

International Earth Rotation and Reference Systems Service (IERS)
Service International de la Rotation Terrestre et des Systèmes de Référence

IERS Annual Report 2017

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IERS Annual Report 2017

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1 Foreword

The big news for the IERS in 2017 was the adoption of the International Terrestrial Reference Frame 2014 (ITRF2014). In support of the ITRF2014, IERS Technical Note #38 (“Analysis and results of ITRF2014”) was released in early 2017. On a related note, IERS Technical Note #39 (“IGN best practices for surveying instrument reference points at ITRF co-location sites”) was also published in 2017.

In accordance with the change in the ITRF, the Earth orientation series of the IERS Earth Orientation Center (EOC) and Rapid Service/Prediction Center (RS/PC) were realigned to be consistent with ITRF2014. As a result, the 14C04 series replaced the 08C04 series.

The IERS Conventions made several changes in 2017. First, the Conventions web site and ftp site were reorganized. Second, a number of modifications to the electronic version of the Conventions were made in order to be consistent with current international standards and conventional models. For more information on these changes, please consult the IERS Conventions web sites.

Along with the International Association of Geodesy (IAG) and the Global Geodetic Observing System (GGOS), the IERS co-sponsored the Unified Analysis Workshop (UAW), which was held 10–12 July 2017 in Paris, France. Some of the recommendations from this meeting have already been adopted by the scientific community while the others are expected to be adopted as time and resources permit.

The IERS Directing Board (DB) welcomed two new DB members. Guangli Wang replaced Chopo Ma as one of the IVS representatives to the IERS and Richard Gross replaced Bernd Richter as the GGOS representative to the IERS. The IERS owes a tremendous debt to both Chopo and Bernd for their decades of service to the IERS and to the international scientific community. We were fortunate to have their leadership for several years and the IERS would not be what it is without their contributions. We wish Chopo and Bernd well in their retirement.

*Brian Luzum
Chair, IERS Directing Board, 2017*

2 The IERS

2.1 Structure

From 2017 to the beginning of 2019, the IERS had the following components. For their functions see the Terms of Reference ([Appendix 1](#)), for addresses and electronic access see Appendices [3](#) and [4](#). Dates are given for changes between 2017 and 1 January 2019. For reports of components see [Chapter 3](#).

Analysis Coordinator	Thomas Herring (until 31 Dec. 2018), Robert Heinkelmann (since 1 Jan. 2019)
Central Bureau	<i>Director:</i> Daniela Thaller
Technique Centres	International GNSS Service (IGS) <i>IGS Representatives to the IERS Directing Board:</i> Rolf Dach, Chuck Meertens <i>IERS Representative to the IGS Governing Board:</i> Richard Gross International Laser Ranging Service (ILRS) <i>ILRS Representatives to the IERS Directing Board:</i> Erricos C. Pavlis, Ludwig Combrinck (until 30 Nov. 2017), Jürgen Müller (Apr. – Nov. 2018), Jean-Marie Torre (since Dec. 2018) <i>IERS Representative to the ILRS Directing Board:</i> Daniela Thaller International VLBI Service for Geodesy and Astrometry (IVS) <i>IVS Representatives to the IERS Directing Board:</i> Chopo Ma (until 30 Sep. 2017), Rüdiger Haas, Guanli Wang (since 12 Oct. 2017) <i>IERS Representative to the IVS Directing Board:</i> Chopo Ma (until 30 Sep. 2017), Rüdiger Haas (since 16 Oct. 2017) International DORIS Service (IDS) <i>IDS representatives to the IERS:</i> Jérôme Saunier, Hugues Capdeville <i>IERS Representative to the IDS Governing Board:</i> Brian Luzum
Product Centres	Earth Orientation Centre <i>Primary scientist and representative to the IERS Directing Board:</i> Christian Bizouard

Rapid Service/Prediction Centre*Primary scientist and representative to the IERS Directing Board:*

Christine Hackman

Production director and lead project scientist: Nick Stamatakos**Conventions Centre***Primary scientists:* Nick Stamatakos, Christian Bizouard*Current representative to the IERS Directing Board:*

Christian Bizouard (until 31 Dec. 2018),

Nick Stamatakos (since 1 Jan. 2019)

ICRS Centre*Primary scientists:* Bryan Dorland, Jean Souchay*Current representative to the IERS Directing Board:*

Jean Souchay

ITRS Centre*Primary scientist and representative to the IERS Directing Board:*

Zuheir Altamimi

Global Geophysical Fluids Centre*Head and representative to the IERS Directing Board:*

Jean-Paul Boy

Co-Chair: Tonie van Dam**Special Bureau for the Oceans***Chair:* Richard S. Gross**Special Bureau for Hydrology***Chair:* Jianli Chen**Special Bureau for the Atmosphere***Chair:* David A. Salstein**Special Bureau for Combination***Chair:* Tonie van Dam**ITRS Combination
Centres****Deutsches Geodätisches Forschungsinstitut (DGFI)***Primary scientist:* Manuela Seitz**Institut Géographique National (IGN)***Primary scientist:* Zuheir Altamimi**Jet Propulsion Laboratory (JPL)***Primary scientist:* Richard S. Gross**Working Groups****Working Group on Site Survey and Co-location***Chair:* Sten Bergstrand*Co-Chair:* John Dawson

Working Group on SINEX Format

Chair: Daniela Thaller

Working Group on Site Coordinate Time Series Format

Chair: Laurent Soudarin

(Status as of 1 January 2019)

2.2 Directing Board

From 2017 to the beginning of 2019, the IERS Directing Board had the following members (for addresses see [Appendix 2](#)):

Chair	Brian Luzum
Analysis Coordinator	Thomas Herring (until 31 Dec. 2018), Robert Heinkelmann (since 1 Jan. 2019)
<i>Product Centres Representatives</i>	
Earth Orientation Centre	Christian Bizouard
Rapid Service/Prediction Centre	Christine Hackman
Conventions Centre	Christian Bizouard (until 31 Dec. 2018), Nick Stamatakos (since 1 Jan. 2019)
ICRS Centre	Jean Souchay
ITRS Centre	Zuheir Altamimi
Global Geophysical Fluids Centre	Jean-Paul Boy
Central Bureau	Daniela Thaller
<i>Technique Centers Representatives</i>	
IGS	Rolf Dach, Chuck Meertens
ILRS	Erricos C. Pavlis, Ludwig Combrinck (until 30 Nov. 2017), Jürgen Müller (from Apr. to Nov. 2018), Jean-Marie Torre (since Dec. 2018)
IVS	Chopo Ma (until 30 Sep. 2017), Rüdiger Haas, Guanli Wang (since 12 Oct. 2017)
IDS	Jérôme Saunier, Hugues Capdeville
<i>Union Representatives</i>	
IAU	Aleksander Brzezinski
IAG / IUGG	Axel Nothnagel
GGOS	Bernd Richter (until 2 Nov. 2017), Richard S. Gross (since 2 Nov. 2017)

2.3 Associate Members

Abbondanza, Claudio	Lemoine, Jean-Michel
Angermann, Detlef	Lestrade, Jean-François
Arias, Elisa Felicitas	Luceri, Vincenza
Behrend, Dirk	Ma, Chopo
Bergstrand, Sten	McCarthy, Dennis D.
Bloßfeld, Mathis	Métivier, Laurent
Boucher, Claude	Moore, Angelyn W.
Bruyninx, Carine	Moore, Michael
Capitaine, Nicole	Müller, Jürgen
Chanard, Kristel	Noomen, Ron
Chen, Jianli	Otsubo, Toshimichi
Chin, Mike	Pearlman, Michael R.
Collilieux, Xavier	Petit, Gérard
Combrinck, Ludwig	Ray, Jim
Craddock, Allison	Rebischung, Paul
Craymer, Michael	Reigber, Christoph
Dawson, John	Rothacher, Markus
Dorland, Bryan	Salstein, David
Fisher, Steven	Seitz, Manuela
Gambis, Daniel	Shelus, Peter J.
Garayt, Bruno	Soudarin, Laurent
Gaume, Ralph A.	Springer, Tim
Gipson, John	van Dam, Tonie
Heflin, Mike	Vondrák, Jan
Herring, Thomas	Weber, Robert
Hugentobler, Urs	Willis, Pascal
Johnston, Gary	Wilson, Clark
Lambert, Sébastien	Yatskiv, Yaroslav S.
Lemoine, Frank	

Ex officio Associate Members:

IAG Secretary General: Drewes, Hermann

IAU General Secretary: Lago, Maria Teresa V.T.

IUGG General Secretary: Ismail-Zadeh, Alik

President of IAG Commission 1: Blewitt, Geoffrey

Chair of IAG Subcommission 1.1: Hugentobler, Urs

Chair of IAG Subcommission 1.2: Collilieux, Xavier

Chair of IAG Subcommission 1.4: Malkin, Zinovy

President of IAG Commission 3: Hashimoto, Manabu

Chair of IAG Subcommission 3.1: Bogusz, Janusz

Chair of IAG Subcommittee 3.2: Shen, Zheng-Kang

Chair of IAG Subcommittee 3.3: Chen, Jianli

President of IAU Division A: Hestroffer, Daniel

President of IAU Commission A1: Souchay, Jean

President of IAU Commission A2: Seitz, Florian

President of IAU Commission A3: Hilton, James

(Status as of 1 January 2019)

3 Reports of IERS components

3.1 Directing Board

The IERS Directing Board (DB) met twice in the course of the year 2017. Summaries of these meetings are given below.

Meeting No. 64 April 23, 2017, Technical University of Vienna, Gusshausstr. 27, Vienna, Austria

Introduction and approval of agenda Brian Luzum welcomed the guests and the members of the IERS Directing Board. The agenda was accepted. Some additional points were added and discussed during the meeting.

Formalities The minutes of IERS DB Meeting #63 were distributed together with the agenda of DB Meeting #64.

IERS Convention Centre: Update Nick Stamatakos reported on recent modifications of the IERS Conventions 2010:

Updates completed

- IERS Conventions code affected by leap second change
- Mean pole wording in Chapter 7

Pending modifications (TBD)

- Update of: W0, mean pole definition and equations, Tables 8.2a and 8.2b, Chapter 9

Recent changes to IERS Conventions

- New IERS conventions web and ftp sites:
<http://iers-conventions.obspm.fr/>
<http://maia.usno.navy.mil/conventions>
<ftp://maia.usno.navy.mil/conventions>

Users can sign up for notification of Conventions updates: <http://iers-conventions.obspm.fr/mail-list.php>.

Zuheir Altamimi announced to provide an update of Chapter 4 in about a month. Nick Stamatakos announced that the next major update is planned for 2019. Tom Herring raised the question whether mirroring the sites to IERS.org is planned.

New Action Item #64.01 Check and coordinate a mirror of the IERS Conventions website at the IERS CB site

**ITRF2014 validation and comparisons
Report from ITRS Centre**

Zuheir Altamimi presented the following report:

Summary of the ITRS Centre activities

- New ITRF website is delayed to end of 2017
- ITRS Centre Operational entity for local survey: an IGN document will be prepared and given to the IERS CB
- Recognize the Operational entity by the IERS (change of the IERS ToR connected to the ITRS Centre, e.g. "Centre is collaborating with the Operational entity"?)

Detlef Angermann noted that the GGOS Bureau of Network and Observations is also working on the topic of local surveys.

ITRF2014 related activities

- ITRF2014 was published on January 21st, 2016 (see http://itrf.ign.fr/ITRF_solutions/2014/forfullinformation)
- PSD models are now successfully implemented by most TCs and other users
- A JGR open access article published in July 2016
- Article on Plate motion model accepted by Geophysical Journal International
- Update of Chapter 4 of the IERS Conventions: still to be done (see Action Item #62.04)

ITRF2014 related TN

- TN38: IERS Technical Note on the official ITRF2014 published
- TNxx: IERS Technical Note on the evaluation of the three solutions: ITRF, DTRF and JTRF
 - No real progress so far
 - To be published by the end of the year at the latest
 - Daniela Thaller: What is the status of evaluation in the Technique Centres?
 - Hugues Capdeville [IDS]: Plans to write an article on the evaluation, which can be published in the TN as well.
 - Chopo Ma: No news from IVS.
 - Erricos Pavlis [ILRS]: Some contributions are expected by the end of June.

Richard Gross will submit a summary of JTRF2014 by the end of June the earliest. Rolf Dach will discuss the subject within the IGS. Detlef Angermann will contribute a summary of DTRF solution and a summary of the comparisons.

