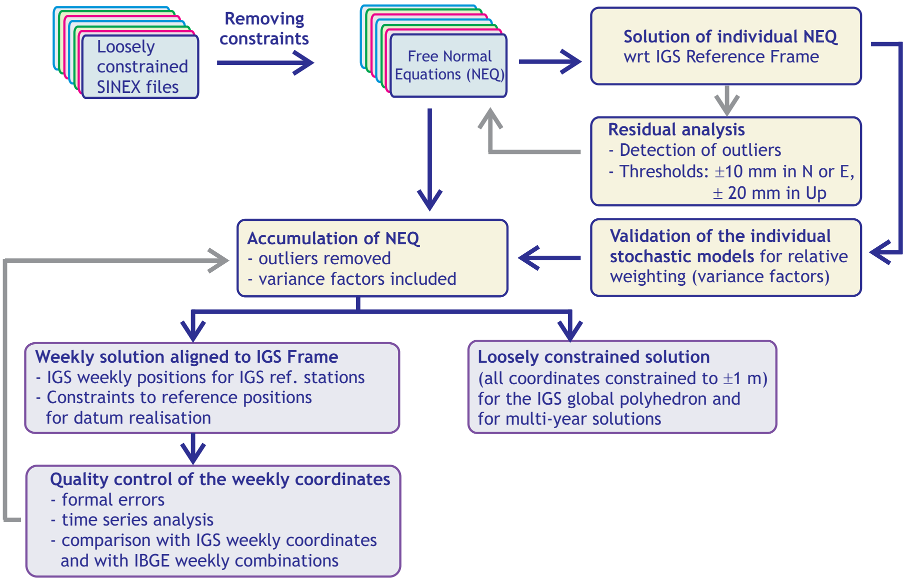
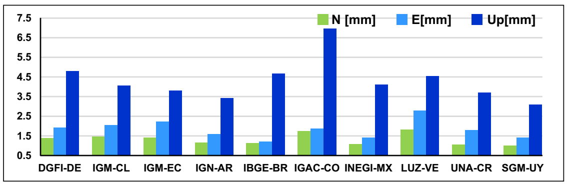


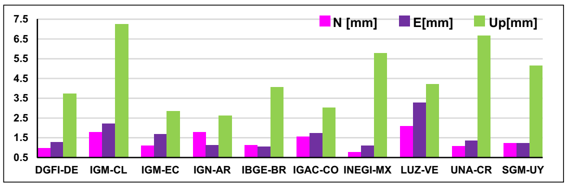
Figure 2: DGFI-TUM strategy for the combination of the weekly solutions delivered by the SIRGAS processing centres

3 Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America

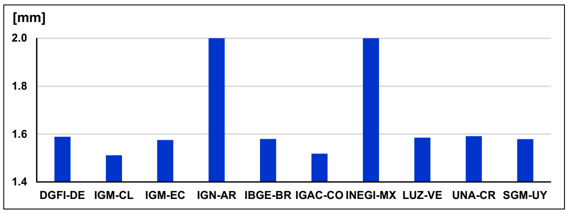
The Maule 2010 earthquake in Chile generated the largest displacements of geodetic observation stations ever observed in terrestrial reference frames (Sánchez et al. 2013). Coordinates changed by up to 4 m, and deformations were measurable in distances of up to more than 1000 km from the epicentre. The station velocities in the regions adjacent to the epicentre 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 et al. 2015a). The 2010 Baja California earthquake in Mexico caused displacements on the dm level also followed by anomalous velocity changes. To ensure the long-term stability of the SIRGAS reference frame, the transformation of station positions between different epochs requires the computation of reliable continuous surface deformation (or velocity) models. To achieve this objective, DGFI-TUM, acting as the IGS RNAAC SIRGAS, computed a new continental continuous crustal deformation model for Latin America and the Caribbean inferred from GNSS (GPS+GLONASS) measurements gained after the strong earthquakes occurred in 2010. It is based on a multi-year velocity solution for a network of 456 continuously operating GNSS stations and covering a five years period. This new deformation model, called VEMOS2015 (Velocity Model for SIRGAS 2015), is computed using the least square collocation (LSC) approach with empirically determined covariance functions as shown in Sánchez and Drewes (2016). The result is summarised as follows: While the effects of the Baja California earthquake can



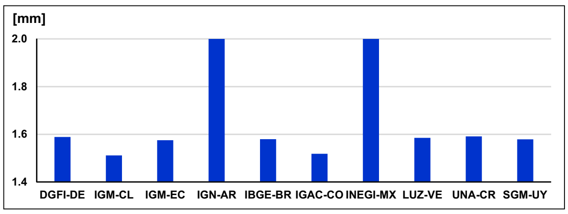
a) Mean RMS values for the weekly repeatability of the station positions within the SIRGAS processing centre solutions: about ± 1.8 mm in the North and the East, and ± 3.5 mm in the height. Large values in the IGAC solutions are unclear.



b) Mean RMS values of the station position residuals for each analysis centre with respect to the IGS weekly final solutions. This comparison allows to assess the accuracy of the individual solutions: about ± 1.3 mm in the North and the East, and ± 4 mm in the vertical component. Large values in the vertical component presented by the INEGI-MX, LUZ-VE and UNA-CR solutions are caused by Mexican stations processed by the IGS with a wrong antenna model. Large residuals in the IGM-CL solutions are caused by a lack of IGS reference stations in the southern part of the SIRGAS region.



c) Standard deviation of station positions after solving the individual solutions with respect to the IGS reference frame. These values represent the formal errors of the individual solutions. Individual standard deviations agree quite well: ± 1.51 mm (IGM-CL, IGAC-CO), ± 1.58 mm (DGFI-DE, IGM-EC, IBGE-BR, LUZ-VE, UNA-CR, SGM-UY), ± 2.0 mm (IGN-AR, INEGI-MX).



d) Quality evaluation of the combined SIRGAS solutions: The coordinate repeatability of the weekly combinations provides an estimate for the accuracy (internal consistency) of the weekly combinations of about ± 1.2 mm in the horizontal component and about ± 3.2 mm in the vertical one. The RMS values derived from the time series for station positions and with respect to the IGS weekly coordinates indicate that the reliability of the network (external precision) is about ± 1.5 mm in the horizontal position and ± 4.2 mm in the height. The differences with respect to the IBGE weekly combinations are at the expected level (less than 0.5 mm).

Figure 3: Quality control of the individual solutions delivered by the SIRGAS processing centres as well as of the combined solutions computed by the IGS RNAAC SIRGAS (mean values from 01-09-2015 to 10-10-2016, 58 weeks).

be considered as local, the effects of the Maule earthquake changed the surface kinematics of a large area (between the latitudes 30°S - 45°S from the Pacific to the Atlantic coasts). Before the Maule earthquake, the strain rate field in this area showed a strong west-east compression with maximum rates of about 0.40 μstrain/a between latitudes 38°S and 44°S (Figure 6). In accordance, the deformation vectors were roughly parallel to the plate subduction direction and their magnitudes decreased with the distance from the subduction front. After the earthquake, the largest compression (0.25 μstrain/a) occurs between the latitudes 37°S and 40°S with a N30°E direction. The maximum extensional strain rate (0.20 to 0.35 μstrain/a) is observed in the Sub-Andean zone in the Patagonia south of latitude 40°S. The extensional axes rotate from a N30°E direction in the central Araucania zone to a westerly direction of N72°W in the western part of Patagonia. In the northern region of parallel 35°S, the extension is also directed to the Maule zone (S45°W) but with quite smaller rates ($<$ 0.06 μstrain/a). This complex kinematics causes a large counter clockwise deformation pattern rotating around a point south of the epicentre (35.9° S, 72.7°W). The magnitude of the deformation vectors varies from 1 mm/a close to the rotation point up to 22 mm/a near the 2010 earthquake epicentre. The direction of the largest deformation vectors points to the epicentre. VEMOS2015 covers the region from 55°S, 110°W to 32°N, 35°W with a spatial resolution of 1° x 1°. The average prediction uncertainty is ±0.6 mm/a in the north-south direction and ±1.2 mm/a in the east-west direction. The maximum is ±9 mm/a in the Maule deformation zone while the minimum values of about ±0.1 mm/a occur in the stable eastern part of the South American plate.

Station coordinates, station position time series as well as velocity and deformation fields computed by the IGS RNAAC SIRGAS within the model VEMOS 2015 are available through the PANGAEA (Data Publisher for Earth and Environmental Science) platform at: `https://doi.pangaea.de/10.1594/PANGAEA.835100` and `https://doi.pangaea.de/10.1594/PANGAEA.863131`.

4 Acknowledgements

The operational infrastructure and results described in this report are only possible thanks to the active support of many Latin American and Caribbean colleagues, who not only make the measurements of the stations available, but also operate SIRGAS analysis centres 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. We are also grateful to the IGS, UNAVCO, and the NGS for making available some of the invaluable GNSS data sets used by the IGS RNAAC SIRGAS. 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`.

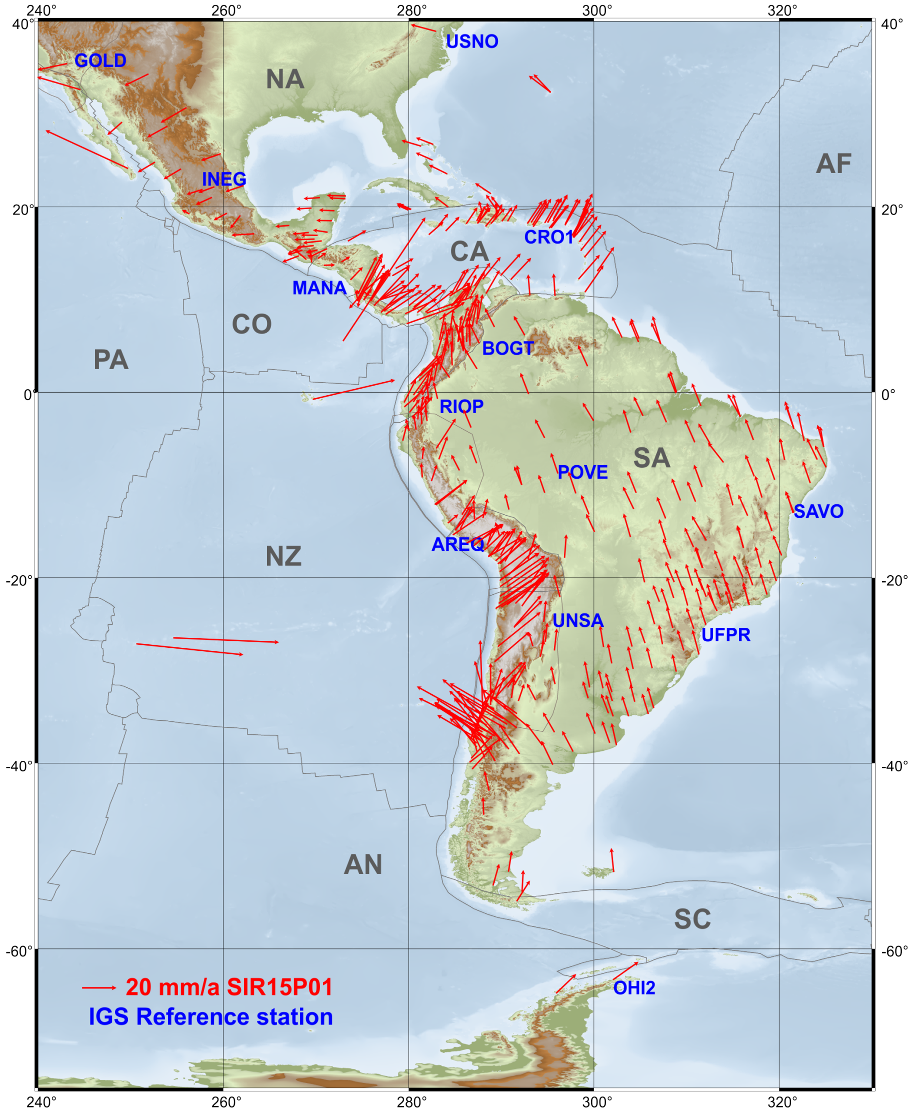


Figure 4: Kinematics of the SIRGAS reference frame. Station coordinates refer to the IGb08 frame, epoch 2013.0. Averaged RMS precision for the considered 456 stations is ±1.8 mm for the station positions, and ±1.0 mm/a for the velocities (taken from (Sánchez and Drewes 2016)).

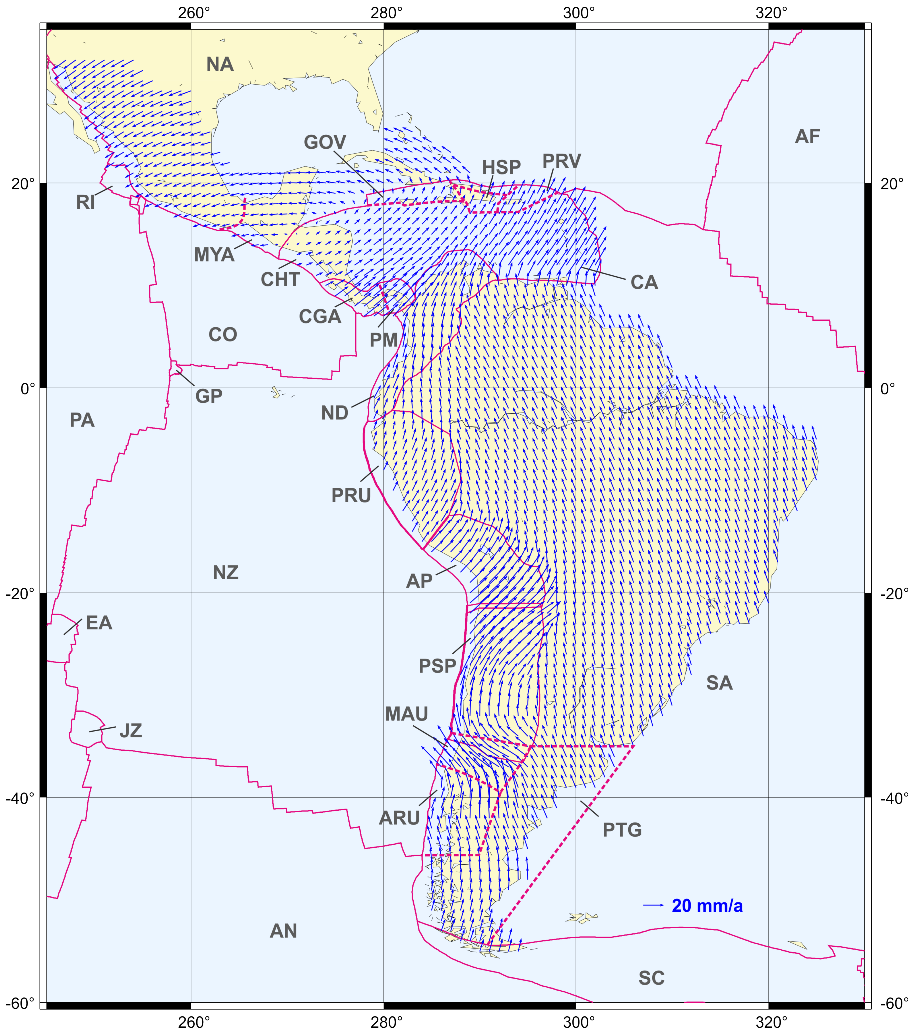


Figure 5: Velocity field VEMOS2015 (taken from (Sánchez and Drewes 2016)). AF: Africa, AN: Antarctica, AP: Altiplano, CA: Caribbean, CO: Cocos, EA: Easter Island, GP: Galapagos, JZ: Juan Fernandez, NA: North America, ND: North Andes, NZ: Nazca, PA: Pacific, PM: Panama, RI: Rivera, SA: South America, SC: Scotia, GOV: Gonave, HSP: Hispaniola, PRV: Puerto Rico and Virgin Islands, MAY: Maya, CHT: Chortis, CGA: Chorotega, PRU: Peru, PSP: Puna-Sierras Pampeanas, MAU: El Maule, ARU: Araucania, PTG: Patagonia.

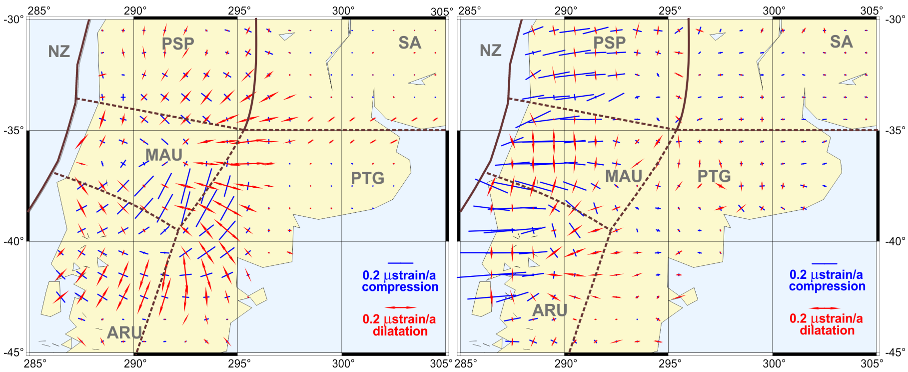


Figure 6: Strain field after (2010 to 2015, left) and before (2000 to 2008, right) the Maule 2010 earthquake (taken from (Sánchez and Drewes 2016)). NZ: Nazca, SA: South America, PSP: Puna-Sierras Pampeanas, MAU: El Maule, ARU: Araucania, PTG: Patagonia.

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Part III

Data Centers

Infrastructure Committee Technical Report 2016

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E–mail: Ignacio.Romero@esa.int

1 Introduction

The IGS Infrastructure Committee (IC) is a permanent body established to ensure that the data requirements for the highest quality GNSS products are fully satisfied while also anticipating future needs and evolving circumstances. Its principal objective is to assure that the IGS infrastructure components that collect and distribute the IGS tracking data and information are sustained to meet the needs of principal users, in particular the IGS analysis centers, fundamental product coordinators, pilot projects, and working groups.

The IC fulfills this objective by coordinating and overseeing facets of the IGS organization involved in the collection and distribution of GNSS observational data and information, including network stations and their configurations (instrumentation, monumentation, communications, etc), and data flow.

The IC establishes policies and guidelines, where appropriate, working in close collaboration with all IGS components, as well as with the various agencies that operate GNSS tracking networks. The IC interacts with International Association of Geodesy (IAG) sister services and projects – including the International Earth Rotation and Reference Systems Service (IERS) and the Global Geodetic Observing System (GGOS) – and with other external groups (such as the RTCM) to synchronize with the global, multi–technique geodetic infrastructure.

Current Members: appointed Dec, 2015 for terms up to Dec 2017;

- Carine Bruyninx (ROB)
- Lou Estey (UNAVCO)
- Nicholas Brown (GA)
- Nacho Romero – Chairman – (ESOC)

- Brian Donahue (NRCan)
- Wolfgang Soehne (BKG)

Ex–officio Members:

- Steve Fisher – Central Bureau
- David Maggert – Network Coordinator
- Michael Moore – Analysis Coordinator
- Tom Herring – Analysis Coordinator
- Axel Ruelke – Real time Working Group Chair
- Bruno Garayt – Reference Frame Coordinator
- Carey Noll – Data Center Working Group Chair
- Michael Coleman – Clock Products Coordinator

2 Summary of Activities in 2016

Over 2016 the IC has supported the Network Coordinator on answering questions from IGS product and data users, plus helping with contacts and new station additions in Taiwan, China, Malaysia, Thailand, etc. This has also included making sure the regional reference frame organizations such as APREF, etc are including as many of their own region's stations in their station position solutions as possible. The IC has participated in the improvements to the IGS website network pages in terms of map selectors, dormant station indicators, etc.

In terms of the very important RINEX 3 data file integration into the IGS the switch to long name data files has been completed over 2016 with 96.7% of RINEX3 files now submitting data files using the correct long names. The IC created a new utility to generate the data file longnames 'RX3name' to assist all station operators from all major networks to generate the correct longnames based on the existing short names they may be using; http://acc.igs.org/software/RINEX3_longname.pdf

The usage of new station long names has been discussed with all product generating working groups for inclusion in the IGS products; clock files, SINEX station position files and Tropo SINEX format. The adoption of the new formats should take place during 2017 after a long consultation period with analysis centers and product users.

3 Activities in 2017

During 2017 the IC will be concentrating on the following issues;

- RINEX 3 station name product inclusion
- Including the TIGA related infrastructure needs as part of the IGS network considerations.
- Improve the usage of the IGS network stations and the reporting back to station operators of how their stations are doing
- Continued contacts and investigation on the establishments of an IGS–wide NBS repository

CDDIS Global Data Center Technical Report 2016

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1 Introduction

The Crustal Dynamics Data Information System (CDDIS) is NASA's data archive and information service supporting the international space geodesy community. For over 35 years, the CDDIS has provided continuous, long term, public access to the data (mainly GNSS-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 2016 are summarized below; this report also includes any recent changes or enhancements made to the CDDIS.

2 System Description

2.1 Computer Infrastructure

The CDDIS archive of IGS data and products are accessible worldwide through anonymous ftp (ftp://cddis.nasa.gov). The CDDIS has also implemented web-based access to the archive (https://cddis.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 facility is fully redundant with primary and secondary/failover systems. Until December 2016, the CDDIS server configuration consisted of multiple incoming and outgoing servers dedicated to specific functions and was equipped with 32 Tbytes of online storage. Throughout early 2016, a new virtual machine (VM) based system configured with 100 Tbytes of unified storage was tested within the EOSDIS computer facility and network infrastructure. The new CDDIS computer system, shown in Figure 2.1, became operational on December 01, 2016. This new system configuration provides a more reliable/redundant environment (power, HVAC, 24-hour on-site emergency personnel, etc.) and network connectivity; a disaster recovery system is installed in a different location on the GSFC campus for rapid failover when required. The new system location addresses a key operational issue CDDIS has experienced over the past several years: the lack of consistent and redundant power and cooling in its computer facility. Furthermore, multiple, redundant 40G network switches are available to take full advantage of a high-performance network infrastructure by utilizing fully redundant network paths for all outgoing and incoming files along with dedicated 10G network connections between its primary operations and its backup operations. The use of the virtual machine technology provides multiple instance services for a load balancing configuration and allows for VM instances to be increased or decreased due to demand. Furthermore, the VM technology allows for system maintenance (patching, upgrades, etc.) to proceed without any downtime or interruption to user access. The large, unified storage system will easily accommodate future growth of the archive and facilitate near real-time replication between its production and disaster recovery sites. The entire archive is also mirrored to traditional storage arrays for additional complete copies of the archive.

2.2 Web Applications

The CDDIS maintains two applications for querying site information or archive contents. The Site Log Viewer (https://cddis.nasa.gov/Data_and_Derived_Products/\discretionary{-}{}{}SiteLogViewer/index.html) is an application for the enhanced display and comparison of the contents IAG service site logs; currently the IGS, ILRS, and IDS site logs are viewable through this application. 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

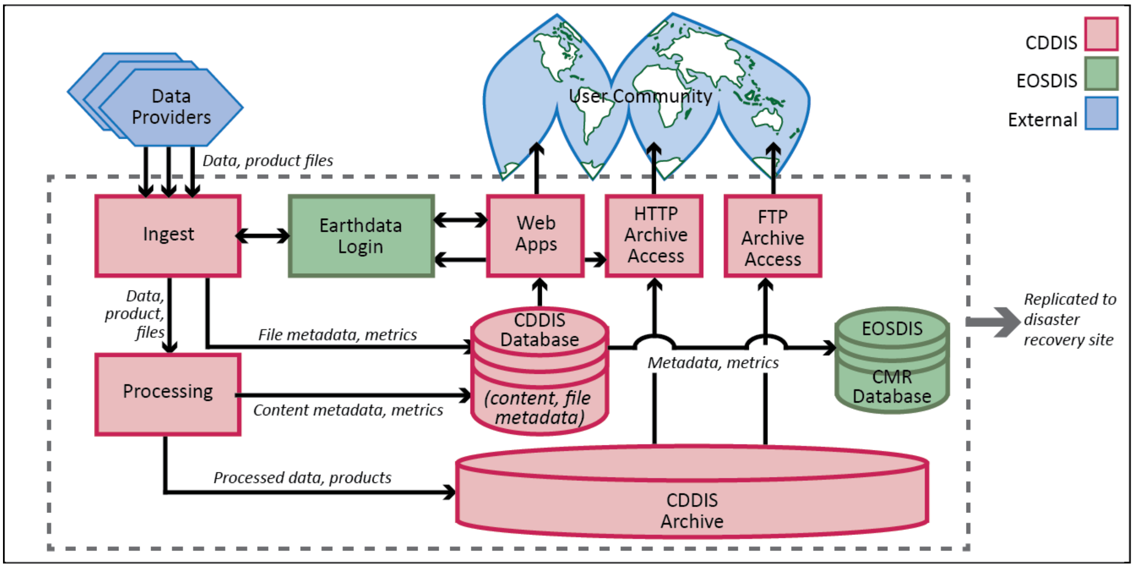

Figure 1: System architecture overview diagram for the new CDDIS facility installation within the EOSDIS infrastructure.

systems having particular equipment or characteristics. Access to IVS/VLBI site logs will be provided in a future release of the application.

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

3 Archive Contents

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 17.5 Tbytes in size (over 190 million files) of which 16.5 Tbytes (95%) is devoted to GNSS data (15.4 Tbytes), products (1.1 Tbytes), and ancillary information. All data and products are accessible through subdirectories of ftp://cddis.nasa.gov/gnss.

Table 1: GNSS Data Type Summary.

Data Type	Sample Rate	Data Format	Available
Daily GNSS	30 sec.	RINEX V2	Since 1992
Daily GNSS	30 sec.	RINEX V3	Since 2016
Hourly GNSS	30 sec.	RINEX V2	12+ years
Hourly GNSS	30 sec.	RINEX V3	Since 2016
High-rate GNSS	1 sec.	RINEX V2	Since 2001
High-rate GNSS	1 sec.	RINEX V3	Since 2016
Satellite GPS	10 sec.	RINEX V2	2002-2012

Table 2: GNSS Data Archive Summary for 2016.

Data Type	Avg. No. Sites/Day	No. Unique Sites	Avg. Volume/Day	Total Volume/Year	No. Files	Directory Location
Daily GNSS (V2 filename)	495	545	1,570 MB	580 GB	828K	/gnss/data/daily
Daily GNSS (V3 filename)	210	111	215 MB	80 GB	121K	/gnss/data/daily
Hourly GNSS (V2 filename)	385	344	680 MB	250 GB	7,455K	/gnss/data/hourly
Hourly GNSS (V3 filename)	119	55	160 MB	60 GB	1,627K	/gnss/data/hourly
High-rate GNSS (V2 filename)	335	204	4,110 MB	1,500 GB	12,518K	/gnss/data/highrate
High-rate GNSS (V3 filename)	36	22	935 MB	345 GB	891K	/gnss/data/highrate
High-rate GNSS (V3 filename)	36	22	935 MB	345 GB	891K	/gnss/data/highrate

3.1 GNSS Data

3.1.1 Main Data Archive

The user community has access to GNSS data available through the on-line global data center archives of the IGS. Over 70 operational and regional IGS data centers and station operators make data (observation, navigation, and meteorological) available in RINEX format to the CDDIS from receivers on a daily, hourly, and sub-hourly basis. The CDDIS also accesses the archives of other 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. Table 3.1.1 and 3.1.1 below summarizes the types of IGS GNSS data sets available in the CDDIS in the operational, non-campaign directories of the GNSS archive.

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*. Since January 2016, RINEX V3 data, using the V3 filename specification, are archived with the RINEX V2 data (see Section 3.1.2 for more information).

The CDDIS archives three major types/formats of GNSS data, daily, hourly, and high-rate sub-hourly, all in RINEX format, as described in Table 1a; the network distribution of submitted files is shown in Figure 2. Daily RINEX data are quality-checked, summarized (using UNAVCO's teqc software), and archived to public disk areas in subdirectories by year, day, and file type; the summary and inventory information are also loaded into an on-line database. Over 177K daily station days from 545 distinct GNSS receivers were

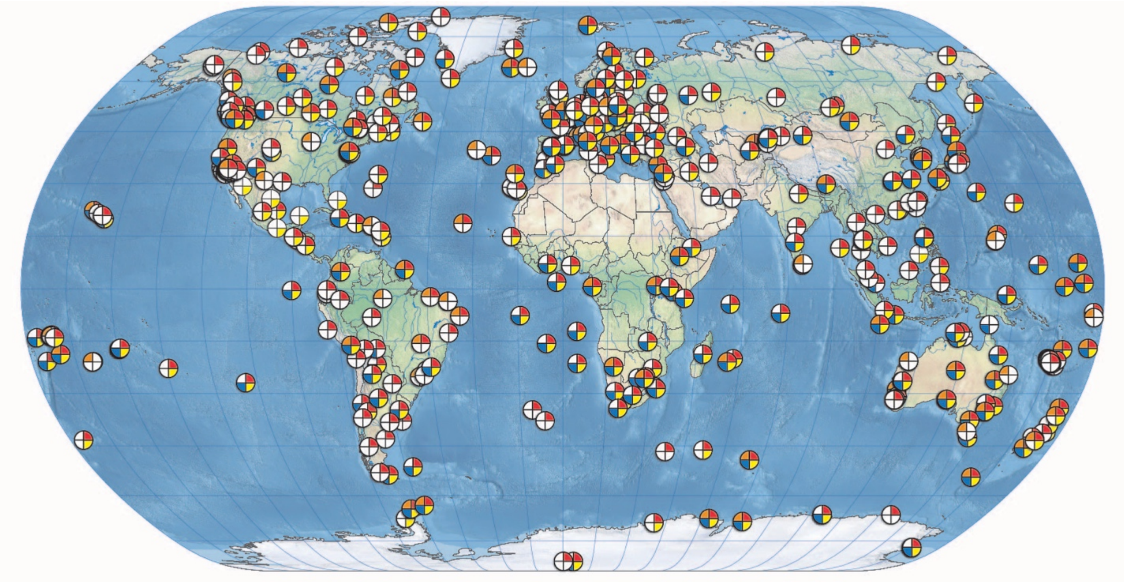

Figure 2: CDDIS GNSS archive includes data in daily (red), hourly (yellow), sub-hourly (blue), and/or real-time (orange) increments. Hourly, sub-hourly, and real-time data allow analysts to generate products for applications needing more frequent updates.

archived at the CDDIS during 2016; 209 RINEX V3 sites (including 46 RINEX V3-only) supplied RINEX V3 data. 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.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 385 unique hourly sites (over 7.4 million files) were archived during 2016; 119 hourly sites provided data in RINEX V3 format (12 RINEX V3-only).

High-rate (one-second sampling rate) GNSS data are made available 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 335 unique high-rate sites (over 12 million files) were archived in the CDDIS in 2016; 36 high-rate sites provided data in RINEX V3 format (20 RINEX V3-only).

The CDDIS generates global broadcast ephemeris files (for both GPS and GLONASS) on a daily and hourly basis. The hourly concatenated broadcast ephemeris files are derived from the site-specific ephemeris data files for each hour and are appended to a single file that contains the orbit information for all GPS and GLONASS satellites for the day up through that hour. The merged ephemeris data files, named *hourDDD0.YYn.Z*, are

Table 3: GNSS MGEX Data Archive Summary for 2016.

Data Type	Avg. No. Sites/Day	No. Unique Sites	Avg. Volume/Day	Total Volume/Year	No. Files	Directory Location
Daily GNSS	111	210	121K	375 MB	136 GB	/gnss/data/campaign/mgex/daily
Hourly GNSS	55	120	1,630K	80 MB	29 GB	/gnss/campaign/mgex/data/hourly
High-rate GNSS	22	36	890K	2,300 MB	740 GB	/gnss/campaign/mgex/data/highrate

then copied to the day's subdirectory within the hourly data file system. Within 1-2 hours after the end of the UTC day, after sufficient station-specific navigation files have been submitted, this concatenation procedure is repeated to create the daily broadcast ephemeris files (both GPS and GLONASS), using daily site-specific navigation files as input. These daily broadcast files, named *brdcDDD0.YYn.Z* and *brdcDDD0.YYg.Z*, are then copied to the corresponding subdirectory under the daily file system. Users can thus download this single, daily (or hourly) file to obtain the unique navigation messages rather than downloading multiple broadcast ephemeris files from the individual stations.

The CDDIS generates and updates "status" files, (*/gnss/data/daily/YYYY/DDD/ YYDDD.status* for RINEX V2 data and *YYDDD.V3status* for RINEX V3 data) that summarize the holdings of daily GNSS data. 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 (for RINEX V2 data). The user community can thus view a snapshot of data availability and quality by checking the contents of such a summary file.

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 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*).

3.1.2 IGS Products

The CDDIS worked with the IGS Infrastructure Committee (IC) to integrate data in RINEX V3 format into the operational, main archives at the IGS Global Data Centers. The resulting "RINEX V3 Transition Plan" addressed a key recommendation from the IGS 2014 Workshop: "one network one archive" and provided for the better integration of multi-GNSS data into the entire IGS infrastructure. Starting in 2015, stations began submitting RINEX V3 data using the format's "long" filename specification. The transition plan specified that RINEX V3 data from IGS network sites using the V3 filename structure should be archived in the same directory structure as the operational RINEX V2 data. Therefore, starting on January 01, 2016, all daily, hourly, and high-rate data submitted to the CDDIS in RINEX V3 format and using the long, V3 filename specification have been archived in the same directories as the RINEX V2 data (which use the 8.3.Z filename for

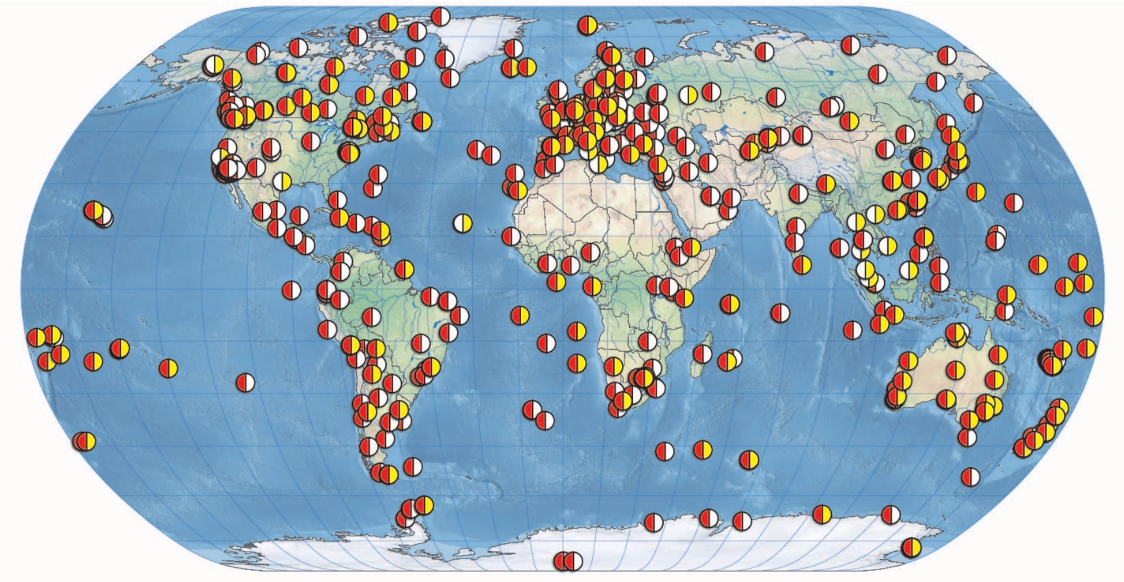

Figure 3: The main, operational archive at CDDIS now includes data in RINEX V2 format using the 8.3.Z filename specification (red) and RINEX V3 format using the V3 filename specification (yellow).

daily and hourly files and the 10.3.Z filename format for high-rate files). In addition, these RINEX V3 files are compressed in gzip (.gz) format; files in RINEX V2 format continue to use UNIX compression (.Z). Figure 3 shows the network of IGS sites providing daily data in RINEX V2 and/or V3 formats.