EOPs: 14C04: an interpolation issue

- EOP08C04 and EOP14C04: doubled noise (?)

Z. Altamimi: Proposal: provide the 14C04 at two epochs: noon & midnight or publishing two separate series.

S. Lambert noted that the series at noon are dominated by GNSS.

R. Gross: JPL publishes one series at noon and one at midnight, separately.

R. Dach proposes an hourly solution and suggests to put this topic on the agenda for the upcoming GGOS UAW.

VLBI & SLR Scale Issue

DGFI and IGN agreed to analyze their respective SLR & VLBI cumulative solutions, using SLR-VLBI co-location sites only (no GNSS).

Discussion

Tom Herring raised the question about adding Flicker noise to the scale. Zuheir Altamimi proposed to add GNSS co-location sites.

***Report from ITRS
Combination Centre at
DGFI-TUM***

This report was presented by Detlef Angermann.

Scale analysis of VLBI and SLR solutions:

- Results are sensitive to single particular stations, e.g., Yarragadee. No significant scale offset and rate between IGN and DGFI single technique solutions for VLBI and SLR.
- Different methods for scale investigations:
 - a. Direct transformation
 - Only few transformation stations, dependency on local tie fits!
 - Large variation of estimated scale differences; smaller offset for DGFI
 - b. Indirect transformation using GNSS as reference
 - Difference between SLR and VLBI: DGFI 0.1 to 0.7 mm, IGN -3.3 to -1.3 mm
 - Set up scale for VLBI or SLR in DTRF2014 – 3 Tests: Transformation via a set of good and globally well distributed

- VLBI only, SLR only, GNSS only

Summary:

- The results of the direct transformation between VLBI and SLR are affected by a poor distribution of transformation stations and local tie misfits. It is thus critical if the results rely on this method only. High dependency from single stations, e.g. Yarragadee.
- The transformation of VLBI and SLR via GNSS provides much more stable results:
 - Range of estimated scale offsets via GNSS (epoch: 2000.0):
DGFI-TUM: 0.1 to 0.7 mm, IGN: -3.3 to -1.3 mm
- The observed scale rate differences might explain some part of the scale offset at 2010.0 obtained by IGN.

Comments:

Axel Nothnagel asked for the physical reasons of the scale discrepancies. Zuheir Altamimi proposed to use appropriate local-tie weighting; Detlef Angermann will do the tests with the DTRF2014.

Reconstruction of IGN tests:

- Large scale offset not reconstructed

Report from ITRS Combination Centre at JPL

The report from ITRS CC at JPL was given by Richard Gross.

Correlation in ground deformation

- Account for regional correlations in ground deformation

Joint TRF/EOP/CRF Determination

- Kalman filter to determine CRF from VLBI-only data developed

JTRF2014

- Article submitted to JGR-Solid Earth
- Starting to write an article for IERS TN
- Development capability to provide monthly updates to JTRF 2014

Helmert transformation parameters (at 2005.0) (Kalman filter vs. linear propagation of ITRF2014)

- 10 years signal for scale parameter

Geocentre

- Velocity fields (numbers = correlation coefficients): horizontal: JTRF2014, vertical: ITRF2014

Earth orientation parameters

- Seasonal signal due to comparison to linear parameterization

Zuheir Altamimi mentioned that the operational IGS series are still aligned to 2008.

New Action Items

#64.02 Propose revised wording for ToR to acknowledge operational entities in general

#64.03 Provide input to Technical Note on ITRF/DTRF/JTRF including validation

**Reports from Technique
Centres
IDS**

This report was presented by Hugues Capdeville.

DORIS constellation

- Current Missions: 6 DORIS missions in flight with DGXX(S) Receiver (7 channels)
- Future Missions: 10 missions planned between 2018 and 2023

Network

- 45 co-locations out of 57 DORIS sites
- 9 beacons are currently out of order (5 for over a year)
- Reliable service: annual mean of 89% of active sites in 2016
- Recent events: New station at Wettzell observatory; local tie survey at Papeete, Tahiti; RF compatibility tests at Papenoo, Tahiti; restarting at Socorro Island, MX
- Future events: New stations in San Juan, AR, Guam, US, and Easter Island, Chile, Rothera, Antarctic, Ny-Ålesund, Norway, Kathrine, AS, Changchun, CN and Papenoo, Tahiti

Analysis update

- 6 active ACs (using 5 different software packages for orbit determination)
- Processing routine: IDS Combination Centre is finalizing the extension of combined series until 2016 day 360
- Work in progress:
 - Implementation of DORIS RINEX data processing since the launch of Jason-3, Sentinel-3A (DORIS data is only delivered in RINEX-like format)

- Work on the open points following ITRF reprocessing: DORIS scale increase in 2012 (understood and can be removed); Increase of DORIS residuals from Jan. 2013 for all missions
- Jason-2 and Jason-3 USOs are sensitive to the SAA (a solution was proposed to minimize the SAA effect)
- Switch to ITRF2014 for IDS operational products soon

Comparison on the DTRF2014, ITRF2014 and JTRF2014 solution using DORIS

- Evaluation of TRF solutions by IDS CC
- Evaluation of TRF solutions in POD by CNES/CLS IDS AC (positive: ITRF2014 fits better)
- Article in progress on this subject, which can also be used as reference for the IERS TN on ITRF2014 evaluation.

DPOD2014: DORIS extension of the ITRF for Precise Orbit Determination Switch to ITRF2014 for IDS operational products

- Version 1 available (SINEX and text format)
- Updated twice a year
- Switch to ITRF2014 when ACs use DPOD2014

IDS news

- Next IDS AWG meeting in London (UCL), May 22–24, 2017
- IDS website upgraded
- New version of the web service: time series visualization tool
- New products from the Combination Centre: DPOD (Cumulative solution)

IGS Rolf Dach presented the IGS report.

- Transition to ITRF2014 has been done on 29 January as announced (no unforeseen occurrences)
- In combination protocol: JPL does not contribute because of reprocessing, other ACs took the chance to make model changes and to review the station lists
- Ongoing process: transition to RINEX3, 30% of stations provide RINEX3 data or both formats
- IGS workshop in Paris, 3–7 July 2017

- Internal structure: new chair of the antenna unit (R. Schmid stopped working, now: A. Villiger)

Since the beginning of 2017, a new working group on monitoring and assessment of GNSS products has been established as a joint effort with ICG. It is a neutral entity, not belonging to any system administration (U. Hugentobler chair, T. Springer coordinator of operational concerns). ORBEX: orbits exchange in SINEX-like format (also altitude information?)

In frame of MGEX: exchange orbits planned

ILRS Erricos Pavlis presented this report.

Recent ILRS Developments

- ILRS GB is in the process of selecting two associates to be appointed as “At-Large” members (according to the newly adopted ToR)
- “Quality Control Board” (QCB): meeting monthly by telecon; plans the next phase of the implementation of near-real-time QC analysis tools and procedures to help the stations’ engineers resolve systematic errors affecting their systems

ILRS Network

New initiatives in Russia, NASA SGP, Ny Ålesund, Metsahovi, etc., but still large geographic gaps. Mix of new and legacy technologies (expanded use of the newer technologies to move from legacy to new technology status).

ILRS Network Development

- Activities in the Chinese Network: San Juan being repaired and upgraded, Wuhan being repaired and upgraded, Shanghai has a 10kHz system and a newly implemented Super-Conducting Nanowire Single Photon Detector (SNSPD), 1-meter aperture telescope under development at Wuhan
 - New SLR systems underway: Metsahovi (Core Site), Yebes (Core Site), Mt Abu and Ponmudi in India (2017)
- Several sites now working routinely at kHz rates:
 - Current: Herstmonceux, Sejong, Wettzell (SOS-W), Changchun, Beijing, Shanghai, Potsdam, Graz
 - Future: SGSLR (McDonald, Ny Ålesund, Hawaii, ...), others?
- Riyadh station is still not operational.

Missions

- ~100 satellites routinely tracked in 2017
- New satellites added; GNSS satellites routinely tracked
- Future missions: SWOT, HY-2C, ACES, NISAR, COSMIC-2, and ICESat-2

ILRS ASC – Analysis Activities

- ITRF2014 implementation completed (some ACs still need to join)
- Pilot Project on station systematics over next 2 months
- New products related to near real-time system evaluation (in development stage)
- Next PP will deliver low-degree gravity coefficients (weekly product) and introduce LARES for ITRF support
- ILRS special issue in the Journal of Geodesy progressing
- Significant scale differences found comparing the ILRSA scale w.r.t. three TRF Models (DTRF2014, ITRF2014, JTRF2014)

ITRF2014/SLRF2014 Implementation Schedule

- All ACs will have completed the implementation by end of May 2017
- SLRF2008 and SLRF2014 series of products will run in parallel up to the middle of June 2017
- After mid-June 2017 a single “pos+eop” and “orbits” product will be generated and released, with ITRF2014/SLRF2014 being the underlying TRF

IERS 2010 Conventions Update

- CMP: Chapter 7, Section 7.1.4

IERS CMP Comparison

- Large X- and Y-Pole variations for different versions

Future Meeting Schedule

- October 01–05, 2017, Riga (Latvia): ILRS Technical Workshop on Laser Ranging
- Next ASC meeting: Sunday, October 01, 2017, Riga (Latvia)
- 21st International Workshop on Laser Ranging: November 04–09, 2018 in Canberra (Australia)

IVS Tom Herring presented this report prepared by Rüdiger Haas.

IVS Transition to ITRF2014

- Two IVS Analysis Centres have started submitting SINEX files with ITRF2014 as a priori (several more are ready to do so in the near future)
- IVS Combination Centre has started to submit ivs2017a which uses ITRF2014 as a priori (waiting for more ACs to make the switch)

Importance of HF-EOP

- Study by Tim Springer: full year 2016 with two identical 24 h multi-GNSS processing runs; using 60 multi-GNSS tracking stations; using all available GPS, GLONASS, Galileo satellites (two runs with different sub-daily ERP models: 1. IERS conventional model (ortho_erp.f), 2. Gipson “hfeop_withlibra” model based on VLBI analysis)
- Amplitude spectra of the difference in the Right Ascension of the Ascending Node at the day boundary (dRAAN0h): similar effects visible for radial, along-, and cross-track differences, direct X, Y, and Z differences, inclination, semi-major axis, and cross-track overlaps.
- Results confirm a previous study in 2011
- Now also shown for GLONASS and Galileo → real improvement due to the VLBI-based model by Gipson

Intensives for EOP

USNO uses intensives from USNO, GSFC and GSI in its EOP series:

- All sessions are standard 1-hour S/X Intensives

NASA/GSFC has done simulations comparing:

- a) KOKEE-WETTZELL S/X Intensives with
- b) KOKEE12M-WETTZ13N VGOS (broadband) sessions
- VGOS sessions get ~4 times as many observations
- Formal errors ~1/2 those of S/X observations
- VGOS sessions less sensitive to atmospheric turbulence

Next step: schedule some KOKEE12M-WETTZ13N sessions at the same time as standard S/X sessions.

Improving “Intensives”

Simulation study by Chalmers University of Technology (Kareinen et al., Earth Planets Space 2017). Goal: finding optimum additional stations locations to improve INT → “cheap” way to effectively improve INTs

VLBA “Intensives”

Over the last few years USNO has started to schedule “Intensives” using the VLBA:

- Schedules made using software “SCHED”
- Duration: originally 45 minutes, in February 2017 switched to 90 minutes.
- Dynamically scheduled: do not occur at the same time every day, ± 4 hours of 6:30 UT
- Usually use Mauna Kea – Pie Town if this is available
- NASA/GSFC has just started working with USNO to import these data and make it available to IVS
- “Pilot project” starts with data from January 2017
- Need to make “master file” which uses: actual starting time, actual duration, actual stations
- Need to make schedule file that can be used by IVS (VEX file used for correlation; additional information needed)
- Expect to have some results by the end of the summer

VGOS (broadband) sessions

Began “regular” broadband sessions in January 2015 on trial basis: baseline GGAO12M–Westford, 1 h sessions 2015-Jan-20, worked up to 24 h sessions 2015-Dec-08

Beginning in 2016 added additional stations as they became available: 2016-Feb-12: KOKEE12M, 2016-Jul-07: RAEGYEB (Yebes13M), WETTZ13S; 2016-Sep-20: ISHIOKA

Process continues in 2017: two 24 h sessions per month.