3.1.3 RINEX V3 (MGEX) Archive

During 2016, the CDDIS continued the archiving of data in RINEX V3 format from multi-GNSS receivers participating in the Multi-GNSS Experiment (MGEX) as well as products derived from the analysis of these data. The data include all available multi-GNSS signals (e.g., Galileo, QZSS, SBAS, BeiDou, and IRNSS) in addition to GPS and GLONASS. These data, in RINEX V3 format but using the 8.3.Z filename specification, continue to be archived in a campaign directory structure at CDDIS (*/gnss/campaign/mgex/data*). The summary of the MGEX data holdings at the CDDIS is shown in Table 3.1.1 below. Daily status files are also provided that summarize the MGEX data holdings; however, data quality information, generated for data holdings in RINEX V2 format, is not available through the software used by CDDIS to summarize data in RINEX V3 format. CDDIS continues to investigate and evaluate software capable of providing data summary/QC information for RINEX V3 data. As station operators converted RINEX V3 data to the long, RINEX V3 filename specification (see Section 3.1.2), the amount of data archived in the campaign directories has decreased.

Table 4: GNSS Product Summary for 2016.

Product Type	Number of ACs/AACs	Volume	Directory
Orbits, clocks, ERP, positions	14+Combinations	1.4 GB/week	/gnss/products/WWWW (GPS, GPS+GLONASS) /glonass/products/WWWW (GLONASS only)
Troposphere	Combination	3 MB/day, 1.1 GB/year	/gnss/products/troposphere/YYYY
Ionosphere	6+Combination	4 MB/day, 1.5 GB/year	/gnss/products/ionosphere/YYYY
Real-time	Combinations	28 MB/week	/gnss/products/rtpp/YYYY
Repro2	10+Combinations	850 MB/week	/gnss/products/WWWW/repro2

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

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 fÂÍur Luft- und Raumfahrt (DLR), is similar to the daily and hourly concatenated broadcast message files in RINEX V2 format provided by the CDDIS for the operational GPS+GLONASS data sets; it contains all the unique broadcast navigation messages for the day. The file, named *brdmDDD0.YYp.Z*, is stored in daily subdirectories within the MGEX campaign archive at CDDIS (*/gnss/data/campaign/mgex/daily/rinex3/YYYY/DDD/YYp*) and in a yearly top level subdirectory (*/gnss/data/campaign/mgex/daily/rinex3/YYYY/brdm*).

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). Table 3.2 below 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 continue 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 year and day of year. Global ionosphere maps of total electron content (TEC) from the IONEX AACs are also archived in subdirectories by year and day of year. Real-time clock comparison products have been archived at the CDDIS in support of the IGS Real-Time Pilot Project, and current IGS Real-Time Service, since 2009.

In 2015, the IGS analysis centers completed the upload of products for the second IGS reprocessing campaign (repro2). The CDDIS provided support through upload of files from the ACs and online archive of these products (*/gnss/products/WWWW/repro2*); additional files were submitted in 2016. Six AACs (CODE, GFZ, GRGS, JAXA, TUM, and Wuhan) generated weekly products (orbits, ERP, clocks, and others) in support of

MGEX. These files are archived at the CDDIS in the MGEX campaign subdirectory by GPS week (*/gnss/products/mgex/WWWW*).

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

3.3 Real-Time Activities

In 2013, the CDDIS staff configured a server and began testing a caster to provide a real-time streaming capability at GSFC and support the IGS Real-Time Service (IGS RTS). The CDDIS successfully tested obtaining product streams from the BKG and IGS casters and providing access to these streams to authorized users; additional streams from Natural Resources Canada (NRCan) and Geoscience Australia (GA) were later added to the caster. Work was completed in spring 2015 and the CDDIS caster became fully operational, broadcasting nearly 40 product and 165+ data streams in real-time. The caster runs the NTRIP (Network Transport of RTCM via internet Protocol) format. Figure 4 shows the distribution of stations providing real-time streams to the CDDIS caster.

As stated previously, the CDDIS is one of NASA's EOSDIS DAACs and through EOSDIS, has access to a world-class user registration process, the EOSDIS Earthdata Login (EDL, formerly User Registration System, URS), with over 255K 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 EDL 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. New users complete a registration form available on the CDDIS website; once completed, the data are passed to the EDL, which generates an email to the user with a validation link. The user accesses the link and the EDL validates the form's data; this process is accomplished within a minute or less. The user's validated access request is submitted to CDDIS staff for access authorization to the CDDIS caster. This second step is not yet automated and can take several hours to configure depending on the time of day. In addition, users registering in this system have access to the entire suite of EOSDIS products across all 12 EOSDIS DAACs.

Initially, the CDDIS caster provided access to data and product streams from several regional real-time casters. Data streams have also been provided through JPL for receivers

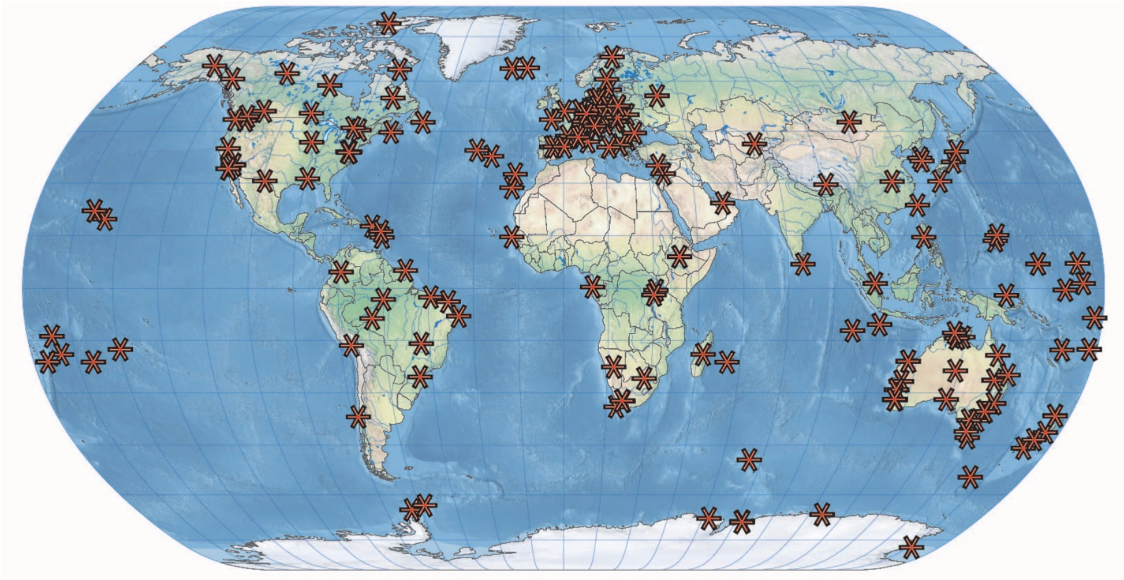

Figure 4: CDDIS is operationally supporting the dissemination of data from over 225 real-time GNSS sites as well as near real-time products derived from these data.

in NASA's Global GPS Network. In 2016, an additional set of stations from JPL's Global Differential GPS (GDGPS) network were added to the CDDIS caster. This network of globally distributed, geodetic quality, dual frequency receivers, provides additional 1 Hz data streams to those current available from the IGS RTS. The CDDIS caster was augmented with new real-time streams as they became available from IGS network sites. The CDDIS caster serves as the third primary caster for the IGS RTS, thus providing a more robust topology with redundancy and increased reliability for the service. User registration, however, for all three casters is unique; therefore, current users of the casters located at the IGS and BKG are required to register through the CDDIS registration process in order to use the CDDIS caster. By the end of 2016, over 100 users from 28 countries have registered to use the CDDIS caster. More information about the CDDIS caster is available at https://cddis-casterreg.gsfc.nasa.gov/index.html.

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

3.4 Supporting Information

Daily status files of GNSS data holdings, reflecting timeliness of the data delivered as well as statistics on number of data points, cycle slips, and multipath, continue to be generated by the CDDIS for RINEX V2 data; status files, with limited information, summarizing

RINEX V3 data holdings are also available. 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.nasa.gov/reports/gnss/status. The daily status files are also archived in the daily GNSS data directories.

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

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

4 System Usage

Figure 5 summarizes the usage of the CDDIS for the retrieval of GNSS data and products in 2016. This figure illustrates the number and volume of GNSS files retrieved by the user community during 2016, categorized by type (daily, hourly, high-rate, products). Nearly 930 million files (nearly 140 Tbytes) were transferred in 2016, with an average of nearly 80 million files per month. Figure 6 illustrates the profile of users accessing the CDDIS IGS archive during 2016. The majority of CDDIS users were once again from hosts in North America, Asia, and Europe.

5 Recent Developments

5.1 Next Generation Hardware

As detailed in the system hardware section above, the CDDIS transferred operations to the new virtual-machine based architecture on December 01, 2016. The transition to the new system was accomplished with less than 30 hours of downtime to the user community.

5.2 Archive Operations

The CDDIS has been operating for over 30 years. During that time procedures and processes have grown to meet both existing data archive needs and new requirements, which

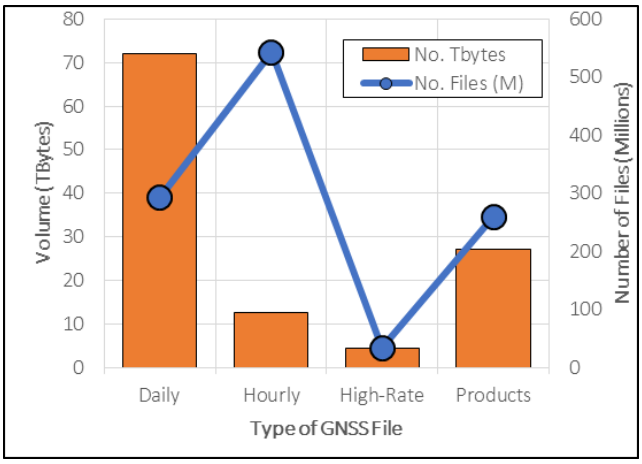

Figure 5: Number and volume of GNSS files transferred from the CDDIS in 2016.

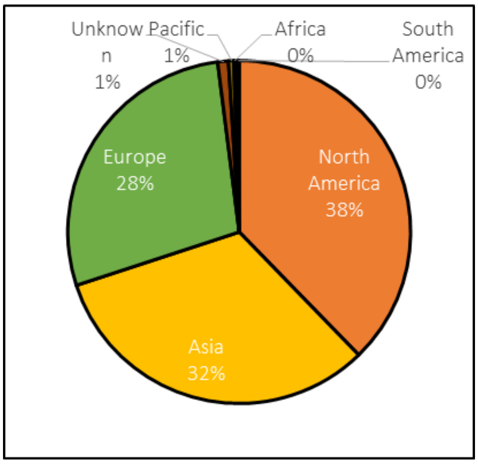

Figure 6: Geographic distribution of IGS users of the CDDIS in 2016.

over time had become unwieldy and hard to support. Therefore, CDDIS conducted a complete review of the entire data ingest operations system in early 2016 to identify and correct process inefficiencies in and improve the QC of incoming files. Software development included the addition of more automation capabilities, better redundancy, easier supportability, and common code sharing. The staff developed and integrated new software to perform routine checksums of and anti-virus scanning on all incoming files. The new operations software was implemented for GNSS data processing prior to the transition to the new hardware system and is now fully operational on this new system. Testing on other data types (e.g., SLR and DORIS) will start in early 2017.

5.3 Archive Operations

CDDIS has traditionally used ftp (with a username/password) for delivery of files from the data and product suppliers. The underlying user accounts to receive these contributions had limited privileges, allowing data and product providers to deposit files but not retrieve files from these disk areas. However, with the installation of the CDDIS servers within the new computer facility, the CDDIS needed to move to a better-supported protocol and at the same time use a single sign-on system to perform authentication. The CDDIS staff developed an https-based protocol method for delivery of files from suppliers of data and products. The authentication is performed through the EOSDIS Earthdata Login (EDL) system, the same system used for access to the CDDIS real-time caster. The file uploads can be performed through a webpage interface or a command line application that can perform an http "post" operation, which is more commonly used for scripting. This process allows data suppliers to authenticate through the EDL system and provide their files through https to CDDIS for ingest into the archive. For several months, suppliers performed significant testing on the new upload system. By late summer, all data and product suppliers were contacted and full testing began. This new delivery method was fully implemented for all suppliers as the CDDIS transitioned operations to the new servers. Unfortunately, some data providers have had difficulty adapting their software to use the new CDDIS upload system which has affected CDDIS data holdings. The CDDIS staff continues to work with these providers to help answer any questions during their transition to the new system. More information on the CDDIS file upload system is available at: https://cddis.nasa.gov/About/CDDIS_File_Upload_Documentation.html.

5.4 Metadata Developments

The CDDIS continues to make modifications to the metadata extracted from incoming data and product files pushed to its archive and implemented these changes in the new operations software system. These enhancements have facilitated cross discipline data discovery by providing information about CDDIS archive holdings to other data portals such as Earth Observing System search client and future integration into the GGOS portal. The staff continues work on a metadata evolution effort, re-designing the metadata extracted from incoming data and adding information that will better support EOSDIS applications such as its search client and the metrics collection effort. The CDDIS is also participating in GGOS metadata efforts within the Bureau of Networks and Observations. The CDDIS continues to implement Digital Object Identifiers (DOIs) to select IGS data sets (GNSS data and products). DOIs can provide easier access to CDDIS data holdings and allow researchers to cite these data holdings in publications. Landing pages are available for each of the DOIs created for CDDIS data products and linked to description pages on the CDDIS website; an example of a typical DOI description (or landing) page, for daily Hatanaka-compressed GNSS data files, can be viewed at: https:/cddis.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 2016 and presented papers on or conducted demos of their activities within the IGS, including:

Noll C. , and P. Michael. ”Developments at CDDIS to Support Real-Time and RINEX V3” (poster), presented at IGS Workshop ”GNSS Futures”, Sydney, NSW, Australia, February 08–12, 2016

Michael P. , and C. Noll. ”Important Upcoming Architecture and User Changes at the CDDIS” (poster),

Michael P. , and C. Noll. "Important Upcoming Architecture and User Changes at the CDDIS" (poster), IGS Workshop "GNSS Futures", Sydney, NSW, Australia, February 08–12, 2016

Pearlman M. , E. Pavlis, C. Ma, C. Noll, D. Thaller, B. Richter, R. Gross, R. Neilan, M. Mueller, R. Barzaghi, S. Bergstrand, J. Saunie, and M. Tamisiea "Update on the Activities of the GGOS Bureau of Networks and Observations" (poster), presented at European Geosciences Union General Assembly, April, 2016, Abstract No. 10095

Noll C. "GGOS: Global Geodetic Observing System", presented at 2016 WDS Members' Forum, Denver, Colorado, September 11, 2016

Stangl G. , and C. Noll. "GGOS: The Global Geodetic Observing System" (poster), presented at 2016 WDS Members' Forum, Denver, Colorado, September 11, 2016

Noll C. , and P. Michael. "CDDIS: NASA's Archive of Space Geodesy Data and Products Supporting GGOS" (poster), presented at the Fall American Geophysical Union meeting, San Francisco, CA, USA, December 06-12, 2016

Michael P. , C. Noll, and J. Woo, and R. Limbacher. "Next Generation Global Navigation Satellite System (GNSS) Processing at NASA CDDIS" (poster), presented at the Fall American Geophysical Union meeting, San Francisco, CA, USA, December 06-12, 2016

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

7 Future Plans

7.1 RINEX V3 Data

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

7.2 Real-Time Activities

The CDDIS will continue to add real-time data and product streams to its operational caster in support of the IGS Real-Time Service. Future activities in the real-time area include capturing the streams for generation of 15-minute high-rate files for archive. This capability requires further testing and coordination with the IC. The staff is also developing software to provide metrics on usage of the CDDIS caster. The staff will also investigate automating the process of adding users to the CDDIS caster configuration files.

7.3 Web-Based User Access

With EOSDIS requesting that EDL should be used for all data delivery to users, CDDIS is investigating possible methods of providing a web-based capability. Over 95% of CDDIS users retrieve files using automated scripts; these scripts will not work with a web-based approach as http does not support globbing. The EOSDIS EDL group has recently developed an Apache-based module to emulate ftp globbing functionality. This module is currently in testing with both CDDIS and EOSDIS. This new module will make the transition between ftp and http easier and CDDIS is investigating implementing EDL within an https download option. CDDIS staff will continue to study possible solutions and best methods for allowing users to retrieve data through https while still maintaining the ability to use scripts. During this development, CDDIS staff will incorporate the lessons learned from their data upload system into the https access capability.

7.4 Contact Information

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

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Greenbelt, MD 20771		

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

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

"IGS RINEX 3 Transition Plan v3.0" IGS website, http://kb.igs.org/hc/en-us/article_attachments/202584007/Rinex_3_transition_plan_v3.0.pdf.

"The Receiver Independent Exchange Format. Version 3.03", IGS website, ftp://igs.org/pub/data/format/rinex303.pdf.

Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2016

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1 Generation of the absolute phase center model igs14.atx

On 29 January 2017 (GPS week 1934), the IGS switched to an IGS-specific realization of the ITRF2014, called IGS14, that is consistent with an updated set of satellite and receiver antenna phase center corrections called igs14.atx. Details can be found in Rebischung et al. (2016). An update of the GPS and GLONASS satellite antenna z-offsets became necessary due to recent orbit modeling changes affecting the scale of the IGS products (Earth radiation pressure, antenna thrust). Besides, existing receiver antenna calibrations had not been updated since the release of igs08.atx in 2011.

Major changes of igs14.atx with respect to igs08.atx:

- satellite antenna z-offsets from igs14.atx are consistent with IGS14, whereas those from igs08.atx were consistent with IGb08
- slightly improved redundancy of satellite antenna z-offsets: GPS values contained in igs14.atx are based on repro2/operational results of 7 ACs (igs08.atx: 5), GLONASS values still on those of only 2
- as GLONASS satellite antenna z-offsets were contained in the SINEX files of two ACs, GLONASS and GPS values could, for the first time, be derived from the same set of solutions
- preliminary block-specific z-offsets for satellites launched since the latest z-offset update in September 2012 were replaced by satellite-specific estimates
- z-offsets trend-corrected to epoch 2010.0 due to a difference of about 0.03 ppb/yr between the "intrinsic GNSS scale rate" (determined by the use of constant satellite antenna z-offsets) and the ITRF2014 scale rate (Rebischung and Schmid 2016)

- satellite-specific x- and y-offsets from pre-flight calibrations for the Block IIR satellites (Dilssner et al. 2016)
- additional and updated robot-based receiver antenna calibrations
- conversion of relative receiver antenna corrections with updated `AOAD/M_T` values

2 Updates and content of the antenna phase center model

Table 1 lists 21 updates of the absolute IGS antenna phase center model `igs08_wwww.atx` (Schmid et al. 2016) that were released in 2016. 16 of them are related to changes of the satellite constellation, and five times an update of the model was released, when new receiver antenna calibrations became available. Further details on all model changes can be found in the corresponding IGSMAILs whose numbers are also given in Table 1.

Table 2 gives an overview of the data sets contained in the IGS phase center model. The numbers refer to `igs08_1928.atx`/`igs14_1928.atx` released in December 2016. For GPS and GLONASS, there are 94 and 101 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. In February 2016 (week 1885), two GLONASS satellites (R854, R855) were renamed according to a recommendation made at the IGS Workshop in Sydney.

Due to several successful satellite launches and due to the first switch of a PRN code in the BeiDou constellation, the number of data sets for Galileo, BeiDou-2 and IRNSS/NavIC increased to 20, 17, and 7, respectively. Due to the lack of phase center offset (PCO) information, the new generation of BeiDou-3 satellites launched in 2015/16 could not be considered for the IGS model so far.

In September 2016 (week 1915), the conventional MGEX PCO values for the Galileo satellites were replaced by PCO estimates derived from terrestrial data after a coordinated effort of three ACs (Steigenberger et al. 2016). Because of the switch from igs08.atx to igs14.atx, these values will probably have to be adapted again. The suitability of IOV pre-launch calibrations (European GNSS Service Centre 2016) for IGS purposes will have to be evaluated by the Multi-GNSS Working Group.

Apart from the satellite antennas, the IGS model igs08.atx contained phase center calibration values for 304 different receiver antenna types at the end of 2016. With the switch to igs14.atx and the consideration of 17 additional absolute robot calibrations, the total number could be increased to 310, whereas the number of copied and converted field calibrations could be reduced at the same time. Among the 310 different types are 101 combinations of an antenna with a certain radome, whereas the remaining 209 antenna types are not covered by a radome.

As Table 2 shows, `igs14_1928.atx` contained, among others, 181 absolute robot cali-

Table 1: Updates of the phase center model `igs08_wwww.atx` in 2016 (`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
1879	12-JAN-16	7227	Added E208, E209
			Decommission date: G034
			Added `TWIVP6000 NONE`
1880	20-JAN-16	—	Added `TPSCR.G5 NONE`
			`TPSCR.G5C NONE`
			`TPSCR.G5C TPSH`
1881	28-JAN-16	7239	Added G049 (G04)
			Decommission date: G023 (G32)
1882	02-FEB-16	7242	Added R802 (R17), R802 (R27)
			Decommission date: R714 (R17), R802 (R27)
1884	16-FEB-16	7249	Added G070
1885	22-FEB-16	7252	Added R802 (R09), R714 (R17)
			Decommission date: R736 (R09), R802 (R17)
			Satellites RENAMED: R754 → R854, R755 → R855
1886	26-FEB-16	7258	Added R851
			Decommission date: R714 (R17)
1887	10-MAR-16	7268	Added R736 (R16)
			Decommission date: R738 (R16)
			Added `TRMR2 NONE`
1888	18-MAR-16	7272	Added I005, I006
			Added `CHCI80 NONE`
1899	31-MAY-16	7308	Added C017, I007
			E201/E202: nadir angle extended to 16 degrees
1900	09-JUN-16	7314	Added E210, E211
			Added `SOKSA500 NONE`
1903	28-JUN-16	7323	Added R853
			Decommission date: R723
1904	08-JUL-16	—	Added `LEIGS15.R2 NONE`
			`LEIGS16 NONE`
1911	26-AUG-16	—	Added `CHAPS9017 NONE`
			`LEICGA60 NONE`
			`MVEGA152GNSSA NONE`
1914	14-SEP-16	7353	Added G032 (G04)
			Decommission date: G049 (G04)
1915	23-SEP-16	7356	Offset UPDATED: E101, E102, E103, E104, E201, E202, E203, E204, E205, E206, E208, E209, E210, E211
1918	14-OCT-16	7361	Added C017 (C13)
			Decommission date: C014 (C13), C017 (C15)

Table 1: continued

Week	Date	IGSMAIL	Change

1924	25-NOV-16	—	Added `JAVTRIUMPH_2A+G JVGR`
			`TPSHIPER_HR NONE`
			`TPSHIPER_HR+PS NONE`

1926	07-DEC-16	7386	Added G034 (G04), E207, E212, E213, E214 Decommission date: G032 (G04) Added `GMXZENITH15 NONE`
1927	15-DEC-16	7392	Added R723 (R12) Decommission date: R737

1928	22-DEC-16	—	Added `TRM105000.10 NONE`
			`TRM115000.00 NONE`
			`TRM115000.00 TZGD`
			`TRM115000.10 NONE`

Table 2: Number of data sets in `igs08_1928.atx` and `igs14_1928.atx` (released in December 2016)

Satellite antennas	Number	Receiver antennas	Number	
			igs08.atx	igs14.atx
GPS	94	`ROBOT`	164	181
GLONASS	101	`FIELD`	90	81
Galileo	20	`COPIED`	36	34
BeiDou	17	`CONVERTED`	14	14
QZSS	1			
IRNSS/NavIC	7			

brations and 81 converted field calibrations. As elevation- and azimuth-dependent calibration values down to 0° elevation are mandatory for new or upgraded IGS stations, altogether 218 different antenna types (181 `ROBOT` + 34 `COPIED` + 3 `CONVERTED`) were approved for installation after the switch to igs14.atx. The remaining 92 types (81 `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.

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, 504 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general/`) on 5 January 2017 were considered. At that time, 97 different antenna/radome combinations were in use within the IGS network. The

Table 3: Calibration status of 504 stations in the IGS network (`logsum.txt` of 5 January 2017, `igs08_1928.atx` vs. `igs14_1928.atx`) compared to former years

Date		Absolute calibration (azimuthal corrections down to 0° elevation)	Converted field calibration (purely elevation-dependent PCVs above 10° elevation)	Uncalibrated radome (or unmodeled antenna subtype)
DEC 2009		61.4%	18.3%	20.2%
MAY 2012		74.6%	8.2%	17.2%
JAN 2013		76.8%	7.7%	15.5%
JAN 2014		78.7%	7.8%	13.5%
JAN 2015		80.1%	7.5%	12.4%
JAN 2016		83.0%	6.5%	10.5%
JAN 2017	**igs08.atx:**	**84.9%**	**6.2%**	**8.9%**
	igs14.atx:	**90.7%**	**2.2%**	**7.1%**

calibration status of these antenna types was assessed with respect to the phase center models `igs08_1928.atx` and `igs14_1928.atx` that were released in December 2016.

Over the last years, the percentage of stations with state-of-the-art robot-based calibrations has improved by about 2% per year. This moderate increase mainly resulted from the upgrade of the equipment at operational stations and from the decommissioning of stations with outdated equipment. The switch to igs14.atx yielded another improvement of about 6% due to the availability of additional robot-based calibrations. In the case of nine antenna types, the latter could replace converted field calibrations (cf. Table 2). Besides, new calibrations for certain antenna/radome combinations became available.

Ten years after the adoption of absolute robot calibrations by the IGS in November 2006, the percentage exceeds 90% for the first time. For most of the remaining 47 stations with inappropriate phase center corrections a calibration with a robot is not possible, as the radome (`AUST`, `DOME`, `ENCL`, `JPLA`, `OSOD`, `SCPL`) is not directly connected to the antenna. Only 15 of the 47 stations are equipped with antenna types for which a calibration would be possible (see Table 4) and still desirable for future model updates.

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Rebischung P. and R. Schmid. IGS14/igs14.atx: a new framework for the IGS products. AGU Fall Meeting, San Francisco, CA, 2016.

Table 4: Calibratable antenna/radome combinations for which robot-based values are missing in January 2017

Antenna	Radome	IGS stations
3S-02-TSADM	NONE	1
AOAD/M_T	SCIS	1
ASH701933B_M	SCIS	2
ASH701945B_M	SCIT	4
ASH701945C_M	SCIT	3
ASH701945E_M	SCIT	2
ASH701945G_M	SCIT	1
TPSCR.G3	SCIT	1
Sum		15

Rebischung P., R. Schmid, and T. Herring. Upcoming switch to IGS14/igs14.atx. IGSMAIL-7399, IGS Central Bureau, 2016.

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Steigenberger P., M. Fritsche, R. Dach, R. Schmid, O. Montenbruck, M. Uhlemann, and L. Prange. Estimation of satellite antenna phase center offsets for Galileo. *Journal of Geodesy*, 90(8):773–785, doi 10.1007/s00190-016-0909-6, 2016.

Bias and Calibration Working Group Technical Report 2016

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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, careful treatment of measurement biases in legacy and new signals becomes more and more crucial for combined analysis of multiple GNSS.

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

2 Activities in 2016

- Regular generation of P1–C1 bias values for the GPS constellation (based on *indirect* estimation) and maintenance of receiver class tables was continued at CODE/AIUB.
- The finalization of the new **Bias-SINEX Format Version 1.00** was a key challenge and achievement in 2016 (see also Section 4).
- At CODE, a refined GNSS bias handling to cope with all available GNSS systems and signals has been implemented and activated (in May 2016) in all IGS analysis

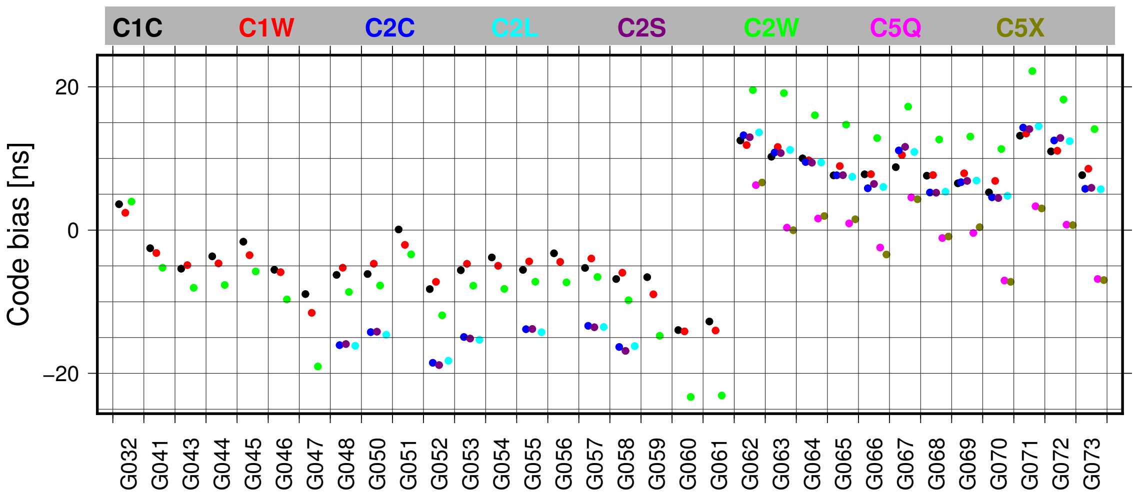

Figure 1: Observable-specific code bias estimates for all available GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE. Note that G032–G061 correspond to Block IIA, IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations.

lines. As part of this major revision, processing steps relevant to bias handling and retrieval were reviewed and completely redesigned.

- It should be mentioned that the current GPS C1W-C1C DSB (P1-C1 DCB) product provided by CODE corresponds to a converted extract from our new OSB final/rapid product line.
- Our new bias implementation allows to combine bias results at normal-equation (NEQ) level. We are thus able to combine bias results obtained from clock analysis and from ionosphere analysis, and, moreover, to compute coherent long-term OSB solutions. This could be already achieved for the period starting with epoch 2016:136:00000 up to now. Corresponding long-term OSB solutions are updated daily (see GPS/GLONASS bias results shown in Figures 1 and 2).
- The tool developed for *direct* estimation of GNSS P1–C1 and P2–C2 DCB values is (still) used to generate corresponding GPS and GLONASS bias results on a daily basis.
- The ambiguity resolution scheme at CODE was extended (in 2011) to GLONASS for three resolution strategies. It is essential that *self-calibrating* ambiguity resolution procedures are used. Resulting GLONASS DCPB(differential code-phase bias) results are collected and archived daily.
- More experience could be gained concerning station-specific GLONASS-GPS intersystem translation parameters, which are estimated and accumulated as part of CODE's IGS analysis (but completely ignored for all submissions to IGS).

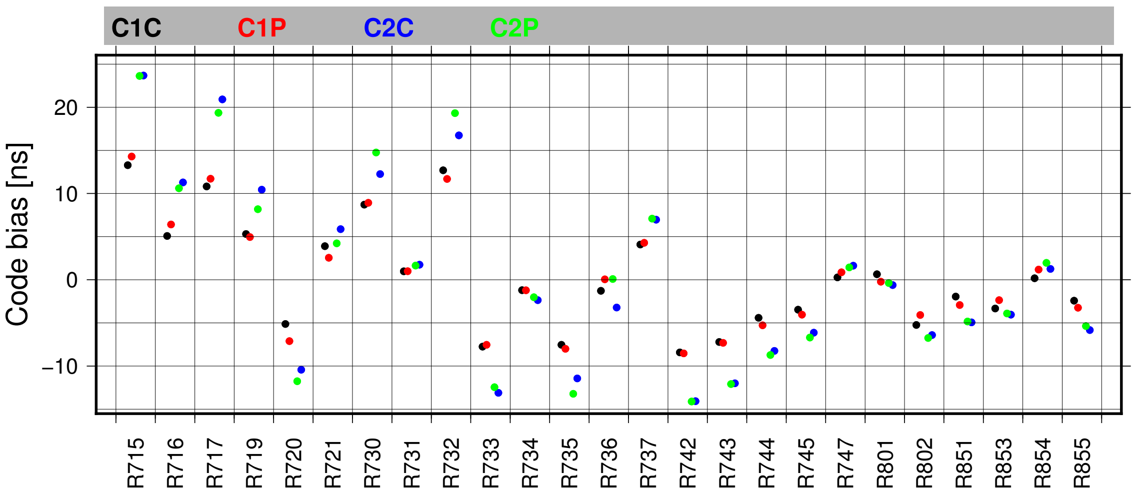

Figure 2: Observable-specific code bias estimates for all available GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE.