Analysis of broadband sessions

Current processing chain uses new VLBI vgosDB database format:

- vgosDBmake: knits correlator output into vgosDB
- vgosDBcalc: adds in a priori and partial information
- vgosDBproclog: adds in met and cable cal data from log file

- nuSolve: Analysis vgosDB data

Same processing chain can be used for both VGOS (broadband) and S/X observing.

VGOS network development

- 3-station broadband network in North America
- Westford 18 m – Goddard 12 m – Kokee Park 12 m
- Wettzell: WETTZ13S (13.2 m)
- Ishioka (13.2 m)
- Yebes: RAEGYEB (13.2m)
- Onsala: ONSA13SW, ONSA13NE (13.2 m)
- Several other VGOS projects (Ny-Ålesund, Shanghai, RAEGE, HartRAO, Metsähovi, ...)

VGOS Twin telescopes in Wettzell (TTW), Onsala (OTT) and Ny-Ålesund (NTT)

Upcoming IVS-meetings

- 9th IVS Technical Operations Workshop, 30 April – 4 May 2017, Haystack Observatory, MIT
- 23rd Working Meeting of the European VLBI group for Geodesy and Astrometry, EVGA2017, 14–19 May 2017, Chalmers University of Technology, Gothenburg

Preparation for CONT17

15 consecutive days: 28 Nov. 0 UT – 12 Dec. 24 UT, using three different networks: two legacy S/X networks of about 13 stations each (one legacy network will include the ten VLBA stations) and one network consisting of VGOS broadband stations.

Preparations ongoing, including simulations, optimal assignment of stations, assignment of correlator resources, etc.

Detlef Angermann asked about scale comparisons.

EOP Products **Report from Earth Orientation** **Centre**

Axel Nothnagel asked about implementing more rigorous combination procedures, i.e. a combination on normal equations including the EOPs and the TRF for generating the IERS EOP series, as already discussed at the previous IERS Retreat (is part of the evaluation process).

Sébastien Lambert replied that Paris Observatory is working on software that uses normal equations from the 4 Techniques. This could lead to a

C04 combination in a more advanced way according to the requests of the IERS Retreat.

Zuheir Altamimi stated that there are not enough co-locations on a weekly basis, which are the limiting factors. Is a project on more rigorous combination of the EOP series needed?

***Report from Rapid Service/
Prediction Centre***

Christine Hackman reported:

Mission

- Provide rapid-turnaround EOPs for real-time users: Weekly (IERS Bulletin A), Daily (estimates and predictions), Sub-daily (estimates and predictions)

Products 2016

- finals.daily (PM, UT1–UTC). Increased UT1 RMS (observed between 18 Mar and 04 Oct 2016) was from UTGPS

RS/PC ITRF2014 Transition

- Transition implemented since March 23, 2017
- PM, UT1–UTC aligned to ITRF2014 series
- Celestial pole offsets aligned to IVS combined 24-h VLBI series

2008→2014 transition discontinuities

- 2008–2014 transition: RMS 20, 54 μs for PMx, y; RMS 21 μs for UT1–UTC
- 05 C04-to-08 C04 transition: RMS 76, 70 μs for PMx, y; RMS 7 μs for UT1–UTC

New Action Items

#64.04 Study procedures for a rigorous combination to derive EOP series (esp. C04)

#64.05 Provide two C04 series (at noon and at midnight epochs); add note to the users that the midnight series is interpolated

**Switch to ITRF2014 for
operational products: Status
and experience**

What is missing?

Open question.

What can be learned?

C. Hackman noted that the schedule for IERS Rapid Service/Prediction Centre will be in near real-time in future: more discussion on how to do the transition (multi-stage process).

Scale comparisons?

See topic “ITRF2014 validation and comparisons” above

**Prepare roadmap and
guidelines for further ITRF
products
*ITRF process***

Brian Luzum presented thoughts about the future ITRF process.

Aim: better planning of resources, availability of persons, etc.

Goals:

- Create a defined process to be followed for future ITRF generation
- Provide documentation for external users

Fast, good, cheap → pick two principle

Brian Luzum presented a possible timeline comprising ITRF transitions at the TCs and validation, as well. Feedback is requested on the timeline, amount of time, steps and wrap-up until December. Detlef Angermann asked whether a validation is foreseen before introducing the ITRF.

Unanswered questions:

- Are fundamental assumptions correct? E.g., is “Pick two” reasonable?
- What is the optimal time from beginning to end? Beginning = ITRS Centre recommending new ITRF, End = adoption of new ITRF
- How do we determine optimal time?

Next steps:

E-mail dialog regarding:

- Missing steps
- Missing dependencies
- Reordering tasks
- Length of time for tasks

Brian Luzum will give an update on the process including the feedback given at the meeting in December.

Zuheir Altamimi noted that there are unforeseeable delays between the call for participation and the contributions from the Technique Centres. It needs about 6–12 months from TC submissions to a new ITRF.

Criteria for choosing a new ITRF: minimum 3 years, maximum 5 years (additional data, models, etc).

New Action Item #64.06 Discuss proposed ITRF process. How to optimize the procedure at the TCs for reprocessing?

UAW 2017 Richard Gross announced that the Unified Analysis Workshop will be hosted by IGN and will take place from noon July 10 to noon July 12.

Topics:

- Technique biases and systematic errors
 - VLBI: Loading effects
 - SLR: Loading effects; range biases
 - GNSS: Antenna patterns
 - DORIS: Antenna patterns; South Atlantic Anomaly
- Model improvements
 - Mean pole: Definition, modeling, and prediction
- Reference systems and frames
 - Deficiencies of current systems and frames: Examples
 - Joint TRF/EOP/CRF determination: What is needed?
 - Towards more frequent TRF updates: What is needed?
- Standards, Conventions, and Formats
 - Metadata: Implementation
 - SINEX format extensions: Radio source positions?
 - SINEX format extensions: Loading parameters?

UAW participants: ~50 participants are invited representing GGOS, IERS, IGS, IVS, IDS, ILRS and IGFS.

**IERS Technical Notes on
ITRF2014: Status and way
forward**

TN on ITRF2014 solutions: This TN was discussed in topic “ITRF2014 validation and comparisons” above.

TN on input and evaluation by the Technique Services: This TN was discussed in topic “ITRF2014 validation and comparisons” above.

TN on C04 series aligned to ITRF2014 (replace TN planned for 08 C04): S. Lambert explained that this was not started yet.

**IERS Workshop celebrating
30th Anniversary in 2018**

Z. Altamimi announced that REFAG2018 will be jointly with the 42nd COSPAR Scientific Assembly and organized by Geoff Blewitt at Caltech in Pasadena, USA, 14–22 July 2018. Another possibility would be the IAU General Assembly in August 2018 in Vienna.

New Action Item #64.07 Ask Geoff Blewitt about the possibility to organize an IERS anniversary event in conjunction with REFAG2018.

**Status of ICRS/ICRF and IAU
Working Group**

Bryan Dorland gave an ICRF3 status update:

ICRF3 Background

- ICRF3 Working Group formed to define next ICRF; target date is 2018 IAU adoption

Goals

- Competitive in precision with Gaia ($\sim 70 \mu\text{as}$, $1-\sigma$, RA & Dec)
- Uniform precision for all sources $\rightarrow$ VCS positions must be improved
- Extend to higher frequency (S/X $\rightarrow$ S/X, K and X/Ka band)
- Possible multi-wavelength catalog
- Improve southern coverage
- Maximize high-quality optical-radio tie sources
- Complete ICRF3 by 2018 (Gaia comparison)

Multi-wavelength? $\rightarrow$ TBD

ICRF3 Status

S/X: Continued contributions from IVS scheduled observations (e.g., R1, R4, CRF)

S/X: VLBA Cal Survey-II (VCS-II) to re-observe VCS sources published

- 2400 VCS sources re-observed in S/X (2062 previously detected and 324 previously undetected)
- Average position uncertainty of 0.24 and 0.41 mas in RA and Dec, respectively, a factor of $\sim 5\times$ improvement
- "Second Epoch VLBA Calibrator Survey Observations - VCS-II," Gordon et al. 2016, AJ, 151, 154

K-band densification

- Dedicated Southern Hemisphere and VLBA observations to increase precision and density of sources
- 788 sources (expect >1000 ultimately), $\sim 50 \mu\text{as}$ precision

X/Ka data continues to be collected and processed.

- 18 VLBA sessions in 2017 to re-observe poorly observed ICRF2 and VCS-II targets

100 μ as zonal declination errors being investigated for all bands: S/X, K, X/Ka

Images available for S/X and K-bands

Gaia Status

ESA Gaia astrometry mission (launched 2013, science data collection since 2014, nominal mission end = 2019, may be extended to 2021, 2023)

Data products:

- Data Release 1 (DR1) – September 2016
- DR2+ ~April 2018, approximately yearly thereafter

Tying reference frames: ongoing work to look at Gaia optical-to-ICRF radio reference frames; frame tie < 1 mas achieved. Precision ~5–10 μ as per rotation angle.

Accuracy dominated by systematics currently bounded at ~0.5 mas level.

USNO-related work

(X/Kz = X/S)

- USNO now publicly releasing Mauna Kea – Pie Town VLBA intensives for use by the general community
- USNO to begin processing backlog in VLBI imaging database this year
- K-band observations supported via USNO VLBA time allocation
- Additional X/Ka observations supported via USNO VLBA time allocation
- UCAC5 Catalog
- UPC: URAT Parallax Catalog
- UBAD, URAT bright star catalogs
- Mid IR AGN Catalog – spans the gap between visible and radio sources
- Ongoing validation work between ICRF3, Gaia and other sources
- Dedicated optical-radio link work commencing in 2018 at CTIO

Summary and future work

- Final observations for ICRF3 underway
 - K-band observations completed, will be considered as part of reference frame
- On-track for 2018 adoption
- Gaia DR1 received and ingested
- VLBA now supporting increased Celestial Reference Frame and Geodesy
- Research
- Additional work being done now
 - Radio imaging database
 - Radio-optical link
 - IR reference frame

New Action Item #64.08 IERS Conventions need to be updated with ICRF3

GGOS Detlef Angermann reported on the GGOS CB meeting of April 22, 2017.

- H. Kutterer sent a designation letter to H. Schuh. Process started to select a new chair, EC meeting on Friday with further information. H. Kutterer will continue until a new chair is selected.
- Bureau of Network and Observation: Meeting on Wednesday evening;
- Bureau of Products and Standards: Meeting on Tuesday; two representatives from IERS (Analysis Coordinator, Convention Centre), but need to be decided who will succeed G. Petit (either N. Stamatakis or Ch. Bizouard)
- GGOS focus areas:
 - Unified height system
 - Geohazards
 - Sea-level change

Proposal for a 4th focus area on atmosphere → decided to be established within GGOS. GGOS Days are planned in conjunction with COSPAR meeting in South Korea in September 2018 (3-3.5 days).

New Action Item #64.09 Clarify representative of IERS Conventions Centre to GGOS Bureau of Products and Standards

Reports from the Working Groups

IERS Working Group on SINEX Format

Daniela Thaller reported that a more user friendly SINEX description as a web interface for each block was set up, which is easier to maintain and to update, and more user friendly to implement or to check. Until now, it is available only internally at the IERS CB; possibilities to access from outside will be evaluated.

Zuheir Altamimi asked to approve a PSD block and a discontinuity part.

IERS Working Group on Time Series Format

Laurent Soudarin presented the report of this WG.

Work plan

Applied method:

- expression of requirements
- establishment of a list of existing formats
- review of the formats
- propositions for the exchange format based on conclusion of the existing
- identification of still open issues to be addressed next

Status

WG meeting at AGU 2012

- Start of the list of requirements (time scale, reference system, coordinate system, metadata)

WG meeting at EGU 2013

- Start of a list of existing formats at IAG services and GPS time series providers. Several issues concerning the time series were discussed (epoch, time tag, accuracy, correlations, ...).

WG meeting at EGU 2015

- Review of some existing formats. Metadata and data have been examined 2015–2016.
- List of the necessary elements for the time series exchange format (metadata content, data table, mandatory and optional inputs) as well as the units, the coordinate system, the date and time system

Main conclusion

Three groups of metadata:

- File information

- Site information
- Product information

Data

Users prefer to plot NEU position variations, but XYZ coordinates are necessary to express positions in a different reference frame or to obtain NEU and then delta NEU on a different ellipsoid.