- 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/y2016/odata2_d335.txt
  ftp://ftp.unibe.ch/aiub/igsdata/y2016/odata2_d335_sat.txt
  Internally, the corresponding information is extracted and produced using metadata stored in an xml database (established in December 2014).
- This RINEX monitoring service is provided in addition for MGEX observation data (available in RINEX3 format). See: ftp://ftp.unibe.ch/aiub/mgex/y2016/

3 Last Reprocessing Activities

In 2012: A complete GPS/GLONASS DCB reprocessing was carried out at CODE on the basis of 1990–2011 RINEX data. The outcome of this P1–C1 and P2–C2 DCB reprocessing effort is: daily sets, a multitude of daily subsets, and in addition monthly sets.

In 2016/2017: A GNSS bias reprocessing (for GPS/GLONASS) using the recently implemented observable-specific code bias (OCB) parameterization was initiated at CODE for 1994-2016 RINEX data. The outcome of this reprocessing effort are daily NEQs for GPS and GLONASS OCB parameters from both global ionosphere and clock estimation. A consistent time series of global ionosphere maps (GIMs) with a time resolution of 1 hour is an essential by-product of this bias reprocessing effort. Analysis and combination of these daily code bias (NEQ) results is planned for 2017.

4 Bias-SINEX Format Version 1.00

A finalized draft version for the new Bias-SINEX Format (Version 1.00) was announced in (Schaer 2016b):

http://www.aiub.unibe.ch/download/bcwg/format/draft/sinex_bias_100_dec07.pdf

This format version has been developed on the basis of

- a first draft proposed and discussed at the IGS Bias Workshop 2015 in Bern, Switzerland,
- an updated draft prepared for the IGS Workshop 2016 in Sydney,
- substantial inputs from the IGS MGEX community (in particular from Oliver Montenbruck, DLR, Germany), and
- our experiences gained as part of the GNSS bias implementation performed at CODE.

The latest essential updates since the IGS Workshop 2016 included:

- Bias-SINEX was completely decoupled from the SINEX format and corresponding format descriptions.
- The previously used 2-digit year tag (YY) was generally replaced by a 4-digit year tag (YYYY) for all time tags (YYYY:DDD:SSSSS).
- Numerous bias (.BIA) example files could be prepared based on the new GNSS bias products generated at CODE.

The latest format document (and the entire format document history) may be found at:

http://www.biasws2015.unibe.ch/documents.html

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IGS Data Center Working Group Technical Report 2016

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1 Introduction

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

2 Recent Activities

2.1 Meetings

A meeting of the IGS DCWG was held in conjunction with the IGS Infrastructure Committee (IC) and RINEX Working Group during the 2016 IGS Workshop in Sydney Australia in February 2016. The DCWG portion of the splinter meeting reviewed recommendations from the 2014 workshop, of which all three were completed. The main issues discussed at the splinter meeting revolved around supporting the integration of RINEX V3 data into the operational IGS archive, mainly by accepting data using the new RINEX V3 filename format.

The following recommendations from the IGS DCWG were put forward at the workshop:

- Encourage providers of RINEX V3 data to submit files (daily/hourly/high-rate) using V3 filename conventions to IGS data centers by the end of 2016. Until this task is implemented by the stations, GDCs should create the files using the V3 naming conventions.

Progress: Starting with data from January 01, 2016, the IGS GDCs at CDDIS and IGN integrated RINEX V3 data following the V3 naming conventions into their main, operational directories. See Section 2.2 for more information.

- ACs and users in general should begin utilizing RINEX V3 data in the V3 filename format.
- Encourage DCWG to strive for implementation of XML Site Log Metadata System. In addition, encourage stakeholders to submit use cases (examples of the required interactions with the system) for XML Site Log Metadata System. Progress: See Section 2.3 on Site Log Metadata developments.

2.2 RINEX V3 Integration

The current parallel structure found at the IGS global data centers (GDCs) supporting the Multi-GNSS Experiment (MGEX) limits the motivation of the ACs to switch to the RINEX V3 format. Integration of the two data archives promotes use of multi-GNSS data and the new format. The IGS IC developed the âĂIJRINEX V3 Transition PlanâĂİ to accomplish the integration and two IGS GDCs (CDDIS and IGN) began storing RINEX V3 data submitted using the V3 filenaming convention into the operational archives in early 2016.

Questions still to be addressed include how to handle RINEX V3 data not supplied in the new filename convention. DCs could use tools such as gfzrnx to create these files with long filenames at the DCs but getting the files from the station operators is preferred.

The DCWG will continue to work with the IC on using tools such as Anubis to QC RINEX V3 data and supply the QC information through the data centers in summary/status files as has been done for data in RINEX V2 format.

2.3 Site Metadata Activities

Another area of interest for the IGS IC and DCWG involves metadata, particularly in the area of site logs. The IGS Central Bureau (CB) uses the Site Log Manager System for handling IGS site logs, which provides a basis for promoting the transmission of these logs in XML format. An XML/database management approach to site logs provides several advantages, such as rapid update of site log contents, utilization of consistent information across data centers, and availability of more accurate station metadata. The DCWG held email discussions and teleconferences to continue the collaboration begun in 2015. The 2015 discussions included adoption of GeodesyML to include the Site Log XML schema (GeodesyML is an application schema of the Open Geospatial Consortium

GML standard). Based on teleconference discussions and following further discussions at the 2016 IGS Workshop, the team at Geoscience Australia completed the agreed-upon modifications to the Site Log XML schema and released GeodesyML 0.3. Once several participants began working with this version, some refinements were identified for the Site Log XML schema. Several institutions in addition to GA, including ROB, BKG, GFZ, UNAVCO and GNS, have begun to experiment with implementing GeodesyML/Site Log XML in test environments. Software tools that can be used for conversion between text and XML formatted site logs are in development and can be shared among all groups.

3 Future Plans

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

- Support of the IGS Infrastructure Committee: A major focus of the DCWG will be to continue its support the IC in its various activities to coordinate the resolution of issues related to the IGS components. These activities will address recommendations from the 2016 IGS Workshop as well as past workshops, including assessment and monitoring of station performance and data quality, generating metrics on these data.
- 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. All data in RINEX V3 format using the V3 naming convention are supplied and archived in gzip format.
- Next meeting: A meeting of the DCWG is planned for the next IGS workshop in 2017.

4 Membership

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

Ionosphere Working Group Technical Report 2016

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1 Space Radio–Diagnostics Research Centre
University of Warmia and Mazury in Olsztyn, Poland (SRRC/UWM)
2 UPC–IonSAT, Barcelona, Spain
3 Canadian Geodetic Survey, Natural Resources Canada, Ottawa, Canada
4 Institute of Geodesy and Geophysics (IGG)
Chinese Academy of Sciences (CAS), Wuhan, China
5 Academy of Opto–Electronics (AOE), Chinese Academy of Sciences (CAS)
Beijing, China
6 GNSS Research Center (GRC) of Wuhan University, Wuhan, China
7 ESOC/ESA, Darmstadt, Germany
8 JPL/NASA, Pasadena, CA, USA
9 CODE/swisstopo, Bern/Wabern, Switzerland
10 UB–D.Electronics, Spain

1 General goals

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

*Chair of Ionosphere Working Group

final VTEC maps is used by the each analysis centers: Each IAACs compute the rapid and final TEC maps independently and with different approaches including the additional usage of GLONASS data in the case of CODE.

2 Membership

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

Prof. Yunbin Yuan and Dr. Ningbo Wang from the Institute of Geodesy and Geophysics (IGG) of the Chinese Academy of Sciences (CAS) have solicited to be member of the IGS Ionosphere WG. Taking into account that all of opinions about Prof. Yunbin Yuan and

Dr. Ningbo Wang's membership applications have been positive we are glad to welcome Drs. Yuan and Wang to the WG.

3 Products

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

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

b rapid GIM

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

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

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

4 Key accomplishments

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

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

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

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

5 Recommendations after IGS Workshop 2016, Sydney, Australia

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

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

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

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

6 The pilot phase of the new IGS ionospheric product

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

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

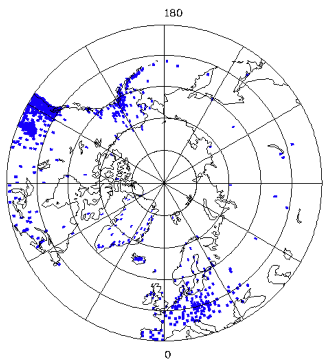

Figure 1: The locations of the stations around the North Geomagnetic Pole.

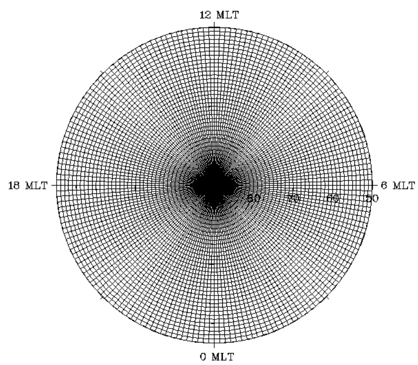

Figure 2: The grid of ROTI maps in polar coordinates with grid 2 degree (magnetic local time) and 2 degree (geomagnetic latitude).

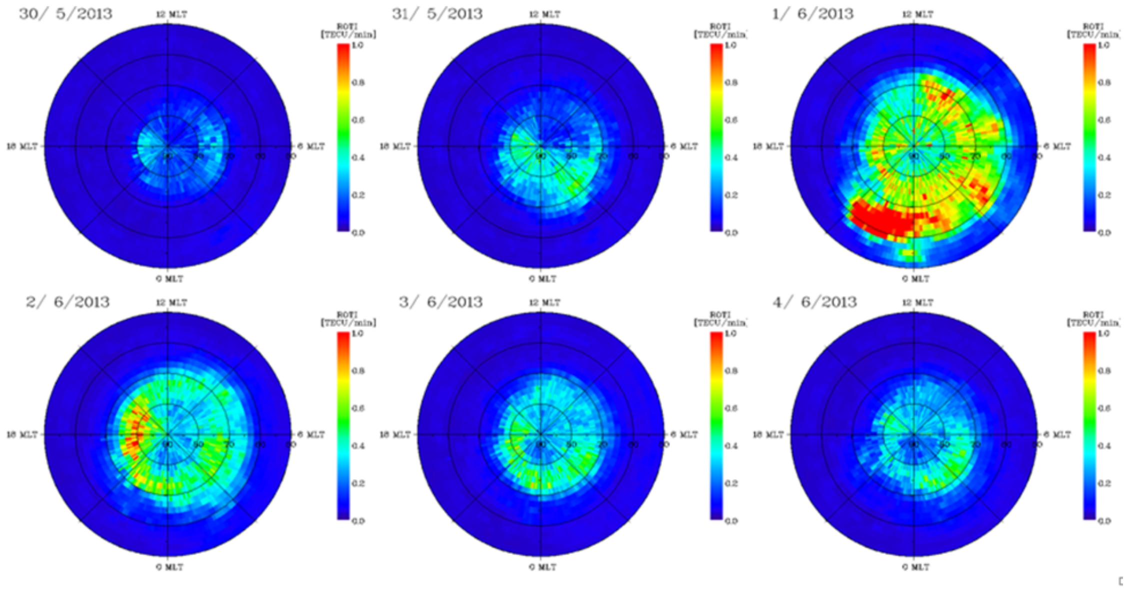

Figure 3: Evolutions of the daily ROTI maps for 30 May – 4 June 2013.

In the updated version, more than 700 permanent stations (available both from UNAVCO and EUREF databases) have been involved into analysis of the ionosphere fluctuation service. In order to describe the TEC variability in the ionosphere, the Rate of TEC (ROT) and its deviation – Rate of TEC Index (ROTI) are used. The ROT is calculated as the difference of two geometry-free observations for consecutive epochs. The ROTI represents the ROT deviation over 5 minute periods with one minute resolution. This ionospheric fluctuations service allows to estimate the levels of TEC fluctuations for spatial range from 50 degree of the north geomagnetic latitude to the North Geomagnetic Pole. The results have visualization as daily ROTI maps in polar coordinates with grid 2 degree (magnetic local time) and 2 degree (geomagnetic latitude). The every grid cell represents the average weighted value of ROTI values included in this cell.

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

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

In this section two independent techniques to assess global Vertical Total Electron Content (VTEC) ionospheric models computed from GNSS data (GIMs) are applied in the context

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

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

of the International GNSS Service (IGS): to the GIMs of CODE, ESA, JPL and UPC (analysis centers contributing since 1998.5), NRCAN (resuming its contribution), and, Chinese Academy of Sciences (CAS) and Wuhan University (WHU) as new contributors.

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

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

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

It is remarkable as well the general agreement of the bias, at 1 to few TECUs level, regarding the altimeter VTEC for the most part of analysis centers. This happens among dif-

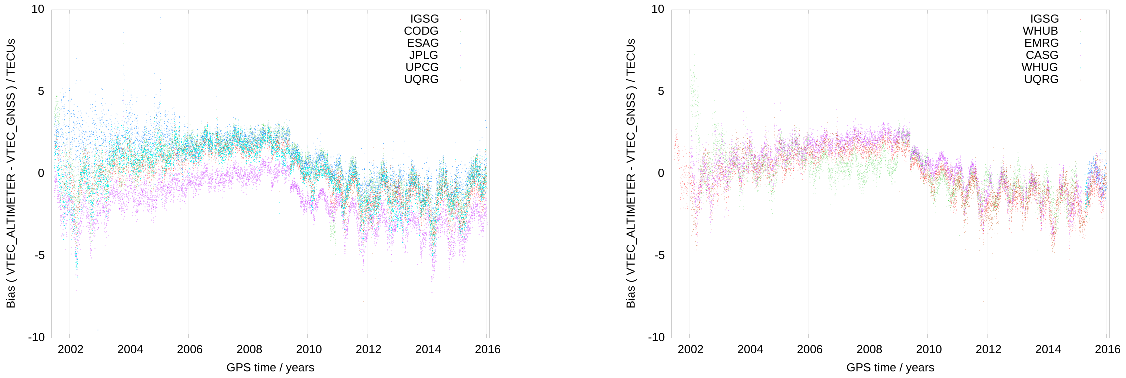

Figure 5: VTEC GIMS Bias regarding JASON* VTEC (daily values, since days 2001.6 to 2016.0).

ferent mapping functions used (related with the general leveling) and the topside electron content climatology between the altimeter and GPS orbit (seen as variations interpreted as "inverse climatology", <VTEC_alt – VTEC_GPS>, in the time series, appearing clearly the Solar Cycle and seasonal cycles, among others.

Multi–GNSS Working Group Technical Report 2016

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1 Introduction

In the beginning of 2016, the status of the Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) was changed to a Pilot Project by the IGS Governing Board. Nevertheless, the name "MGEX" will be retained due to the high recognition received so far. A comprehensive overview of the status of MGEX as of October 2016 is given in the review paper of Montenbruck et al. (2017).

A few changes of membership of the Multi-GNSS Working Group (MGWG) occurred during the reporting period:

- Andrea Stürze succeeded Axel Rülke as representative of Bundesamt für Kartographie und Geodäsie (BKG)
- Zhiguo Deng succeeded Mathias Fritsche as representative of Deutsches GeoForschungsZentrum (GFZ)
- Satoshi Kogure moved from the Japan Aerospace Exploration Agency (JAXA) to the Cabinet Office but is still member of the MGWG
- Inga Selmke joined the MGWG representing Technische Universität München (TUM)

2 GNSS Evolution

This section is limited to the evolving systems Galileo, BeiDou, and IRNSS. The satellite launches of these systems in 2016 are listed in Table 1. The year 2016 marks several important milestones, in particular for Galileo. In November, an Ariane-V launched four

Table 1: GNSS satellite launches in 2016.

Date	Satellite	Type
20 Jan 2016	IRNSS-1E	IGSO
01 Feb 2016	BeiDou M3-S	MEO
10 Mar 2016	IRNSS-1F	GEO
29 Mar 2016	BeiDou IGSO 6	IGSO
28 Apr 2016	IRNSS-1G	GEO
24 Mai 2016	Galileo FOC FM-10/11	MEO
12 Jun 2016	BeiDou GEO 7	GEO
17 Nov 2016	Galileo FOC FM-07/12/13/14	MEO

Galileo satellites at the same time (GPS World Team 2016) increasing the number of Galileo satellites in orbit from 14 to 18. Galileo Initial Services were officially declared by the European Commission on 15 December 2016 (GSA 2016) based on a constellation of 11 satellites for the Open and the Public Regulated Service and 12 satellites for the Search and Rescue service. An update of the Galileo Open Service Signal In Space Interface Control Document was also published in December 2016 (European Union 2016). The two Galileo satellites in eccentric orbit (GSAT-201/2) started an experimental transmission of broadcast messages in August 2016. The satellites are not included in the almanac and the initial update rate was limited to three hours. Starting with November 2016, the update rate was in general increased to 10 min.

Galileo IOV metadata were published by the European Global Navigation Satellite Systems Agency (GSA) on 16 December 2016 (European GNSS Service Center 2016). These data include amongst others information about attitude, transmit antenna phase center corrections, geometry and optical properties, as well as group delays. An important task of the MGWG for 2017 will be the consolidation and exploitation of these data for the generation of the MGEX products.

BeiDou moved forward in completing its constellation with the launch of two second generation (BDS-2) and one third generation (BDS-3) BeiDou satellites (Tan et al. 2016). Version 2.1 of the BeiDou Interface Control Document (China Satellite Navigation Office 2016) was published in November including several clarifications, e.g., for the ionospheric delay model parameters, but not yet covering the BDS-3 signals.