→ Two blocks: XYZ (+sigma ...) and ISO date and time (accurate data), dNdEdU(+sigma ...) and Modified Julian Days (understandable by humans; easy to plot)

Format proposition:

- 1) SINEX-based format
- 2) YAML format

Draft proposal for the station position time series exchange format. The two formal proposals have to be discussed.

Annual Reports Daniela Thaller reported that the AR 2015 was published recently and that the AR 2016 needs to be drafted.

Next DB meeting (#65) The next DB meeting (half-day afternoon meeting) will take place on Saturday, December 09, 2017 before the AGU in New Orleans.

New Action Item #64.10 Prepare next DB meeting #65 in New Orleans.

Meeting No. 65 December 9, 2017, Hilton New Orleans Riverside Hotel, 2 Poydra Street, New Orleans, USA

Introduction and approval of agenda Brian Luzum welcomed the guests and the members of the IERS Directing Board. The agenda was accepted.

Changes in IERS personnel Brian Luzum presented an overview of the following changes:

- Guanli Wang replaces Chopo Ma as IVS representative to the IERS DB
- Richard Gross replaces Bernd Richter as GGOS representative to the IERS DB
- Rüdiger Haas replaces Chopo Ma as the IERS representative to the IVS Directing Board
- Still open: IERS representative to the WDS (replacing Bernd Richter); the next conference “International Data Week” will be

held in Botswana, November 5–8, 2018. Any suggestions and/or volunteers for the IERS representative to the WDS should be sent to the CB.

New Action Item #65.01 Suggestions for the IERS representative to the WDS

Associate Members The current list of IERS Associate Members was distributed by the IERS Central Bureau in advance. Any changes/additions should be sent to the CB before December 31st, 2017.

ITU request “Future of the UTC time scale”

Brian Luzum reported on the ITU request:

- The IERS needs to prepare an answer on the ITU request “Future of the UTC time scale” (ITU-R 236-2/7).
- A Working Group should be established to prepare the answers.
- Groups that need to be represented: Technique Services, Earth Orientation Centre, Rapid Service/Prediction Centre
- Work of the group needs to be coordinated with BIPM (Patrizia Tavella), IUGG, IAU.
- H. Schuh: similar request as 10–15 years ago; a very good document with pros and cons had been generated at that time; to be checked whether this document is publicly available (via IAU?).

New Action Items #65.01 Establish Working Group to prepare answer to ITU request on “Future of the UTC time scale”, chaired by Brian Luzum

#65.02 Prepare IERS answer to ITU request

UAW 2017 Summary

Richard Gross presented the topics discussed at the UAW, including the recommendations achieved for each session:

- The sessions were dedicated to systematic errors and biases in all four space-geodetic techniques, site survey/co-locations, reference systems/frames, conventional mean pole, standards/Conventions/Formats, Interoperability of portals and metadata.
- A detailed report of the UAW is available from ggoss.org: <http://176.28.21.212/en/meetings/2017/unified-analysis-workshop/general/> [See also Chapter 4 in this Report]
- Achieved outcomes are (as of Dec. 2017):
 - A new linear mean pole model is available.
 - Differences in different formulations of relativistic effects are understood.

– Working Group on sub-daily EOP variations is established (chaired by John Gipson).

- H. Schuh: The Working Group on sub-daily EOP variations should be organizationally part of either GGOS or IERS → R. Gross will clarify this issue with John Gipson.

New Action Item #65.03 Clarify whether WG on sub-daily EOP variations will be part of IERS (or GGOS)

ITRF2014 and beyond

Report from ITRS Centre Zuheir Altamimi presented the report of the ITRS Centre.

Summary of the ITRS Centre activities:

- Work on new ITRF website is still in progress.
- ITRS Centre operational entity for local surveys will focus on establishing a database for local survey observations (work is in progress with priority to archive local tie vectors).
- Modification of IERS ToR to recognize the operational entity of the ITRS Centre (follow up Action Item #64.02).

Discussion:

- The operational entity at the ITRS Centre is responsible only for Data Management, but not exclusively for local surveys, as many other institutions are carrying out local surveys at their geodetic sites, too.
- Conduct email voting on modification of IERS ToR.

Presentation for ITRF Error Budget Workshop, organized by Tom Johnson, to be held on Thursday, Dec. 14, 2017:

- Comparison of DGFI- and JPL-internal technique solutions with ITRF to evaluate scale
- Scale discrepancy of ~1.4 ppb between SLR and VLBI
- Statement: DTRF and JTRF solutions are keeping the technique-specific scales of SLR and VLBI (therefore a good agreement with SLR and VLBI solutions); ITRF explicitly allows for scale parameters by the techniques, therefore, combined scale is an average of SLR and VLBI scale
- DTRF scale w.r.t. ITRF at 2010.0: 4.2 mm (VLBI), 0.6 mm (GNSS), 4.3 mm (SLR)

- JTRF scale w.r.t. ITRF at 2010.0: 4.2 mm (VLBI), 2.5 mm (GNSS), 3.9 mm (SLR)

***Report from ITRS
Combination Centre at
DGFI-TUM***

This report was given by Mathis Bloßfeld.

Summary of the ITRS-CC activities:

- Comparisons between three TRF solutions carried out; discrepancies at the cm-level detected after 2 years of propagation only

Presentation for ITRF Error Budget Workshop, organized by Tom Johnson, to be held on Thursday, Dec. 14, 2017:

- A detailed list of contributions to the current ITRF error budget was compiled; errors can be grouped into:
 - Limitations of input data (this is partly resolvable by an ITRF roadmap as suggested by B. Luzum, and by a transparent communication among the Services)
 - Limitations of current ITRF solutions, mainly related to network and co-locations (hard to solve as network improvements are required)
 - Limitations of the absolute ITRF accuracy and the statistical information (partly resolvable, but requires clear communication)

***Report from ITRS
Combination Centre at JPL***

Richard Gross provided an overview of the work by summarizing science talks at AGU:

- JPL works towards more frequent updates of the TRF: bi-monthly updates based on solutions provided by Technique Services as operational products.
- Consistency between EOPs and TRF could be ensured with more frequent updates.
- Actual time series of geocentre motion (CM-CN) could be provided based on the assimilation of new data.
- Ongoing work related to joint TRF-EOP-CRF determination based on Kalman filter method.

New Action Item #65.04 Email voting on modification of IERS ToR

Roadmap for next ITRF generation

Brian Luzum recalled the idea of preparing a roadmap for the next ITRF before starting with the generation of the ITRF (as already presented at IERS DB Meeting No. 64).

Mathis Bloßfeld presented the thoughts of the ITRS CC at DGFI-TUM:

- Currently missing: feedback loops, responsibilities, product specifications, future steps.
- It needs to be defined, who is responsible for the CfP, and who should approve the CfP.
- Test scenarios and evaluation criteria needs to be defined thoroughly (GGFC should also be involved in testing).
- A feedback loop based on the internal and external validations needs to be incorporated (e.g. by higher frequency of UAWs).
- ITRF publication and documentation should be authored by all IERS CCs and Technique Centres.

Discussion:

- Duration for reprocessing (Step 4) needs to be at minimum 1 year.
- Duration for initial TRF combination (Step 5) needs to be at minimum 9 months.
- Details for Call for Participation (Step 1) needs to be defined in advance: IERS internal discussion before fixing details of CfP; CfP will be sent out by ITRS Centre to IERS DB, Technique Centres and Analysis Coordinators.
- Ch. Hackmann / N. Stamatakis: Step 9 (adoption of new EOP series) should be split into two parts, i.e., adoptions at the Earth Orientation Centre and adoption at the Rapid Service/Prediction Centre.
- H. Schuh suggested to include an external (independent) review process and evaluation.
- R. Gross emphasized that external verification is highly important.
- Z. Altamimi mentioned that he will distribute soon a list of proposed models for the next ITRF and ask the TCs for their input.
- The roadmap should be finalized at next IERS DB meeting in April 2018; any comments and suggestions should be sent to B. Luzum; he will update the documents.

New Action Item #65.05 Send comments on ITRF roadmap to Brian Luzum

EOP Products Christian Bizouard presented the recent activities at the Earth Orientation Centre:

- C04 series is now consistent with ITRF2014 solution.
- Combination procedure has been updated: nutation offsets dX/dY are directly combined; new weighting method; modelling of bias or trends by piece-wise linear functions; reanalysis since 1984
- Problem: C04 is provided with 30 days latency, but IVS Quarterly solution cannot be considered for recent epochs → are there improvements possible?
- Publication in Journal of Geodesy is accepted: Bizouard C., Lambert S.B., Becker O., Richard J.Y., The IERS EOP14 C04 Solution for Earth Orientation Parameters Consistent with ITRF2014
- Interpolation issue: 14C04 at noon epochs (as answer to Action Item #64.05) is available at
ftp://hpiers.obspm.fr/iers/eop/eopc04/eopc04.dX_dY.12h.84-now
 and
ftp://hpiers.obspm.fr/iers/eop/eopc04/eopc04.dPsi_dEps.12h.84-now

Christine Hackman presented the recent activities at the Rapid Service/Prediction Centre:

- New email addresses are in place: @navy.mil
- Contact email for IERS RS/PC: navobsy_eop@navy.mil (not ser7@maia.usno.navy.mil anymore)
- UT was improved when taking out UTGPS → to be revised in 2018
- Improvements of predictions for PM and UT1 via AAM/OAM

Ch. Bizouard presented the idea of Leonid Petrov to incorporate his NERS (Network Earth Rotation Service) as an official IERS component:

- Delivery of the EOP products to the customers is the weakest point: printed version until 1990s; ftp servers since 1990s.
- Modern requirements are different: NTP protocol; seamless client/server interaction; internet services; “internet of things” / interaction of internet services.
- NTP client for UTC available (function and command line interface) → is a similar tool possible that provides UT1 or the Earth Rotation matrix?

- NERS implemented EOP dissemination in a modern form, including short-term EOP forecast.
- NERS project is supported by NASA and Paris Observatory.
- Suggestion by L. Petrov and Ch. Bizouard: accept NERS as an official IERS product (in addition to other products) or extend pilot phase.

Discussion:

- The delivery of the IERS products in general (not only EOPs) should be improved and modernized.
- Ch. Hackman: The Rapid Service/Prediction Centre UT is already distributed via NTP by the National Institute of Standards and Technology (NIST).
- H. Schuh: The ideas of NERS should be included into the official IERS products instead of establishing parallel structures.
- B. Luzum suggests to prepare a graphical overview at which time which value of the EOPs is the official IERS product.
- General agreement within DB:
 - There should be only one official IERS product to avoid confusions.
 - Accessibility and availability of official IERS products need to be ensured for long time; this is questionable with project-funded developments as NERS is.
 - The methods for IERS product distribution should be revisited and modernized where needed.
 - A working group should investigate the actual product distribution within IERS (not only EOPs) and propose possible improvements to the IERS DB.
 - The WG should be chaired by the IERS Analysis Coordinator.
 - Members of the WG should be all Product Centres (EOC, RS/PC, ICRS Centre, ITRS Centre), the ITRS CCs, the CB.

New Action Item #65.03 Establish an IERS WG to investigate possible improvements related to the distribution of the IERS products, chaired by T. Herring

Reports from the Technique Centres

IDS Report Hugues Capdeville presented the IDS report:

- New 3-technique site San Juan (Argentina).

- New 4-technique site Ny-Alesund (Norway) by relocation of the beacon.
- IDS combined series is extended to 2017-183.
- DORIS scale increase in 2012 is understood and can be removed (HY2A with new position of the CoM need to be used).
- DPOD2014 is available since October 31st (in SINEX and text format).
- IDS Workshop to be held in Ponta Delgada (Azores), September 24–29, 2018.
- IDS Retreat planned in 2018 to define the activities for the next 5–10 years.

IGS Report This report was given by Rolf Dach.

- Workshop held in Paris in early July 2017.
- Next Workshop will be held in Wuhan (China), October 29 – November 2, 2018.
- An IGS Associate Member Meeting will be held tomorrow during AGU week.
- Transition with RINEX-3 naming is almost closed; for products it is still under discussion.
- Real-time GNSS: Open data policy will be continued by IGS.
- Galileo: new 4-satellite launch planned for 2018; at least a few ACs will include Galileo in their official products.
- Metadata for Galileo satellites and partly QZSS satellites are available.

ILRS Report The presenter of this report was Erricos Pavlis.

- ILRS Governing Board was enlarged with 2 “At-large Members”: A. Sokolov, Z. Zhongping.
- New ILRS Network Application form is available.
- New data Quality Control Board (QCB) is established to address laser ranging data quality issues.
- LARES-2 is approved by ASI; the satellite will have improved laser reflector design.
- ITRF2014 (SLRF2014) was adopted as the ILRS TRF for operational products starting June 15, 2017.