With the launch of the 3rd GEO satellite, the 7-satellite constellation of the Indian Regional Navigation Satellite System (IRNSS) was completed in April 2016. Along with this, the system was renamed to “Navigation with Indian Constellation” (NAVIC).

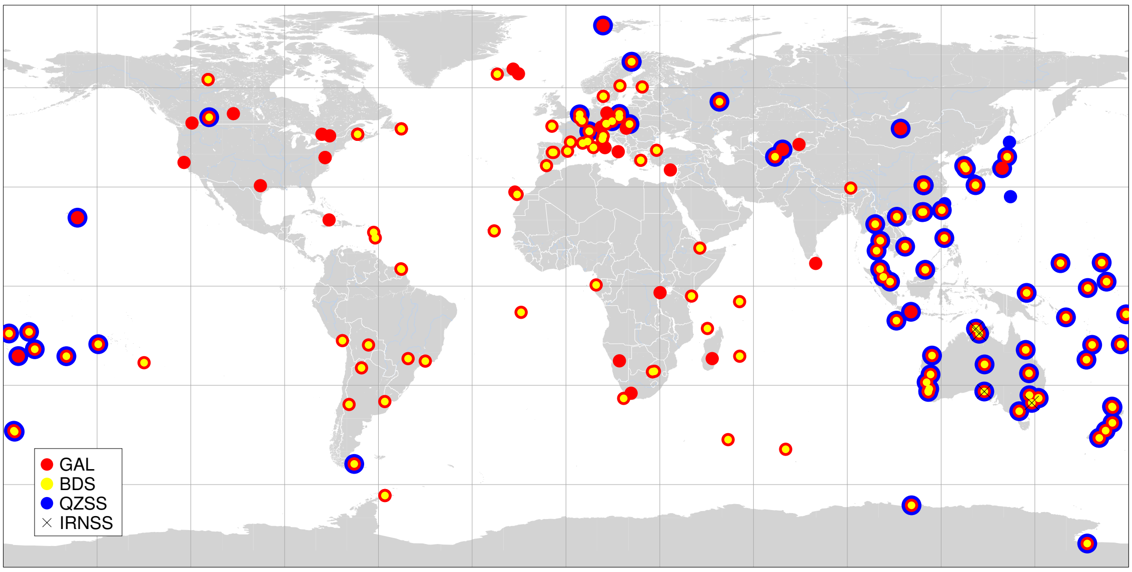

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2017.

3 Network

In 2016, the number of IGS multi-GNSS stations increased from almost 130 to about 180, see Figure 1. About half of the stations also provide real-time streams, mainly via the dedicated MGEX caster (`http://mgex.igs-ip.net/`) but also via the IGS-IP caster (`http://igs-ip.net`). Both casters are operated by BKG and provide the real-time streams in different versions of the RTCM-3 MSM format. First Galileo E6- and IRNSS L5-capable receivers were installed at several locations by Geoscience Australia. The signals of the BDS-3 satellites (Xiao et al. 2016) can only be tracked on the B1 frequency by selected receivers of the IGS network.

4 Products

Six analysis centers (ACs) contribute orbit and clock products to MGEX as listed in Table 2. A detailed review of the MGEX product quality is given in Montenbruck et al. (2017). Recent results of individual ACs are given in Prange et al. (2017) for the Center for Orbit Determination in Europe (CODE) and in Guo et al. (2016b) for Wuhan University. Guo et al. (2017a) evaluated the MGEX Galileo, BeiDou, and QZSS orbit and clock products and found an orbit consistency of 10 – 25 cm for Galileo, 10 – 20 cm for BeiDou MEOs, 20 – 30 cm for BeiDou IGSOs, and 20 – 30 cm for QZSS.

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
Centre National d'Etudes Spatiales/ Collecte Localisation Satellites (CNES/CLS)	grm	GPS+GLO+GAL
Center for Orbit Determination in Europe (CODE)	com	GPS+GLO+GAL+BDS+QZS
Deutsches GeoForschungsZentrum (GFZ)	gbm	GPS+GLO+GAL+BDS+QZS
Japan Aerospace Exploration Agency (JAXA)	qzf	GPS+QZS
Technische Universität München (TUM)	tum	GAL+QZS
Wuhan University	wum	GPS+GLO+GAL+BDS+QZS

Steigenberger et al. (2016) estimated satellite antenna phase center offsets (PCOs) for the Galileo satellites. They proposed rounded PCO values for three different groups of Galileo satellites: In-Orbit Validation (IOV) satellites, Full Operational Capability (FOC) satellites in nominal orbit, and FOC satellites in eccentric orbit (FOCe, i.e., GSAT-201 and -202). These PCO values are given in Table 3 and included in the IGS antenna model starting with the release `igs08_1915.atx` (Schmid 2016). They are used by the MGEX ACs since September 2016.

Table 3: Galileo satellite antenna PCOs as used within the IGS since September 2016. IOV: In-Orbit Validation; FOCe: Full Operational Capability in eccentric orbit; FOC: Full Operational Capability in nominal orbit.

Satellite group	x [cm]	y [cm]	z [cm]
IOV	−17	+3	+95
FOCe	+16	−1	+105
FOC	+12	−1	+110

Version d of the SP3 format (Hilla 2016) was released in February 2016 but none of the MGEX ACs currently uses this format. Major advantage of this format is the increased number of 999 satellites compared to 85 in SP3-c.

The TUM AC switched to a more recent version of the Bernese GNSS Software and implemented the a priori solar radiation pressure (SRP) model of Montenbruck et al. (2015) as well as the "dynamic yaw steering attitude" model of Ebert and Oesterlin (2005) for the Galileo satellites in November 2016 (Selmke 2016). Whereas the original model of Montenbruck et al. (2015) is limited to Galileo IOV, Steigenberger and Montenbruck (2016) provide updated coefficients for the Galileo FOC satellites. Guo et al. (2017b) developed an adjustable box-wing model for BeiDou MEO and IGSO satellites that in particular improves the orbit quality during orbit-normal (ON) mode.

Fritsche (2016) adopted the IGS orbit and clock combination software to include Galileo, BeiDou, and QZSS. They report weighted root-mean square differences with respect to

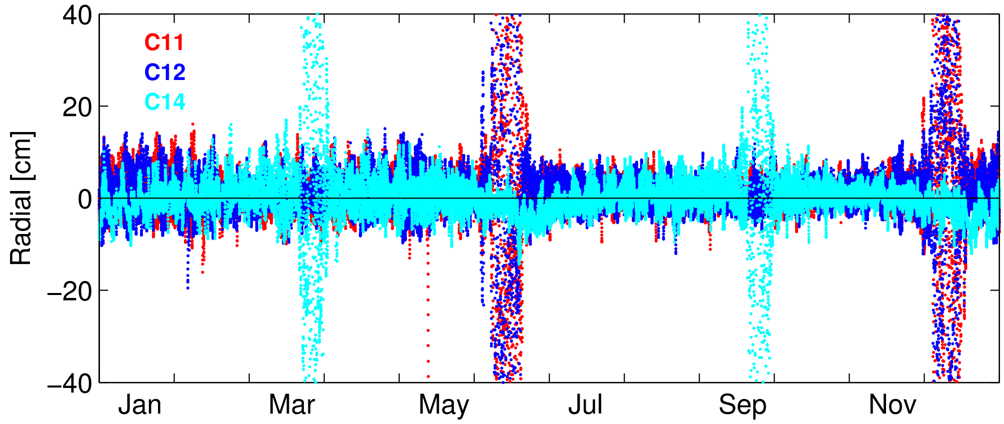

Figure 2: Radial differences for CODE and GFZ BeiDou MEO satellite orbits.

the combined orbit of 5 cm for Galileo, 3 – 5 cm for BeiDou MEOs, 10 – 20 cm for BeiDou IGSOs and QZSS in yaw-steering (YS) mode. During ON mode, these values can be exceeded by far, see Figure 2.

In April 2016, an *Analysis* section was established on the MGEX webpage (`http://mgex.igs.org/analysis/index.php`). It is updated on a weekly basis and includes information on

- MGEX product availability;
- GNSS satellite signal transmission for GPS, GLONASS, BeiDou, Galileo, IRNSS, and SBAS;
- Clock time series of individual BeiDou and Galileo satellites;
- SLR residuals for GLONASS, BeiDou, Galileo, and QZSS;
- Orbit comparisons between the various ACs for GPS, GLONASS, BeiDou (separately for MEO, IGSO, GEO), Galileo, and QZSS.

An example for the comparison of BeiDou MEO satellite orbits of CODE and GFZ is given in Figure 2. Large differences can be seen during ON mode as this attitude mode is not yet considered by CODE.

Two ACs contribute Differential Code Bias (DCB) products to MGEX. Whereas the Chinese Academy of Sciences (CAS) DCB product (Wang et al. 2016) is updated on a daily basis, the Deutsches Zentrum für Luft- und Raumfahrt (DLR) product has a quarterly update rate. Since the second quarter of 2016, the DLR DCB product is provided in version 1.00 of the Bias SINEX format (Schaer 2016a). Please note that the December 2016 version of the Bias SINEX format (Schaer 2016b) uses a 4-digit year whereas the version of February 2016 (Schaer 2016a) which is implemented by DLR uses a 2-digit year for specifying validity intervals.

Acronyms

BKG Bundesamt für Kartographie und Geodäsie

CAS Chinese Academy of Sciences

CLS Collecte Localisation Satellites

CNES Centre National d'Etudes Spatiales

CODE Center for Orbit Determination in Europe

DLR Deutsches Zentrum für Luft- und Raumfahrt

GFZ Deutsches GeoForschungsZentrum

JAXA Japan Aerospace Exploration Agency

TUM Technische Universität München

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IGS Reference Frame Working Group Technical Report 2016

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1 Introduction

Besides the generation of the operational IGS SINEX combination products (Section 2), the main activity of the Reference Frame Working Group in 2016 was the preparation of the IGS realization of ITRF2014, IGS14, and of the associated set of satellite and ground antenna calibrations, igs14.atx, in cooperation with the Antenna Working Group (Section 3).

2 Operational SINEX combinations

Figure 1 shows the RMS of the AC station position residuals from the daily IGS SINEX combinations of year 2016, i.e. the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed. The RMS of the AC station position residuals have globally remained at the same levels as in 2015, with two notable exceptions:

- The RMS of GRG's residuals have substantially decreased starting with GPS week 1915, after an error in the handling of ground antenna calibrations was corrected.
- The RMS of JPL's residuals show several excursions actually due to numerical issues which distorted a few daily JPL solutions during their pre-processing. The origin of the problem has now been identified and solved.

The AC Earth Orientation Parameter (EOP) residuals from the IGS SINEX combinations of year 2016 (Figure 2 and 3) show similar features as in the previous years. The main notable difference is the appearance of spikes in JPL's pole coordinate residual time

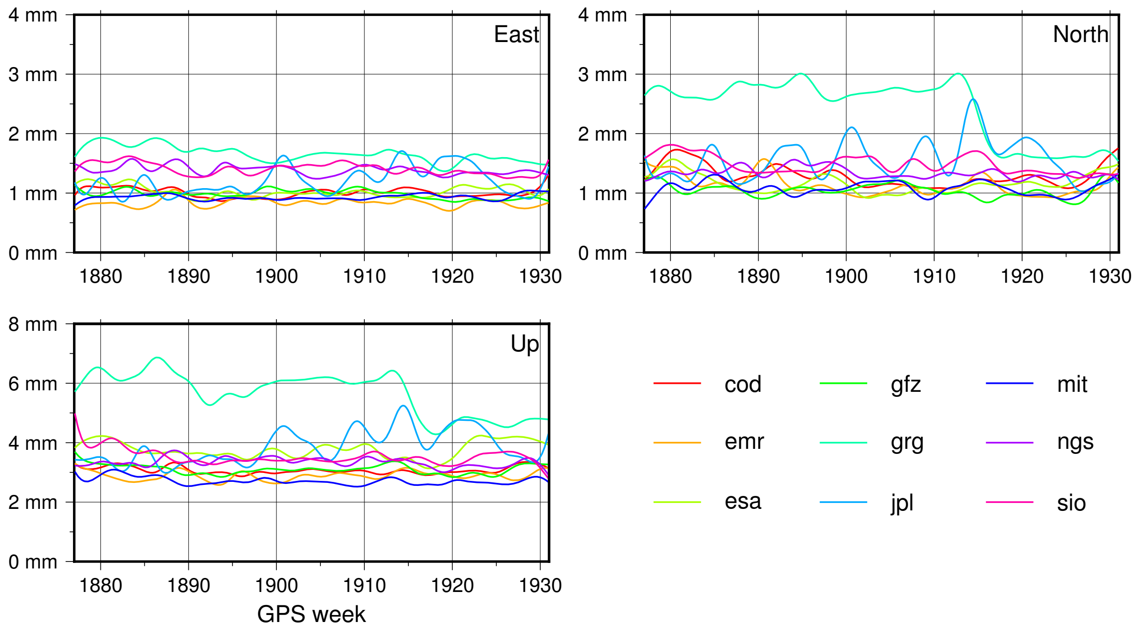

Figure 1: RMS of AC station position residuals from the 2016 daily IGS SINEX combinations. All time series were low–pass filtered with a 10 cycles per year cut–off frequency.

series, corresponding to the same daily solutions with abnormally large station position residuals.

3 Preparation of the IGS14/igs14.atx framework

After the latest release of the International Terrestrial Reference Frame (ITRF2014; Altamimi et al. (2016)) was published in January 2016, the Reference Frame Working Group and the Antenna Working Group started preparing the IGS realization of ITRF2014, IGS14, and the associated set of satellite and ground antenna calibrations, igs14.atx. This preparation included:

- selection of the most suitable reference frame (RF) stations from the complete set of GNSS stations in ITRF2014, and design of a well–distributed core network of RF stations for the purpose of aligning global GNSS solutions (Section 3.1),
- updates of the ground antenna calibrations of various antenna types and assessment of the impact of these updates on station coordinates (Section 3.2),
- re—evaluation of the radial components of all GPS and GLONASS satellite antenna phase center offsets (Section 3.3),
- actual implementation and validation of the new IGS14/igs14.atx framework (Section 3.4).

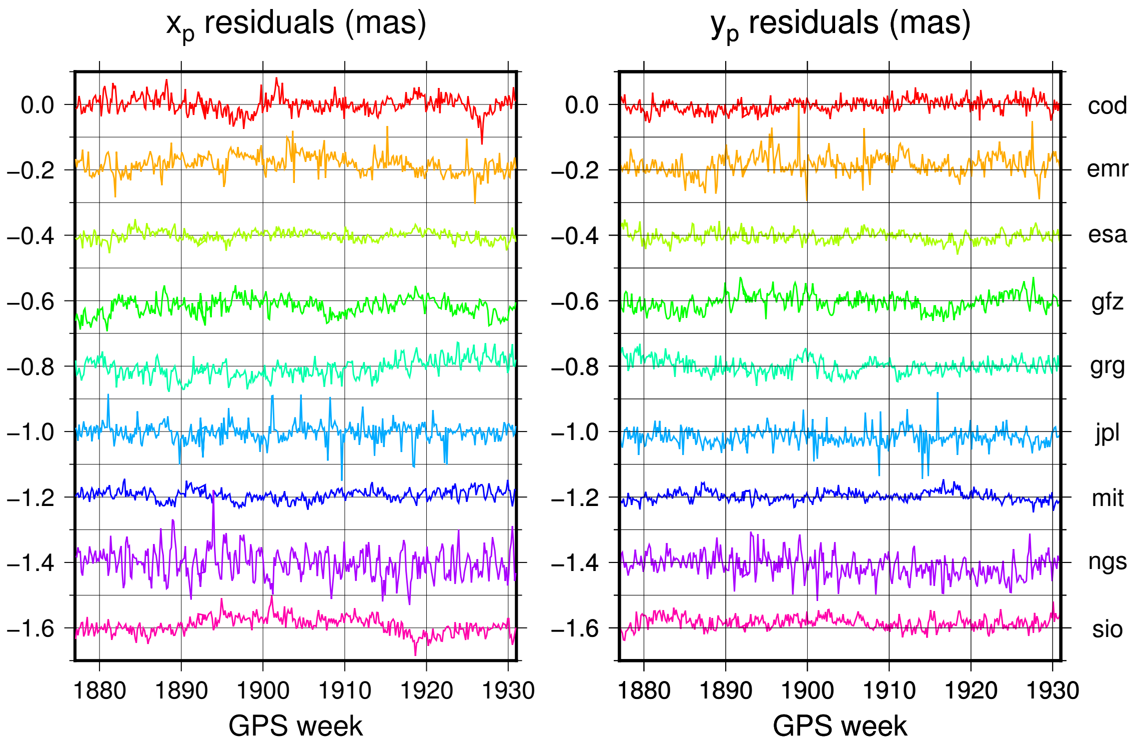

Figure 2: AC pole coordinate residuals from the 2016 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 0.2 mas for clarity.

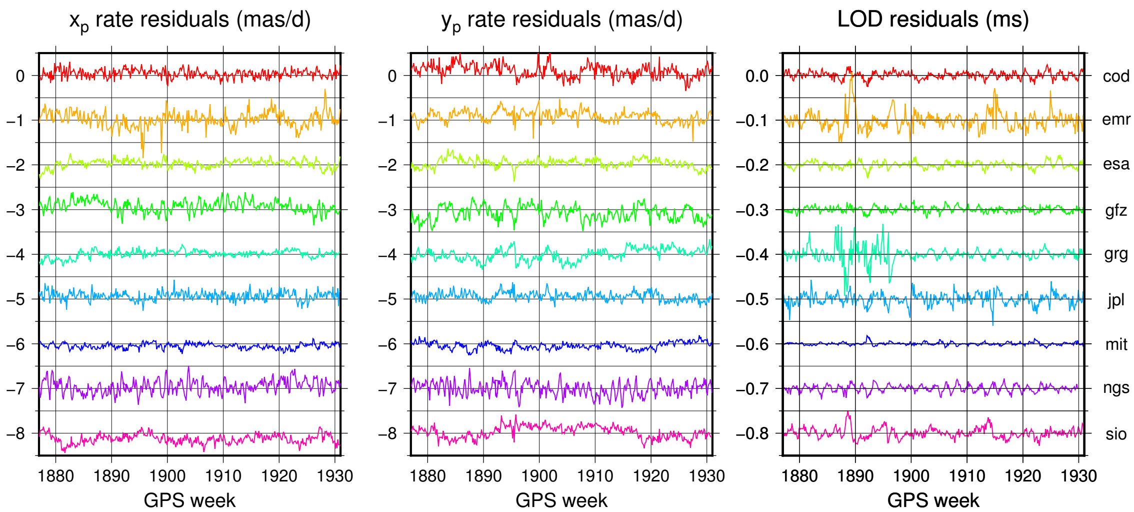

Figure 3: AC pole rate and LOD residuals from the 2016 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 1 mas/d and 0.1 ms for clarity.

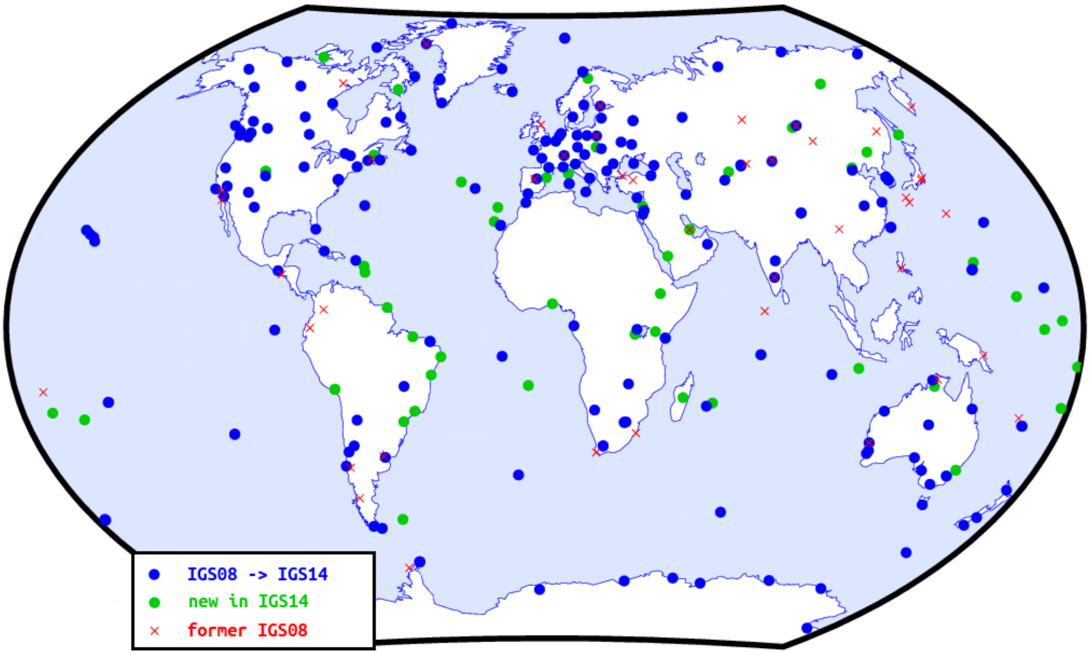

Figure 4: Distribution of the IGS14 and of the former IGS08 RF stations.

3.1 IGS14 and IGS14 core network design

A first selection of the potential IGS14 RF stations from the full set of IGS stations in ITRF2014 was made according to the following criteria:

- ITRF2014 time series longer than 5 years; at least 1000 (daily) data points,
- WRMS of ITRF2014 residual time series (including seasonal signals) smaller than 2.5 mmin horizontal and 7.5 mmin vertical,
- maximum formal error of ITRF2014 coordinates over expected IGS14 lifetime smaller than 1.5 mmin horizontal and 3 mm in vertical.

In "dense" areas, multi–GNSS and real–time, but also previous IGb08 RF stations were favored, while in "sparse" areas, a few stations had to be retained that do not strictly meet all criteria. A notification was then sent to the operators of the pre–selected stations (thanks to D. Maggert and N. Romero), resulting in slight adjustments of the station selection according to the answers received. The final list of selected IGS14 RF stations comprises 252 stations (compared to 235 in IGb08) whose distribution is shown in Figure 4.

A well–distributed IGS14 core network was additionally designed for the purpose of aligning global GNSS solutions. It is composed of 51 clusters of stations (i.e., 51 primary stations, each with possible substitutes) selected to ensure a homogeneous global distri-

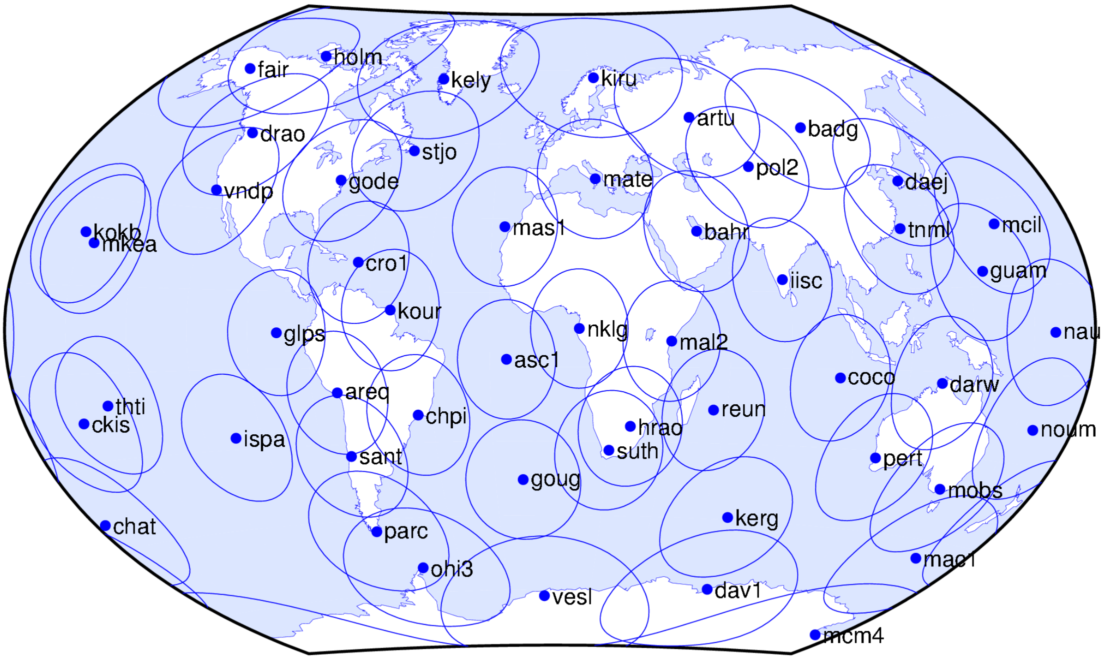

Figure 5: Distribution of the 51 primary stations of the IGS14 core network.

bution (Figure 5) and the best possible temporal stability of the core network.

3.2 Ground antenna calibration updates and their impact on station positions

Compared to igs08.atx, igs14.atx includes robot calibrations for 17 additional ground antenna types. 19 type–mean robot calibrations could also be updated thanks to the availability of calibration results for additional antenna samples. The impact of these ground antenna calibration updates on IGS station positions was assessed by means of differential PPP solutions. In general, the estimated position offsets are not negligible and can reach up to 6 mm in horizontal and 19 mm in vertical (see ftp://igs-rf.ign.fr/pub/IGS14/igs08_to_igs14_offsets.txt).

While ITRF2014 coordinates are consistent with the igs08.atx set of antenna calibrations, IGS14 needs to be consistent with the updated igs14.atx set. After the coordinates of the 252 selected IGS14 stations were extracted from ITRF2014, they thus had to be corrected in order to account for ground antenna calibration updates from igs08.atx to igs14.atx. For that purpose, the position offsets estimated from our PPP analyses were applied to the ITRF2014 coordinates of the affected IGS14 stations whenever exceeding 1 mm in either direction. The coordinate corrections actually applied are listed in ftp:

//igs-rf.ign.fr/pub/IGS14/ITRF2014_to_IGS14.txt.

Finally, so that users can assess the impact of the ground antenna calibration updates from igs08.atx to igs14.atx on the positions of specific (non–IGS) stations, a set of latitude–dependent coordinate change models was developed and made available at ftp://igs-rf.ign.fr/pub/IGS14/lat_models.txt.

3.3 Satellite antenna calibration updates

Despite the negligible scale difference between ITRF2008 and ITRF2014 (0.02 ppb), the radial components of all GPS and GLONASS satellite antenna phase center offsets (z–PCOs) had to be updated in igs14.atx, because of recent modeling changes affecting the scale of the IGS products (Earth radiation pressure, antenna thrust). This was achieved by deriving time series of satellite antenna z–PCO estimates, consistent with the ITRF2014 scale, from the daily repro2 and latest operational SINEX solutions of seven ACs. The AC z–PCO time series were then trend–corrected to epoch 2010.0 before computing weighted averages. The igs14.atx satellite antenna z–PCO values are therefore expected to give access to the ITRF2014 scale at epoch 2010.0. From igs08.atx to igs14.atx, satellite antenna z–PCOs change by –6 cm on average, which induces a net scale change of the IGS terrestrial frame solutions by approximately +0.5 ppb (+3 mm).

Time series of satellite antenna x– and y–PCOs were also derived from the daily AC repro2 and operational SINEX solutions (Rebischung and Schmid 2016a)). They were however found to be contaminated by large Sun–elevation– and eclipse–related signals, and the agreement between the mean values obtained from the different ACs was judged too poor to use them to update the satellite antenna x– and y–PCOs in igs14.atx. Finally, only the x– and y–PCOs of the GPS Block IIR satellites were updated in igs14.atx, based on pre–flight calibration values (Dilssner et al. 2016).

3.4 Validation and implementation

Preliminary versions of IGS14 and igs14.atx were made available to the IGS ACs in July 2016. Parallel IGS14–based solutions were requested from the ACs providing final products for validation purposes and combinations of the parallel AC SINEX solutions were carried out for GPS weeks 1925–1929. The residuals of these test combinations were at the same level as in the operational combinations and the differences to the operational products did not show any unexpected features.

In order to gain more insight into the impact of the switch from IGb08/igs08.atx to IGS14/igs14.atx on GNSS–derived geodetic parameters, the daily repro2 AC solutions were additionally re–combined with two changes compared to the official daily repro2 SINEX combinations (Rebischung et al. 2016):

- Satellite PCOs were fixed to their igs14.atx values in the input AC solutions.
- The combined solutions were aligned to the IGS14 core network.

The results of these test combinations are presented in (Rebischung and Schmid 2016b). Only marginal impacts were obtained for both Earth Orientation Parameters and apparent geocenter coordinates.

In coordination with the IERS, GPS week 1934 (29 January 2017) was finally chosen as the date for the switch of the IGS products from the IGb08/igs08.atx to the IGS14/igs14.atx framework. T he switch was announced to the community in [IGSMAIL–7399], together with details about the elaboration of IGS14 and igs14.atx and their impact on user results.

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IGS Realtime Service Technical Report 2016

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1 Introduction

The Real Time Service (RTS) expands the capacity of the International GNSS Service (IGS) to support applications requiring real-time access. It utilises a global receiver network and provides infrastructure for data and product dissemination. Analysis products include individual Analysis Centre as well as combination solutions. There is a large variety of potential applications for the service with a strong focus on scientific and educational applications.

2 Observation network

The IGS-RTS is based on a global network of IGS stations providing data streams to the RTS observation broadcasters. There are several observation broadcasters in operation including the first level global casters at BKG, CDDIS and IGS Central Bureau. In order to reduce work load for the operators second level casters are going to be installed. There is one caster already operating at Wuhan University/China. Another caster operated by Geoscience Australia is almost ready to go live and will take care of users in the region of Southeast Asia and Australasia. Other regional data centres are proposed for North and South America and Europe. In order to improve redundancy in the case of failure, the station operators are encouraged to provide their data streams to at least two independent global data centres.

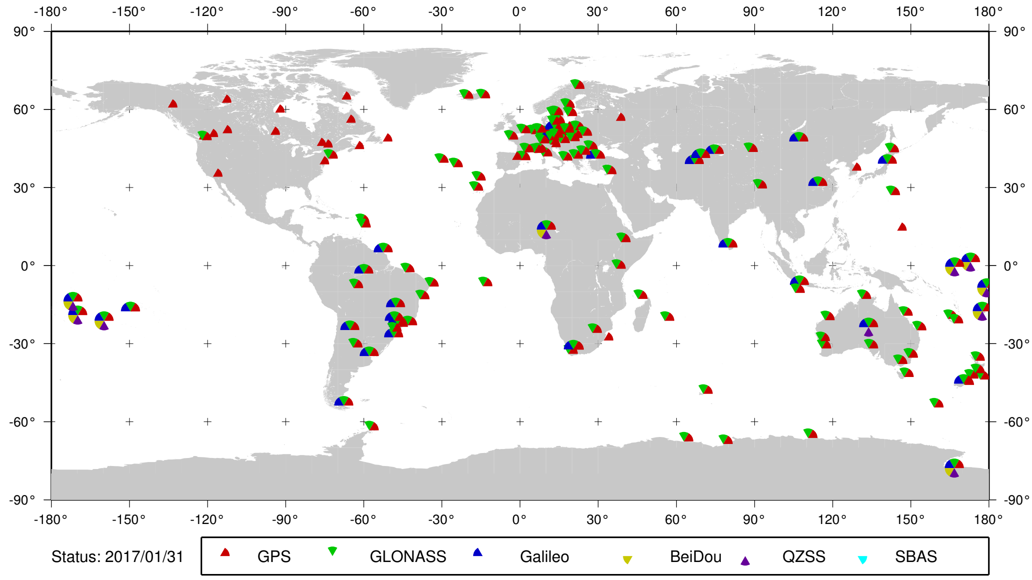

Figure 1: Global distribution of IGS real time sites from real time caster `igs-ip.net`.

The station network is operated by a large number of contributors on a best effort basis. Figures 1 and 2 display the present distribution of sites across the globe for the IGS caster and the MGEX caster at BKG respectively. Since IGS supports open data standards both casters provide data streams following the RTCM standard. All streams on the IGS caster are receiver generated RTCM streams as supported by the receiver firmware. The streams on the MGEX caster are converted from raw data by an external software conversion tool. As soon as more receivers providing RTCM3 multi constellation data (MSM5 or better MSM7) become available the number of software generated streams will be reduced.

3 State Space Respresentation correction streams

There are eight real time Analysis Centres (AC) which use different software packages to compute epoch-wise orbit and clock products. The large number of ACs ensures a high redundancy of the service on the one hand and a strong quality control on the other hand. The estimates are converted into RTCM SSR format and can be accessed via IGS RTS product casters. The orbit products are available with respect to the satellite Antenna Phase Centre (APC) and in most cases they are also available with respect to the Centre of Mass (CoM). The clock products are updated every 5 seconds. Table 1 gives a summary of all individual product streams by the different ACs. The performance of the service is illustrated for GPS and GLONASS clocks and orbits in Figure 3.

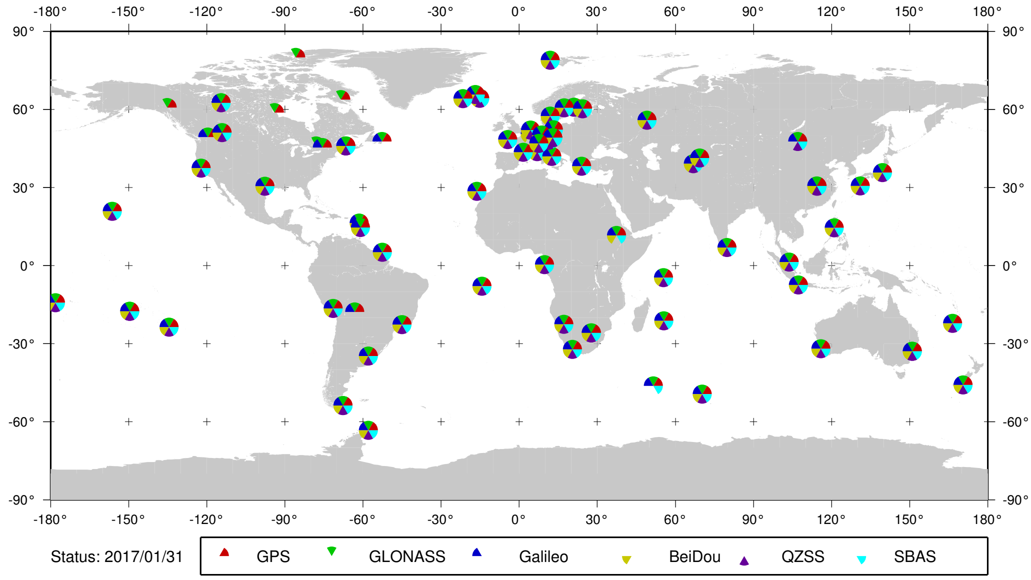

Figure 2: Global distribution of IGS real time sites providing multi constellation GNSS data from real time caster `mgex.igs-ip.net`.