- A complete re-analysis using ITRF2014 is planned.
- A new model for Centre-of-Mass corrections will be developed in 2018.
- Pilot project on systematic biases is running and hopefully improving the scale contribution by SLR.
- Special Issue of Journal of Geodesy (JOGSILR) is waiting for submissions; deadline February 28, 2018.
- A Technical Workshop was held in Riga (Latvia) on October 2–5, 2017: https://cddis.nasa.gov/2017_Technical_Workshop/Program/index.html
- Next Workshop will be held in Canberra (Australia) on November 4–9, 2018.

IVS Report John Gipson reported for IVS:

- The TWIN telescopes at Onsala were inaugurated during the EVGA meeting in May 2017.
- VGOS sessions are scheduled every 2 weeks, with 5 operational telescopes included (3 in US, 2 in Europe).
- CONT'17 is running at the moment; 3 independent network configurations are scheduled in parallel: Legacy network, VLBA+others, VGOS network.
- WG dealing with aberration is working in close cooperation with ICRF-3 generation.
- Next IVS General Meeting will be held in Ny-Alesund (Norway) on June 4–8, 2018.
- Ludwig Combrinck (from Hartebeesthoek) resigned from all IVS activities.

IERS Technical Notes related to ITRF2014

Zuheir Altamimi and Mathis Bloßfeld gave an overview of the status.

- IERS TN No. 38 (Analysis and results of ITRF2014) is published.
- IERS TN No. 39 (IGN best practice for surveying instrument reference points at ITRF co-location sites) is published.
- IERS TN on the evaluation of the three solutions ITRF, DTRF and JTRF (follow up Action Item #64.03):
 - There seems to be no real progress so far; no input available yet.

- Scientific papers are (partly) available → can be summarized for the TN.
- DGFI-TUM is preparing two contributions (DTRF2014 solution; Validation of DTRF2014 w.r.t. other ITRS realizations).
- Discussion of “external” contributions / validations: e.g. GIA vs. up velocities; annual signals vs. geophysical signals → Can GGFC contribute on this topic?

Action Item #64.03 with new date: Provide input for the IERS TN on evaluation of ITRF2014, DTRF2014, JTRF2014

IERS Workshop Celebrating 30th Anniversary In earlier DB meetings, a session during REFAG2018 (integrated in COSPAR GA) was seen as a good choice. However, nobody is volunteering to organize such kind of event.

IAU Report Richard Gross summarized some news from IAU:

- IAU General Assembly to be held in Vienna (Austria), on August 20–31, 2018.
 - 2 Sessions of interest for IERS: Reference Systems and Frames; Gaia.
 - Division Days are Friday, August 24 and Monday, August 27.
- IAU Commission A2 (Rotation of the Earth) has its Centennial Anniversary on July 28, 2019.
 - A workshop is planned to be held in Brussels (Belgium) on October 7–11, 2019.
 - Workshop proposal is due by December 15; otherwise the event will be held independent of IAU, e.g. in conjunction with Journées.
- New President of IAU Commission A2 will be Florian Seitz, starting after IAU GA 2018; new Vice-President needs to be elected.

Status of ICRS/ICRF and IAU Working Group

Bryan Dorland reported about the current status:

- ICRF-3 Working Group is on track for an adoption by IAU during its General Assembly 2018
- ICRF-3 will be a multi-wavelength reference frame: S/X, K, X/Ka
- 2nd Gaia data release is foreseen for April 2018
- Frame tie between IVS / ICRF and Gaia should be better than 1mas (from first assessments); but still ongoing work on the link optical-to-radio reference frames

- 50% of VLBA network is supporting ICRF-3

Updates on IERS Conventions

Nick Stamatakos presented the recent updates:

- W0 has been modified in Table 1.1 to correspond to value adopted in the IAG 2015 resolution No. 1.
- Substantial updates in Chapters 6 and 7 to reflect UAW recommendations regarding the filtered (former mean) pole.
- Next major revision to IERS Conventions estimated to be 2021.
- Starting selection process for obtaining experts for each chapter, including editor-in-chief, chapter experts, assistant experts (more details to follow); an official call for experts will be issued soon.
- IERS Conventions Software version control has been established.

UN-GGIM Subcommittee on Geodesy

Zuheir Altamimi outlined the developments:

- A follow-up of the UN General Assembly Resolution 69/266 in February 2015, “A global Geodetic Reference Frame for Sustainable Development”.
- The former working group now became “UN-GGIM Subcommittee on Geodesy”, with a first meeting held in Mexico on November 26, 2017 (chaired by Gary Johnston; co-chaired by Alexej Trifonov).
- The 5 major fields for realizing the UN resolution are:
 - Geodetic infrastructure
 - Policies, standards, conventions
 - Education, training, capacity building
 - Appropriate governance
 - Outreach and communication
- At the moment, the implementation plan is developed (to be ready by June 2018); IAG and all of its components will be solicited to provide input to the document.

Annual Reports

Daniela Thaller reported that the Annual Report 2016 is almost ready.

Next DB meeting (#66)

The next DB meeting (half-day morning meeting) will take place on Sunday, April 8, 2018 before the EGU in Vienna.

New Action Item

#65.06 Prepare IERS DB meeting No. 66.

Daniela Thaller, Sabine Bachmann, Wolfgang R. Dick

3.2 Central Bureau

General activities

The IERS Central Bureau (CB), hosted and funded by Bundesamt für Kartographie und Geodäsie (BKG), organized and documented the IERS Directing Board (DB) Meetings No. 64, April 23, 2017, at Technical University of Vienna, Austria, and No. 65, December 9, 2017, at Hilton New Orleans Riverside Hotel, New Orleans, Louisiana, USA (see Section 3.1 for minutes of these meetings). Between the meetings the CB coordinated the work of the DB.

Members of the CB took also part in the following meetings: European Geosciences Union General Assembly 2017 (including meetings of the GGOS Coordinating Board, the GGOS Bureau of Networks and Observations, the GGOS Standing Committee PLATO, and IAG Commission 1 “Reference Frames”), 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA), ISO Working Week, IAG/GGOS/IERS Unified Analysis Workshop (see Section 4), IAG and IASPEI Joint Scientific Assembly, 2017 ILRS Technical Workshop, SIR-GAS 2017 Symposium, and AGU 2017 Fall Meeting.

IERS components maintain individually about 10 separate web sites. The central IERS site www.iers.org, established by the CB, gives access to all other sites, offers information on the structure of the IERS, its products and publications and provides contact addresses as well as general facts on Earth rotation studies. It contains also electronic versions of IERS publications, as well as link lists for IERS, Earth rotation in general and related fields. Throughout 2017 the web site was continually updated, several new pages and documents were added. New pages include “Other realizations of the International Terrestrial Reference System (ITRS)” and a document on the history of the International Latitude Service. An extended list of meetings related to the work of the IERS was maintained and updated frequently. The CB maintains also the web pages of the IERS working groups. In an internal area, accessible for DB members and IERS Associate Members, all presentations given at IERS DB meetings since 2000 are available, and further documents were added.

The IERS Annual Report 2015 was printed and distributed. The CB edited the IERS Annual Report 2016 and published it online in December 2017. Along with the reports of the IERS components, provided by them, the annual reports contain general information on the IERS assembled by the CB. The CB compiled also summaries of DB meetings and its own report. Starting with the report for 2016, the CB uses $\LaTeX$ instead of InDesign for formatting the IERS annual reports. For this the $\LaTeX$ template was further improved.

Technical support was given in editing the Technical Notes No. 38 (“Analysis and results of ITRF2014”, by Z. Altamimi, P. Rebischung, L.

Métivier, and X. Collilieux) and No. 39 (“IGN best practice for surveying instrument reference points at ITRF co-location sites”, by J.-C. Poyard, with contributions by X. Collilieux, J.-M. Muller, B. Garayt and J. Saunier). Both Technical Notes were published online, printed and distributed to subscribers.

The contribution of IERS to the IAG Reports 2015–2017 was submitted in June 2017 (available online at: <https://iag.dgfi.tum.de/en/iag-publications-position-papers/iag-reports-2017-online/>).

During the year 2017, 27 IERS Messages (Nos. 320–346) were edited and distributed. They include news from the IERS and of general type as well as announcements of conferences.

Address and subscription information have regularly been updated in the IERS user database. There were about 2800 users in 2017 with valid addresses who subscribed to IERS publications for e-mail and regular mail distribution.

Questions from IERS users concerning IERS publications and products as well as Earth rotation and reference frames in general were answered or forwarded to other specialists.

The Director of the CB, Daniela Thaller, chairs the IERS Working Group on SINEX Format and is ex officio member of the other IERS WGs. She also leads, together with Benjamin Männel of GFZ, the GGOS Standing Committee PLATO (Performance Simulations and Architectural Trade-Offs), which is also a Joint Working Group with IAG Sub-Commission 1.1. Wolfgang Dick continued to work in the Control Body for an ISO Geodetic Register Network, which will contain standardized and proved data on reference systems.

IERS Data and Information System (DIS)

The IERS Data and Information System (IERS DIS) is continuously being adapted and extended by new components in order to fulfil the requirements for a modern data management and for the access to the data by the users. Besides routine work like maintenance of the data bases of users, products and web pages, in 2017 further developments of the IERS DIS concentrated on the new system for data management and the development and improvement of interactive tools and graphics.

The implementation of a first draft of the new data management system was tested and improved within a testing environment and processing routines were optimized.

New products and format changes to the EOP C01 series were introduced to the IERS DIS. The IERS Website, the IERS FTP Server and the IERS online tools were updated accordingly.

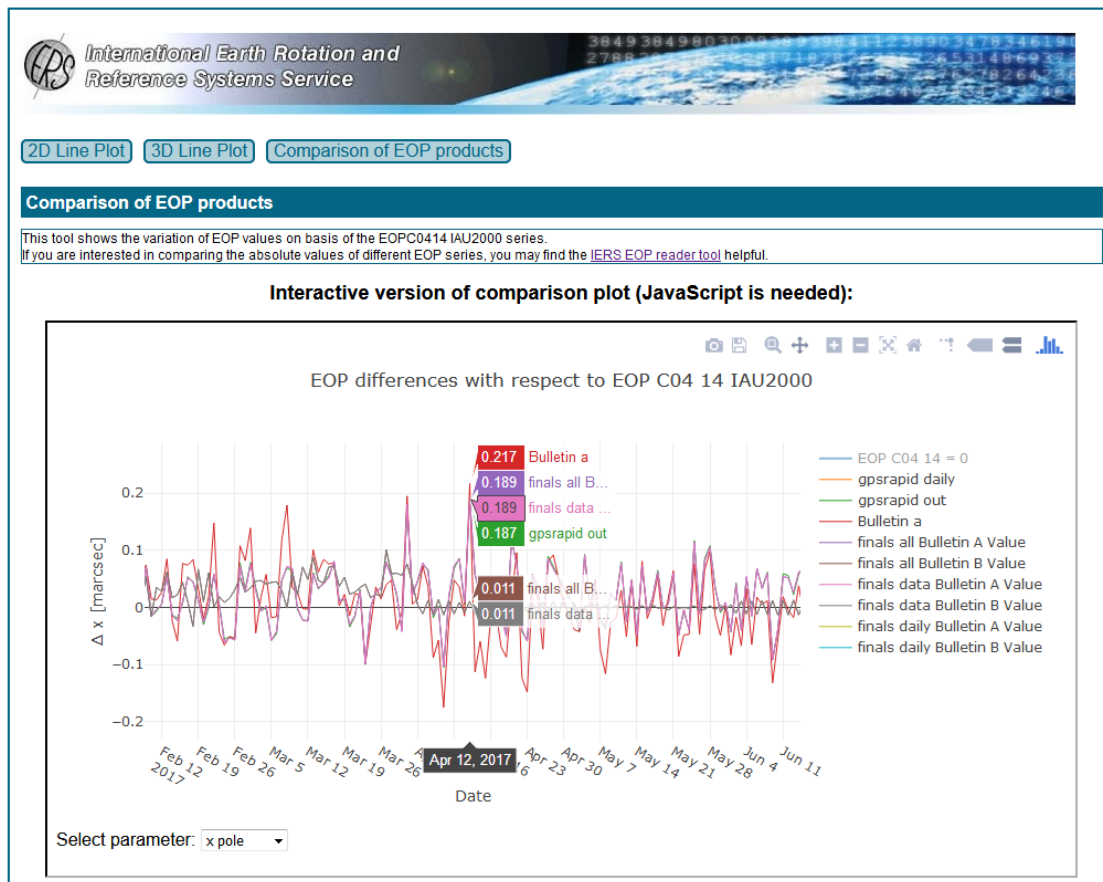


Fig. 1: Example for interactive plots: EOP differences with respect to EOP C04 14 IAU2000 - x pole, for more plots see <https://www.iers.org/plottool>

Further improvements of the IERS DIS included the enhancement of the IERS plot tool with new technologies in order to provide interactive plots.

Staff in 2017

Dr. Daniela Thaller, *Director*
 Sabine Bachmann, *scientist*
 Dr. Wolfgang R. Dick, *scientist*
 Sonja Geist, *technician*
 Sandra Schneider-Leck, *technician*

Publications

Dick, W. R.: How to Talk to the Public About the Leap Second? The Experience of the IERS Central Bureau. In: The Science of Time 2016. Time in Astronomy & Society, Past, Present and Future. E. F. Arias, L. Combrinck, P. Gabor, C. Hohenkerk, P. K. Seidelmann (eds.). Cham: Springer International Publishing, 2017, pp. 277–286

Wolfgang R. Dick, Daniela Thaller, Sonja Geist

3.3 Analysis Coordinator

Introduction In this report, we outline the activities of the Analysis Coordinator during 2017. The main activities were contributions to the Unified Analysis Workshop (UAW) held Paris in 2017 and examining published paper that use IERS products and earth orientation parameters. The ACC is still examining the analyses of the VLBI and SLR contributions to ITRF2014 and the robustness of the estimate of the scale difference between VLBI and SLR.

2017 Unified Analysis Workshop: GNSS discussion

The 2017 Unified Analysis Workshop was held in Paris, France July 10–12, 2017 following the IGS Workshop and like the IGS Workshop. Both workshops were hosted by the Institut National de l'Information Géographique et Forestière (IGN). Both the IGS Workshop and UAW were held at the University of Paris-Diderot (15 rue Hélène Brion, 75013 Paris). The organization of 2017 UAW was led by GGOS through its science panel chair Richard Gross.

The ACC contribution to the 2017 UAW focused on systematics in GNSS which is the primary source for polar motion values in the IERS and for densifying the ITRF.

Four primary areas of sources of errors and biases were considered and the following recommendations reached.

1. The gravity fields used in the GNSS orbit integrations should be updated to match modern fields to make them consistent with the fields being used by the other IAG services. The update would include the static part of the field and a time variable component. For the GNSS satellite altitudes, temporal variations in only the lowest degree terms would be needed with just the 2nd degree terms possibly being the only ones needed. Projection of the temporal variations past the time when observed changes are available could use a simple annual sine and cosine fit. Planetary bodies in addition to the Sun and Moon should also be included in gravitational force modeling.
2. Other components of the force models for GNSS should also be updated and validated. The force models associated with radiation forces are the most uncertain and modeling of these forces can be made more consistent with the exchange of attitude information. The IGS plans to develop an attitude format and make attitude information available so that analysis centers can validate their models. The IGS has noted the appearance of the GPS draconitic period and harmonics of this period in time series of various geodetic products (e.g., positions and Earth orientation parameters). Long orbital arc analyses (longer than the 24-hrs

used by most IGS analysis centers) should be investigated to assess the levels of spurious signals in these analyses and to better understand the origin of the draconitic signals.

3. An updated short-period (diurnal and semidiurnal) model is needed and a method to determine whether this is an ocean-tide only with libration terms added or an empirical model based on VLBI data needs to be established. (GNSS estimates of short period EOP terms might be affected by orbital modeling errors). The number of tidal waves to be included and the representation of the tidal signals needed also be decided.
4. Site dependent calibration of GNSS antennas are needed since these have a direct effect on the ITRF realization and position offsets when antennas are changed. Tests of the use of antenna specific phase center models are encouraged when these values are available without disturbing an existing antenna installation. Investigation and potential development of an in-situ antenna calibration system are strongly encouraged. In-situ calibration would be deployed at core sites where GNSS sites are tied to other geodetic systems

Literature search for publications using IERS products and EOPs

This year we looked at the types of publications that used IERS products. Over all there were 340 publications that appear in Google Scholar and have keywords IERS, Earth Orientation parameters. Of these publications, we list below those that have been published in journals and have been cited at least once. The list may not be complete but the 44 papers listed cover the range of topics addressed by the papers. The topics can be divided into four main areas (1) use of the IERS Conventions; (2) use of IERS Earth orientation parameters; (3) algorithms for improvements to IERS products and comparison between products; and (4) interpretation of variations in the EOP products i.e., excitation mechanisms of Earth rotation changes. Most of the papers use the IERS Conventions or IERS EOP series. Only four papers in 2017 discuss excitation mechanism (*Haddad and Bonaduce*, 2017; (*Naghbi et al.*, 2017; *Winska et al.*, 2017, *Youm et al.*, 2017). In 2017, most of the use of IERS products were for reference frame realization (using the ITRF and EOP estimates) and production (using IERS Conventions). There was little direct uses of the EOP estimates to directly study the rotation of the Earth. There is ongoing study into methods of improving EOP estimates (*Belda et al.*, 2017; *Haas et al.*, 2017; *Karbon et al.*, 2017; *Lei et al.*, 2017; *Liu et al.*, 2017; *Nilsson et al.*, 2017). The most highly cited paper in 2017 (so far) is Nothnagel et al. (2017) which discussed the International VLBI Service.

IERS/EOP literature

- Abbondanza, Claudio, Toshio M. Chin, Richard S. Gross, Michael B. Heflin, Jay W. Parker, Benedikt S. Soja, Tonie van Dam, and Xiaoping Wu. 2017. "JTRF2014, the JPL Kalman Filter and Smoother Realization of the International Terrestrial Reference System." *Journal of Geophysical Research: Solid Earth* 122 (10). John Wiley & Sons, Ltd: 8474–8510. doi:10.1002/2017JB014360.
- Belda, Santiago, Robert Heinkelmann, José M. Ferrándiz, Tobias Nilsson, and Harald Schuh. 2017. "On the Consistency of the Current Conventional EOP Series and the Celestial and Terrestrial Reference Frames." *Journal of Geodesy* 91 (2). Springer Berlin Heidelberg: 135–49. doi:10.1007/s00190-016-0944-3.
- Chatzinikos, Miltiadis, and Athanasios Dermanis. 2017. "Interpretation of Numerically Detected Rank Defects in GNSS Data Analysis Problems in Terms of Deficiencies in Reference System Definition." *GPS Solutions* 21 (3). Springer Berlin Heidelberg: 1239–50. doi:10.1007/s10291-017-0608-7.
- Devoti, Roberto, Nicola D'Agostino, Enrico Serpelloni, Grazia Pietrantonio, Federica Riguzzi, Antonio Avallone, Adriano Cavaliere, et al. 2017. "A Combined Velocity Field of the Mediterranean Region." *Annals of Geophysics* 60 (2): S0215. doi:10.4401/ag-7059.
- Virgilio, Angela D. V. Di, Jacopo Belfi, Wei-Tou Ni, Nicolo Beverini, Giorgio Carelli, Enrico Maccioni, and Alberto Porzio. 2017. "GINGER: A Feasibility Study." *The European Physical Journal Plus* 132 (4). Springer Berlin Heidelberg: 157. doi:10.1140/epjp/i2017-11452-6.
- Ding, Hao, and Benjamin F. Chao. 2017. "Solid Pole Tide in Global GPS and Superconducting Gravimeter Observations: Signal Retrieval and Inference for Mantle Anelasticity." *Earth and Planetary Science Letters* 459 (February). Elsevier: 244–51. doi:10.1016/J.EPSL.2016.11.039.
- Dong, Guangliang, Dezhen Xu, Haitao Li, and Huan Zhou. 2017. "Initial Result of the Chinese Deep Space Stations' Coordinates from Chinese Domestic VLBI Experiments." *Science China Information Sciences* 60 (1). Science China Press: 012203. doi:10.1007/s11432-016-0195-9.
- Gondelach, David J., Roberto Armellin, and Aleksander A. Lidtke. 2017. "Ballistic Coefficient Estimation for Reentry Prediction of Rocket Bodies in Eccentric Orbits Based on TLE Data." *Mathematical Problems in Engineering* 2017 (December). Hindawi: 1–13. doi:10.1155/2017/7309637.
- Gualandi, Adriano, Jean-Philippe Avouac, John Galetzka, Joachim F. Genrich, Geoffrey Blewitt, Lok Bijaya Adhikari, Bharat Prasad Koirala, et al. 2017. "Pre- and Post-Seismic Deformation Related to the

- 2015, Mw7.8 Gorkha Earthquake, Nepal. " *Tectonophysics* 714–715 (September). Elsevier: 90–106. doi:10.1016/J.TECTO.2016.06.014.
- Guo, X., P. Ditmar, Q. Zhao, R. Klees, and H. H. Farahani. 2017. "Earth's Gravity Field Modelling Based on Satellite Accelerations Derived from Onboard GPS Phase Measurements." *Journal of Geodesy* 91 (9). Springer Berlin Heidelberg: 1049–68. doi:10.1007/s00190-017-1009-y.
- Gurzadyan, V. G., I. Ciufolini, A. Paolozzi, A. L. Kashin, H. G. Khachatryan, S. Mirzoyan, and G. Sindoni. 2017. "Satellites Testing General Relativity: Residuals versus Perturbations." *International Journal of Modern Physics D* 26 (05). World Scientific Publishing Company: 1741020. doi:10.1142/S0218271817410206.
- Haas, Rüdiger, Thomas Hobiger, Shinobu Kurihara, and Tetsuya Hara. 2017. "Ultra-Rapid Earth Rotation Determination with VLBI during CONT11 and CONT14." *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 831–37. doi:10.1007/s00190-016-0974-x.
- Haddad, Mahdi, and Antonio Bonaduce. 2017. "Interannual Variations in Length of Day with Respect to El Niño – Southern Oscillation's Impact (1962–2015)." *Arabian Journal of Geosciences* 10 (11). Springer Berlin Heidelberg: 255. doi:10.1007/s12517-017-3049-2.
- Hofmeister, Armin, and Johannes Böhm. 2017. "Application of Ray-Traced Tropospheric Slant Delays to Geodetic VLBI Analysis." *Journal of Geodesy* 91 (8). Springer Berlin Heidelberg: 945–64. doi:10.1007/s00190-017-1000-7.
- Jiang, Nan, Yan Xu, Tianhe Xu, Guochang Xu, Zhangzhen Sun, and Harald Schuh. 2017. "GPS/BDS Short-Term ISB Modelling and Prediction." *GPS Solutions* 21 (1). Springer Berlin Heidelberg: 163–75. doi:10.1007/s10291-015-0513-x.
- Johnson, Christopher W., Yuning Fu, and Roland Bürgmann. 2017. "Stress Models of the Annual Hydrospheric, Atmospheric, Thermal, and Tidal Loading Cycles on California Faults: Perturbation of Background Stress and Changes in Seismicity." *Journal of Geophysical Research: Solid Earth* 122 (12). John Wiley & Sons, Ltd: 10,605–10,625. doi:10.1002/2017JB014778.
- Karbon, Maria, Robert Heinkelmann, Julian Mora-Diaz, Minghui Xu, Tobias Nilsson, and Harald Schuh. 2017. "The Extension of the Parametrization of the Radio Source Coordinates in Geodetic VLBI and Its Impact on the Time Series Analysis." *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 755–65. doi:10.1007/s00190-016-0954-1.
- Karbon, Maria, Benedikt Soja, Tobias Nilsson, Zhiguo Deng, Robert Heinkelmann, and Harald Schuh. 2017. "Earth Orientation Parameters from VLBI Determined with a Kalman Filter." *Geodesy and Geo-*