After processing the individual AC solutions in Real Time, RTS combination products are made available to users of the service (Table 2). Two basic techniques, a single epoch combination developed by ESOC and a Kalman filter based combination developed by BKG and Prague Technical University, are used. Although a combination increases the robustness of the product it also increases the latency of the combined product significantly. Since many of the individual streams have a latency of about 10s or less, the latency of the combined product is in the range of 20-30s. The reduction of latency is an important goal of the real time service and requires an optimized selection of reference stations and processing schemes.

The RTCM streams of the RTS can be used directly in order to perform Real Time Precise Point Positioning (PPP). In order to monitor the overall performance, a number of stationary sites are processed continuously using all available correction streams. Figure 4 shows the real time results for the FFMJ reference station located in Frankfurt am Main/Germany. The left subfigure clearly shows the typical running-in-characteristic (convergence time) of about 30 minutes after a re-initialization (cold start) of the processing. The right figure shows the present potential of the service in a long-running experiment.

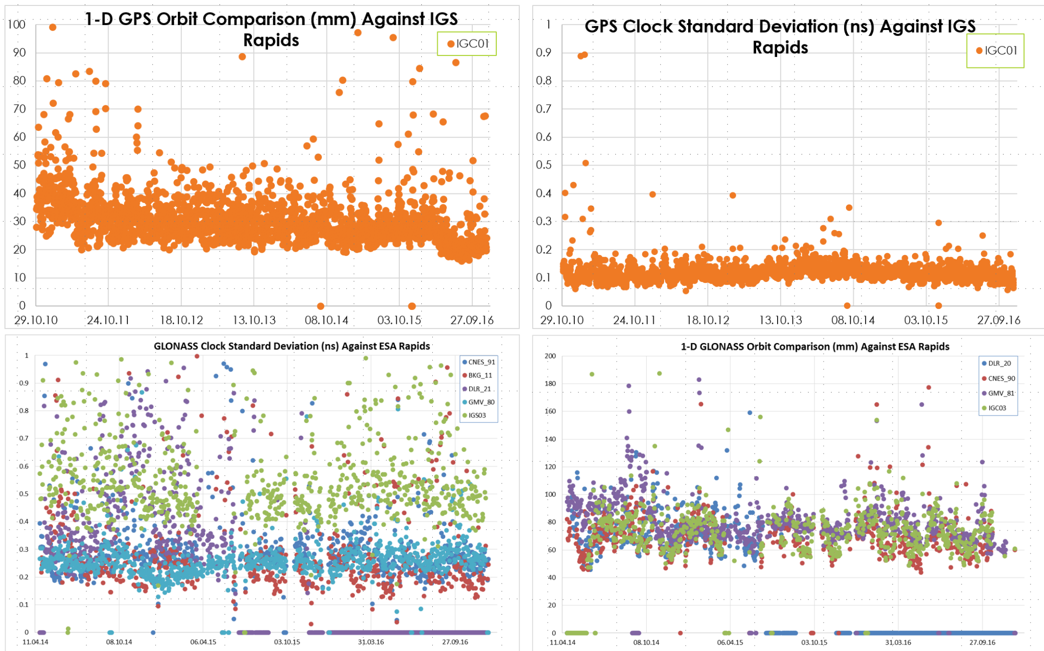

Figure 3: Performance of orbit and clock estimates for the IGS RTS solutions. Top: IGC01 combination orbit and clock performance for GPS, bottom: Statistics for AC and IGC03 solutions for GLONASS.

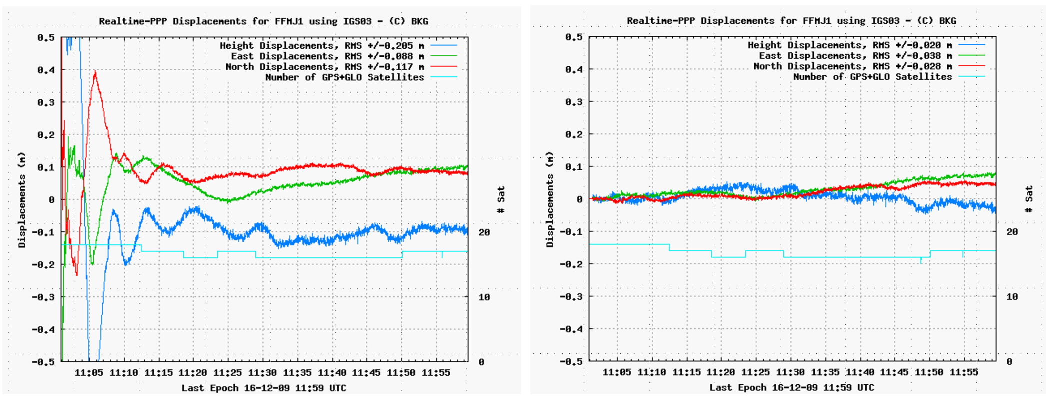

Figure 4: Performance of the coordinate estimates from FFMJ (Frankfurt am Main) from IGS RTS correction data stream IGS03. Left: cold start with running-in-characteristic. Right: warm start.

4 Summary

Thanks to the contributions from a large number of partners, the IGS RTS operates a dense high quality real time GNSS network. The observation data is used to derive orbit and clock products which allow user PPP at decimetre accuracy. A limitation is the convergence time of about 30 minutes and the latency of the combined products of 20-30s.

The IGS RTS ensures open access to its data and products and supports open standards and data formats. Data and products are provided via TCP/IP connections. The range of applications is focused on scientific and educational topics, such as positioning, navigation and timing, Earth observations and research; and other applications that benefit the scientific community and society.

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Weber, G., L. Mervart, L. Agrotis, and A. Stürze. Real-time Combination of GNSS Orbit and Clock Correctors for Precise Point Positioning. presented at IUGG/IAG General Assembly, Melbourne, July 2011.

Table 1: Correction streams from IGS Real Time Service by individual ACs

Center	Description	NTRIP MP CoM/APC
BKG	GPS GPS + GLONASS RT orbits and clocks using IGU orbits	CLK00/10
	GPS + GLONASS RT orbits and clocks using IGU orbits	CLK01/11
CNES	GPS RT orbits and clocks based on IGU orbits	CLK92/93
	GPS+GLONASS orbits and clocks	CLK90/91
DLR	GPS RT orbits and clocks based on IGU orbits	CLKC0/A0
	GPS+GLONASS orbits and clocks (DLR caster)	CLKC1/A1
ESOC	RT orbits and clocks using NRT batch orbits every 2 hours which are based on IGS Batch hourly files	CLK50/51
	RT orbits and clocks using NRT batch orbits every 2 hours which are based on RINEX files generated from the RT stream	CLK52/53
GFZ	RT orbits and clocks and IGU orbits	CLK70/71
GMV	RT orbits and clocks based on NRT orbit solution	CLK81/80
NRCan	GPS orbits and clocks using NRT batch orbits every hour	-/CLK22
WUHAN	GPS orbits and clocks based on IGU orbits	CLK15/16

Table 2: Combined correction stream by IGS Real Time Service by individual Combination Centres

Centre	Description	NTRIP MP
ESOC	GPS-only combination – epoch-wise approach	IGC01/IGS01
BKG	GPS-only combination – Kalman filter approach	-/IGS02
	GPS+GLONASS combination – Kalman filter approach	-/IGS03

Tide Gauge Benchmark Monitoring Working Group Technical Report 2016

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May 11, 2017

1 Introduction

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

The main aims of the TIGA Working Group are:

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

2 Main Progress in 2016

- TIGA Working Group members actively participated in the IGS Workshop in Sydney/Australia with several posters (see http://kb.igs.org/hc/en-us/sections/200763007-2016-IGS-Workshop-Sydney-Australia)
- Working group meeting during the IGS Workshop in Sydney/Australia
- TIGA reprocessing period was extended by all TIGA analysis Centers to cover all data to the end of 2015.
- GeoScience Australia is now contribution to the TIGA reprocessing
- TIGA Network operator works with Tide Gauge and GNSS station operators to make existing stations available to TIGA, a main (ongoing) task is to update the current database of existing local ties between GNSS and tide gauge benchmarks. By the end of 2016 about 173 local ties information are available at http://www.sonel.org/-Stability-of-the-datums-.html?lang=en. For the stations directly committed to TIGA the number of ties raised to 76. The current number of GNSS@TG stations is 820 stations (with 119 stations decommissioned).
- The TIGA-WG carried forward the GLOSS-Task "Priorities for installation of continuous Global Navigation Satellite System (GNSS) near to tide gauges. Report to Global Sea Level Observing System (GLOSS)" by King, M.A. (2014) for the densification and extension of the TIGA Observing Network to GGOS. The response by the GGOS Coordinating Board was received early 2017.

3 Current data holding of TIGA reprocessed individual solutions

Table 1: Current data holding of TIGA reprocessed individual solutions.

TIGA Analysis Center (TAC)	Start GPS week	End GPS week
AUT (Geoscience Australia)	0834	1891
BLT (University of Nottingham , University of Luxembourg)	0782	1722
DG2 (DGFI/TUM Germany)	0887	1824
GT2 (GFZ Potsdam TIGA Solution)	0730	1877
UL2 (University La Rochelle)	0782	1773

4 TIGA Working Group Members in 2016

Working group members are listed in Table 2.

Table 2: TIGA Working Group Members in 2016

Name	Entity	Host Institution, Country
Guy Wöppelmann	TAC, TNC, TDC	University La Rochelle, France
Laura Sánchez	TAC	DGFI TU Munich, Germany
Heinz Habrich	TAC	BGK, Frankfurt, Germany
Minghai Jia		GeoScience Australia, Australia
Paul Tregoning		ANU, Australia
Zhiguo Deng	TAC	GFZ Potsdam, Germany
Daniela Thaller	Combination	BGK, Frankfurt, Switzerland
Norman Teferle	TAC/Combination	University of Luxembourg, Luxembourg
Richard Bingley	TAC	University of Nottingham, UK
Ruth Neilan	IGS Central Bureau	ex officio, USA
Tom Herring	IGS AC coordinator	ex officio, USA
Michael Moore	IGS AC coordinator	ex officio, Australia
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 South Florida, USA
Mark Merrifield	GLOSS GE (past chair)	UHSLC, Hawaii, USA
Matt King		University of Tasmania, Australia

IGS Troposphere Working Group Technical Report 2016

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1 Introduction

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

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

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

2 IGS Final Troposphere Product Generation/Usage 2016

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 GNSS Software Dach et al. (2015) using precise point positioning (PPP, (Zumberge et al. 1997)) and the GMF map-

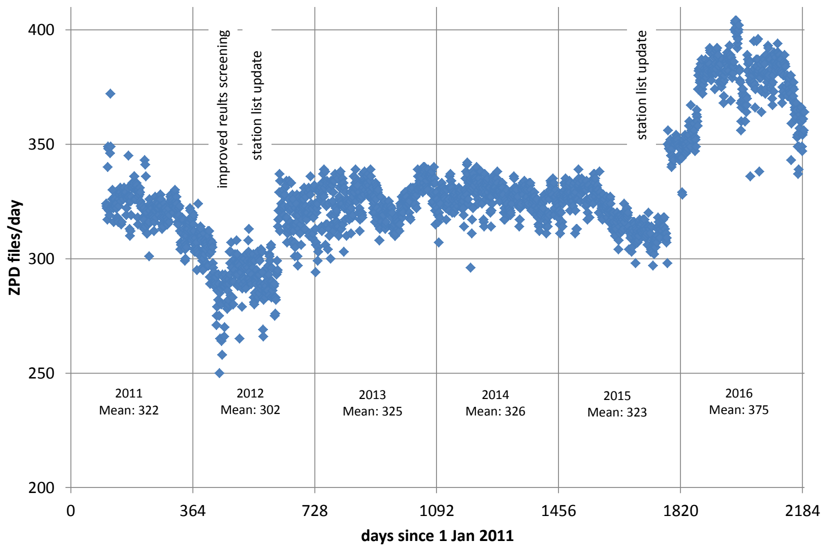

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011-6. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011.)

ping function Boehm et al. (2006) with IGS Final satellite orbits/clocks and earth orientation parameters (EOPs) as input. Each site-dayâĂŹs 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 2011-6. The average number of quality-checked station result files submitted per day in 2016 was 375, much higher than the 2015 average value of 323 due to an updated station list in December 2015. The result files can be downloaded from `ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd`. 46.3 million files were downloaded in 2016 by users from over 1000 distinct hosts Noll (2016), a marked increase in usage over the 20.9 million files downloaded in 2015.

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

3 IGS Troposphere Working Group Activities 2016

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

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

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

3.1 2016 Working Group Meetings

The working group met once in 2016: in conjunction with the 2016 IGS Workshop in Sydney, Australia, February 2016. The meeting planned in conjunction with the 2016 AGU in San Francisco, CA was postponed due to Dr. Byram being unable to travel.

The February 2016 meeting featured presentations by:

- WG chair S Byram on (1) the quality and production of IGS Final Troposphere Estimates, (2) the status of current working-group projects, and (3) a discussion of future projects
- Dr. Jan Douša, Geodetic Observatory Pecny (GOP; Czech Republic) on the status of the troposphere inter-technique comparison database/website (see "Working Group Projects" below)

Presentations from the meeting were distributed via the IGS TWG email list (message IGS-TWG-143) and can be obtained by contacting this report's author.

3.2 Working Group Projects

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

One way to assess the accuracy of GNSS-derived troposphere estimates is to compare them to those obtained for the same time/location using an independent measurement technique, e.g., VLBI[1] , DORIS[2] , radiosondes, or from a numerical weather model. Comparisons

[1] Very Long Baseline Interferometry
[2] Doppler Orbitography and Radiopositioning Integrated by Satellite

of GNSS-derived troposphere estimates computed by different analysis centers or using different models can also serve this purpose.

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

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

In 2014, a grant proposal, Automated Intra- and Inter-technique Troposphere Estimate Comparisons, made to the Kontakt II Czech-US research partnership by Dr. Douša with supporting documents authored by then 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 in November 2016.

Completion of this project is expected in 2017 when the website will be accessible to the community. This system has received interest from climatologists/meteorologists, e.g., those associated with the GRUAN[3] and COST[4] Action 1206 (GNSS4SWEC) projects, as it will simplify quality-comparison and perhaps acquisition of data used as input to their studies.

3.2.2 Standardization of the tropo_sinex format

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

This project, spearheaded by IGS Troposphere WG members Drs. Rosa Pacione and Jan Douša, is being conducted within the COST Action 1206 (GNSS4SWEC) Working Group 3. This COST WG consists of representatives from a variety of IAG[5] organizations and other communities; its work is further supported by the EUREF Technical Working

[3] GCOS (Global Climate Observing System) Reference Upper Air Network: http://www.gruan.org
[4] European Cooperation in Science and Technology: http://www.cost.eu
[5] International Association of Geodesy

Group[6] as well as E-GVAP[7] expert teams. The WG is currently defining in detail a format able to accommodate both troposphere values and the metadata (e.g., antenna height, local pressure values) required for further analysis/interpretation of the troposphere estimates, with progress made in 2016, and a format to be circulated for discussion/approval in 2017. For more information, please contact Dr. Pacione at rosa.pacione@e.geos.it or Dr. Douša.

3.2.3 Automated Analysis Center Estimate Comparisons

A suggestion was made by an IGS Analysis Center representative that the next working group project should be to re-establish the troposphere estimate comparisons for each AC. This project would consist of first comparing the Repro2 Analysis Center results in the comparison database developed by J Douša and then automating the comparison of the final troposphere estimates of the ACs as they become available. A survey asking for interest and participation in such a comparison was sent via the IGS TWG email list (message IGS-TWG-143) and AC email list (message IGS-ACS-1088).

3.3 Activities at the 2016 IGS Workshop

WG chair Dr. Sharyl Byram organized troposphere-related activities for the 2016 IGS Workshop, soliciting presenters for the troposphere plenary and poster sessions, and holding the working-group meeting.

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.

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

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

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

5 Acknowledgements

Development of the troposphere-comparison database/website is supported by KONTAKT II project number LH14089. The author furthermore thanks the University of New South Wales for hosting the February 2016 working group meeting, IGS (especially A Craddock) for providing a room for the (cancelled) December 2016 meeting, and the IGS Central Bureau for the use of its gotomeeting.com subscription.

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Appendix A. IGS Troposphere Working Group Members

Last Name	First Name	Institution	Country
Ahmed	Furqan	Universite du Luxembourg	Luxembourg
Amirkhani	Mohammad	Islamic Azad Univ. Tehran	Iran
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Appendix B. IGS TROPOSPHERE WORKING GROUP CHARTER

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

The primary goals of the IGS TWG are to:

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

Science background

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

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

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

Be it resolved that the IGS troposphere WG will:

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

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