- dynamics* 8 (6). Elsevier: 396–407. doi:10.1016/J.GEOG.2017.05.006.
- Lei, Yu, Min Guo, Dan-dan Hu, Hong-bing Cai, Dan-ning Zhao, Zhao-peng Hu, and Yu-ping Gao. 2017. “Short-Term Prediction of UT1-UTC by Combination of the Grey Model and Neural Networks.” *Advances in Space Research* 59 (2). Pergamon: 524–31. doi:10.1016/J.ASR.2016.10.030.
- Li, Zhen, Jianping Yue, Wang Li, Dekai Lu, and Xiaogen Li. 2017. “A Comparison of Hydrological Deformation Using GPS and Global Hydrological Model for the Eurasian Plate.” *Advances in Space Research* 60 (3). Pergamon: 587–96. doi:10.1016/J.ASR.2017.04.023.
- Liu, Chengjun, and Mian Zhang. 2017. “The Principal Moments of Inertia Calculated with the Hydrostatic Equilibrium Figure of the Earth.” *Geodesy and Geodynamics* 8 (3). Elsevier: 201–5. doi:10.1016/J.GEOG.2017.02.005.
- Liu, J.-C., and N. Capitaine. 2017. “Evaluation of a Possible Upgrade of the IAU 2006 Precession.” *Astronomy & Astrophysics* 597 (January). EDP Sciences: A83. doi:10.1051/0004-6361/201628717.
- Lucchesi, David M., Carmelo Magnafico, Roberto Peron, Massimo Visco, Luciano Anselmo, Carmen Pardini, Massimo Bassan, Giuseppe Pucacco, and Ruggero Stanga. 2017. “The LARASE Research Program. State of the Art on Modelling and Measurements of General Relativity Effects in the Field of the Earth: A Preliminary Measurement of the Lense-Thirring Effect.” In *2017 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 131–45. IEEE. doi:10.1109/MetroAeroSpace.2017.7999552.
- Malkin, Zinovy. 2017. “Joint Analysis of Celestial Pole Offset and Free Core Nutation Series.” *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 839–48. doi:10.1007/s00190-016-0966-x.
- Meyrath, Thierry, Tonie van Dam, Xavier Collilieux, and Paul Rebischung. 2017. “Seasonal Low-Degree Changes in Terrestrial Water Mass Load from Global GNSS Measurements.” *Journal of Geodesy* 91 (11). Springer Berlin Heidelberg: 1329–50. doi:10.1007/s00190-017-1028-8.
- Murray, Jessica R., and Jerry Svarc. 2017. “Global Positioning System Data Collection, Processing, and Analysis Conducted by the U.S. Geological Survey Earthquake Hazards Program.” *Seismological Research Letters* 88 (3). GeoScienceWorld: 916–25. doi:10.1785/0220160204.
- Naghbi, S. E., M. A. Jalali, S. A. Karabasov, and M.-R. Alam. 2017. “Excitation of the Earth’s Chandler Wobble by a Turbulent Oceanic Double-Gyre.” *Geophysical Journal International* 209 (1). Oxford University Press: ggx032. doi:10.1093/gji/ggx032.

- Nilsson, Tobias, Benedikt Soja, Kyriakos Balidakis, Maria Karbon, Robert Heinkelmann, Zhiguo Deng, and Harald Schuh. 2017. "Improving the Modeling of the Atmospheric Delay in the Data Analysis of the Intensive VLBI Sessions and the Impact on the UT1 Estimates." *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 857–66. doi:10.1007/s00190-016-0985-7.
- Nilsson, Tobias, Benedikt Soja, Maria Karbon, Robert Heinkelmann, and Harald Schuh. 2017. "Water Vapor Radiometer Data in Very Long Baseline Interferometry Data Analysis." In Freymueller, J. T., Sánchez, L. (Eds.), *International Symposium on Earth and Environmental Sciences for Future Generations: Proceedings of the IAG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015*, (International Association of Geodesy Symposia; 147), 303–8. Springer, Cham. doi:10.1007/1345_2017_264.
- Nothnagel, A., T. Artz, D. Behrend, and Z. Malkin. 2017. "International VLBI Service for Geodesy and Astrometry." *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 711–21. doi:10.1007/s00190-016-0950-5.
- Plank, L., J. E. J. Lovell, J. N. McCallum, D. Mayer, C. Reynolds, J. Quick, S. Weston, et al. 2017. "The AUSTRAL VLBI Observing Program." *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 803–17. doi:10.1007/s00190-016-0949-y.
- Ray, Jim, Paul Rebischung, and Jake Griffiths. 2017. "IGS Polar Motion Measurement Accuracy." *Geodesy and Geodynamics* 8 (6). Elsevier: 413–20. doi:10.1016/J.GEOG.2017.01.008.
- Ren, Yuanzhen, Huadong Guo, Guang Liu, and Hanlin Ye. 2017. "Simulation Study of Geometric Characteristics and Coverage for Moon-Based Earth Observation in the Electro-Optical Region." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 10 (6): 2431–40. doi:10.1109/JSTARS.2017.2711061.
- Shen, Yi, Jinyun Guo, Xin Liu, Xiaobei Wei, and Wudong Li. 2017. "One Hybrid Model Combining Singular Spectrum Analysis and LS + ARMA for Polar Motion Prediction." *Advances in Space Research* 59 (2). Pergamon: 513–23. doi:10.1016/J.ASR.2016.10.023.
- Soffel, Michael, Sergei Kopeikin, and Wen-Biao Han. 2017. "Advanced Relativistic VLBI Model for Geodesy." *Journal of Geodesy* 91 (7). Springer Berlin Heidelberg: 783–801. doi:10.1007/s00190-016-0956-z.
- Tartaglia, Angelo, Angela Di Virgilio, Jacopo Belfi, Nicolò Beverini, and Matteo Luca Ruggiero. 2017. "Testing General Relativity by Means of Ring Lasers." *The European Physical Journal Plus* 132 (2). Springer Berlin Heidelberg: 73. doi:10.1140/epjp/i2017-11372-5.

- Tercjak, Monika, and Aleksander Brzeziński. 2017. "On the Influence of Known Diurnal and Subdiurnal Signals in Polar Motion and UT1 on Ring Laser Gyroscope Observations." *Pure and Applied Geophysics* 174 (7). Springer International Publishing: 2719–31. doi:10.1007/s00024-017-1552-8.
- Truebenbach, Alexandra E., and Jeremy Darling. 2017. "The VLBA Extragalactic Proper Motion Catalog and a Measurement of the Secular Aberration Drift." *The Astrophysical Journal Supplement Series* 233 (1). IOP Publishing: 3. doi:10.3847/1538-4365/aa9026.
- Wang, Zhaoyang, Xinghua Zhou, Yanxiong Liu, Dongxu Zhou, Huayi Zhang, and Weikang Sun. 2017. "Precipitable Water Vapor Characterization in the Coastal Regions of China Based on Ground-Based GPS." *Advances in Space Research* 60 (11). Pergamon: 2368–78. doi:10.1016/J.ASR.2017.09.017.
- Winska, Malgorzata, Jolanta Nastula, and David Salstein. 2017. "Hydrological Excitation of Polar Motion by Different Variables from the GLDAS Models." *Journal of Geodesy* 91 (12). Springer Berlin Heidelberg: 1461–73. doi:10.1007/s00190-017-1036-8.
- Youm, Kookhyoun, Ki-Weon Seo, Taehwan Jeon, Sung-Ho Na, Jianli Chen, and Clark R. Wilson. 2017. "Ice and Groundwater Effects on Long Term Polar Motion (1979–2010)." *Journal of Geodynamics* 106 (May). Pergamon: 66–73. doi:10.1016/J.JOG.2017.01.008.
- Zhao, Qile, Chen Wang, Jing Guo, Guanglin Yang, Mi Liao, Hongyang Ma, and Jingnan Liu. 2017. "Enhanced Orbit Determination for BeiDou Satellites with FengYun-3C Onboard GNSS Data." *GPS Solutions* 21 (3). Springer Berlin Heidelberg: 1179–90. doi:10.1007/s10291-017-0604-y.
- Zhu, Ping, Attilio Rivoldini, Laurence Koot, and Véronique Dehant. 2017. "Basic Earth's Parameters as Estimated from VLBI Observations." *Geodesy and Geodynamics* 8 (6). Elsevier: 427–32. doi:10.1016/J.GEOG.2017.04.007.

Thomas Herring

3.4 Technique Centres

3.4.1 International GNSS Service (IGS)

The International GNSS Service (IGS, where GNSS stands for Global Navigation Satellite System) was established in 1994 with a mission to provide the highest quality GNSS data and products for scientific use. The IGS provides a variety of products to the scientific community. Products of particular interest to the IERS include the Earth rotation parameters as well as global tracking station coordinates and velocities (typically obtained from a reprocessing effort), which serve as the GNSS technique contribution to the realization of the International Terrestrial Reference Frame (ITRF). In the generation of operational products, the IGS adopts the latest realization of the ITRF and IERS conventions, and thus provides its user community with direct access to these IERS products.

IGS activities and developments in 2017 that are of interest to IERS are summarized within this report. The information was compiled from the 2017 IGS Technical Report, which includes detailed report sections by the heads of all of the IGS Components and Working Groups. The Technical Report should be consulted for more detailed information regarding the IGS activities in 2017. It is available for download from the publications section of the IGS website www.IGS.org.

Routine Operational Activities

IGS network stations are maintained and operated globally by many institutions. This global network makes tracking data openly available at different latencies – from daily RINEX files to real-time streams – for public use. These data contain either the legacy GPS and GLONASS observations in RINEX 2 format, or the full set of potential signals/measurements for all available GNSS in RINEX 3 format. IGS tracking data, which is held by each of the five global Data Centers on permanently accessible servers, increased in volume over the last year by more than 3.2 Tb (26.5 million files). Many of these data are also redundantly provided through the IGS regional Data Centers.

The IGS Analysis Centers and Associate Analysis Centers utilize tracking data from between 70 to more than 350 stations to generate and control the quality of highest-precision products up to four times per day. Product Coordinators combine these contributions into official IGS products on an operational basis including a quality control procedure. Nearly 3.6 Gb IGS Final, Rapid, and Ultra-rapid product files (GPS and GLONASS) as well 28 Mb IGS real-time and 175 Mb for IGS MGEX products are made available weekly. Additionally, ionosphere (5.5 Mb

per day) and daily troposphere files (3 Mb per day) for more than 300 stations are produced.

The level of interest of users in IGS products is best exemplified by the download statistics, indicating typically over 290M files (47.5 Tb) downloads during the year (CDDIS statistics). The Central Bureau assumes responsibility for day-to-day management of the service, interaction with station operators, and answering of the order of 150–200 questions and requests from users per month. These activities are performed all year and day-by-day, with high redundancy and reliability, through the pooled resources of more than 200 institutions worldwide.

Network Status

The Central Bureau monitors a globally distributed network of 504 select GNSS tracking stations that operate according to the IGS guidelines. More than one third of them are providing an extended set of observations for the new GNSS constellations. Approximately 195 IGS stations provide real-time data streams to support the IGS real time activities.

Since GPS week 1934 (29 January 2016), the IGS has been using the IGS14 realization of the ITRF2014 reference frame. It contains the coordinates and velocities for 252 stations, where only a globally well distributed subset of 51 stations are used as so-called core sites for the datum definition when generating the IGS products. For 113 of them the coordinates are affected by the change of the related antenna phase center model. The geographical distribution of the stations is shown in Figure 1.

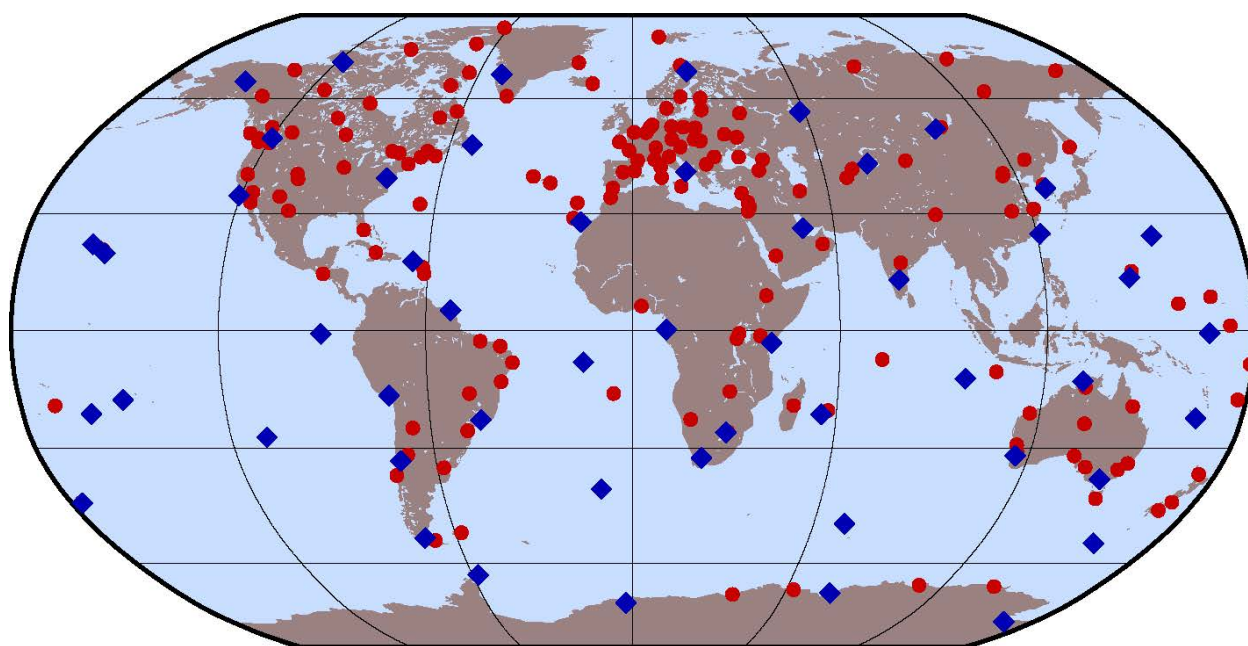


Fig. 1: Geographical distribution of the stations with given coordinates and velocities in IGS14 realization of the ITRF2014 reference frame. The blue diamonds indicate the location of the 51 core stations that are used for the datum definition when generating the IGS products.

Analysis and Core Product Generation

The IGS core products have continued to be routinely combined and delivered to users in a timely manner through 2017. To ensure continued production of high-quality IGS products, the Analysis Center Coordinator (ACC) performed high-level oversight and quality control of Analysis Center (AC) products, combination performance, and maintenance of the ACC website with updated plots acc.igs.org. The ACC also coordinates the ACs to assimilate changes made by them and to ensure that the best analysis models and procedures are used, along with coordination among the other relevant IGS Components, preparation of component reports, and so forth.

Despite a few minor delivery delays caused by power or network outages of the combination server, all of the IGS core products met availability targets (Table 1). The product reliability and quality of the IGS Ultra-rapid and Rapid products has remained similar to previous years. To improve the reliability of the GLONASS Ultra-rapid product, more AC contributions are needed. Details regarding the effects of these factors on the IGS products are described in the Analysis Center Coordinator Section of the IGS Technical Report.

Installing the combination software on two Amazon cloud computers has proven itself in daily use, in particular because two institutions (GA and MIT) are coordinating this activity.

Real-time Service

The IGS Real-Time Service (IGS-RTS) was launched in April 2013. Real-time GNSS observation data from a global observation network is provided via the IGS-RTS observation casters. Eight Real-Time Analysis Centers (RT-AC) and two RT Combination Centers (RT-CC) contribute to the service. The IGS-RTS provides real-time orbit and clock corrections for GPS. Four RT-ACs include GLONASS as well. In addition, experimental orbit and clock corrections are available for GLONASS, BeiDou and Galileo as well as code and phase biases and ionospheric corrections. Two RT-CCs combine orbit and clock corrections to three separate, combined product streams: two GPS-only product streams and one stream containing GPS+GLONASS corrections. At present, the positioning performance using Precise Point Positioning (PPP) is at the level of 10 cm and will be improved as more correction data become available. All IGS-RTS observation and product data streams are based on open RTCM standards. The service is focused on supporting geophysical applications, such as natural hazards monitoring in the framework of GGOS, but it will also support a large variety of applications in positioning, navigation, time transfer, system monitoring, and others.

More information and an updated status of the service can be found on the RTS website at rts.igs.org.

Multi-GNSS Extension

The Multi-GNSS Experiment (MGEX) is considered a key project that will enhance IGS capabilities to support the emerging satellite navigation systems. It has proceeded with high priority since its launch in February 2012. At the Governing Board meeting in February 2016 it was raised to the status of a Pilot Project. In order to keep the well established acronym it was renamed to *Multi-GNSS Extension (MGEX)*.

It was decided at the IGS 2014 workshop in Pasadena, California, USA, that the related dataflow of RINEX 3 files with an extended set of observations be integrated into the legacy dataflow. This activity was coordinated by the Infrastructure Committee and did involve all relevant components of the IGS (station manager, data and analysis centers, and several working groups). Currently about 40% of the IGS stations deliver their data in RINEX 3 format using the new longer station IDs, as foreseen in the RINEX 3 format description.

The focus of MGEX is now on the data processing. Several ACs provide solutions for the new satellite systems with different latency, completeness, and using different strategies. More information on the current status can be found on the website www.igs.org/mgex. This site also contains selected comparisons demonstrating the current performance of the different contributions.

Formats and Standards

The joint IGS/RTCM RINEX Working Group is responsible for maintenance of the RINEX format. The latest adapted version is RINEX 3.03. While tracking data from GNSS-capable equipment shall be solely available in RINEX 3 after a target date to be specified, tracking data from legacy receivers will continue to be available in RINEX 2 for the foreseeable future.

The IGS Infrastructure Committee has established a transition plan to the general usage of RINEX 3 format within the IGS. In the current phase the new and longer station IDs are incorporated into the various product file formats. Additional potential changes in the file formats (mainly driven by the needs of the MGEX Pilot Project) are currently under discussion.

Table 1: IGS core products and availability targets. Availability is defined as the percentage of time that accuracy, latency and continuity of service meet target specification.

		Sampl. Interv.	Accuracy	Latency	Submission	Target Avail.
GPS Satellite Ephemerides / Satellite & Station Clocks						
Broadcast (for comparison)	Orbits Sat. clocks	1 s	≈ 100 cm ≈ 5 ns RMS ≈ 2.5 ns SDev	real time	continuous	99.99%
Ultra-Rapid (predicted half)	Orbits Sat. clocks	15 min	≈ 5 cm ≈ 3 ns RMS ≈ 1.5 ns SDev	predicted	4x daily at 03, 09, 15, & 21 UTC	95%
Ultra-Rapid (observed half)	Orbits Sat. clocks	15 min	≈ 3 cm ≈ 150 ps RMS ≈ 50 ps SDev	3–9 hours	4x daily at 03, 09, 15, & 21 UTC	95%
Rapid	Orbits Sat. & sta. clocks	15 min 5 min	≈ 2.5 cm ≈ 75 ps RMS ≈ 25 ps SDev	17–41 hours	daily at 17 UTC	95%
Final	Orbits Sat. & sta. clocks	15 min 5 min	≈ 2.5 cm ≈ 75 ps RMS ≈ 25 ps SDev	12–18 days	weekly every Thursday	99%
Real-time	Orbits Sat. clocks	5–60 s 5 s	≈ 5 cm ≈ 300 ps RMS ≈ 120 ps SDev	25 seconds	continuous	95%
GLONASS Satellite Ephemerides						
Ultra-Rapid (predicted half)	Orbits	15 min	≈ 10 cm	predicted	4x daily at 03, 09, 15, & 21 UTC	95%
Ultra-Rapid (observed half)	Orbits	15 min	≈ 5 cm	3–9 hours	4x daily at 03, 09, 15, & 21 UTC	95%
Final	Orbits	15 min	≈ 3 cm	12–18 days	weekly, every Thursday	99%
Geocentric Coordinates of IGS Tracking Stations						
Positions of real-time sta.	horizontal vertical	daily	≈ 3 mm ≈ 6 mm	1–2 hours	daily	99%
Final positions	horizontal vertical	daily	≈ 3 mm ≈ 6 mm	11–17 days	weekly every Wednesday	99%
Final velocities	horizontal vertical	daily	≈ 2 mm/yr ≈ 3 mm/yr	11–17 days	weekly every Wednesday	99%

Earth rotation						
Ultra-Rapid (predicted half)	PM PM rates LoD	daily	$\approx 200 \mu\text{s}$ $\approx 300 \mu\text{s/day}$ $\approx 50 \mu\text{s}$	predicted	4x daily at 03, 09, 15, & 21 UTC	95%
Ultra-Rapid (observed half)	PM PM rates LoD	daily	$\approx 50 \mu\text{s}$ $\approx 250 \mu\text{s/day}$ $\approx 10 \mu\text{s}$	3–9 hours	4x daily at 03, 09, 15, & 21 UTC	95%
Rapid	PM PM rates LoD	daily	$\approx 40 \mu\text{s}$ $\approx 200 \mu\text{s/day}$ $\approx 10 \mu\text{s}$	17–41 hours	daily at 17 UTC	95%
Final	PM PM rates LoD	daily	$\approx 30 \mu\text{s}$ $\approx 100 \mu\text{s/day}$ $\approx 10 \mu\text{s}$	12–18 days	weekly every Thursday	99%
Atmospheric parameters						
Final tropospheric zenith path delay with N, E gradients		5 min	$\approx 4 \text{ mm (ZPD)}$	< 4 weeks	daily	99%
Final ionospheric TEC grid 5 deg (lon) $\times$ 2.5 deg (lat)		hourly	$\approx 2\text{--}8 \text{ TECU}$	$\approx 11 \text{ days}$	weekly	99%

Governance

Since the beginning of 2015 Gary Johnston has been the chair of the IGS Governing Board. Other members of the governing board have been replaced for various reasons during the year 2017. The current list of members can be seen at the web page <http://www.igs.org/about/gb>.

The IGS Governing Board met three times in 2017: first 23 April, for a business meeting during the EGU General Assembly in Vienna, Austria; a second business meeting on 02 July prior the IGS Workshop in Paris, France; and finally on 10 December for its regular end-of-year meeting prior to the AGU Fall Meeting in New Orleans, Louisiana, USA. The IGS Executive Committee – consisting of Rolf Dach, Gary Johnston, Chuck Meertens, Ruth Neilan, Chris Rizos, and with regular participation of Steve Fisher, Allison Craddock and of WG Chairs as required – met several times in 2017 by teleconference.

At the December meeting the IGS Governing Board elected Allison Craddock as the new secretary of the Central Bureau replacing Steve Fisher who stepped down from this position in the second quarter of 2017.

Strategic Planning

The current IGS Strategic Plan covers the period 2017–2020.

IGS Workshop

The IGS 2017 Workshop was hosted by l'Institut National de l'Information Géographique et Forestière (National Institute of Geographic and Forest-

ry Information) and Le Centre National d'Études Spatiales (National Centre for Space Studies) at the location of the University of Paris-Diderot in Paris, France. Almost 300 participants from over 30 countries attended the workshop. The main theme "Pathways to improved precisions" was reflected in the scientific program that reviewed the history and provided an outlook into the future of the IGS. The workshop also featured a special keynote lecture on the Galileo system, given by Marco Falcone of the European Space Agency (ESA). Falcone's complete presentation, as well as videos of all other plenary presentations, PDFs of posters, as well as the recommendations are available on the IGS website: <http://www.igs.org/presents/workshop2017>.

The next IGS Workshop will be held from 29 October to 2 November, 2018 in Wuhan, China hosted by University Wuhan.

Outreach

The IGS is represented on the GGOS Coordinating Board. It also plays a leadership role in the International Committee on GNSS (ICG), in particular by co-chairing Working Group D on Reference Frames, Timing and Applications. The trial project of ICG Monitoring and Assessment Task Force (IGMA) has been established, co-organized by IGS and ICG. The IGS is also well represented in the International Earth Rotation and Reference Systems Service (IERS) and in IAG Sub-Commission 1.2 on Global Reference Frames, in the RTCM SC104, and others.

There were numerous IGS-related publications released in 2017. Please visit <http://www.igs.org/library>.

Rolf Dach

3.4.2 International Laser Ranging Service (ILRS)

Introduction The International Laser Ranging Service (ILRS), established in 1998, is responsible for the coordination of Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) missions, technique development, network operations, data analysis and scientific interpretation. Here we summarize the status and developments in 2017.

Network The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2017 the network further expanded with the addition of new sites, the majority deployed by Russia, in support of their GLONASS tracking network. From a technical perspective, the quality and quantity of the observations has improved drastically during the past decade. The single-shot precision of an average station today is better than 10 mm (for the best stations this number is a few millimeters, Figure 2). The absolute quality of the individual observations is on average at the 10 mm level, with the best one dozen stations doing significantly better. Nearly all stations deliver normal points (NPs) with a precision of 1 mm or better, a firm requirement for the GGOS-era network as outlined in the GGOS2020 document and several stations have upgraded to high repetition rate systems to meet such requirements. During 2017 the ILRS Central Bureau (CB) made a major effort to encourage all stations to submit for archival their Full Rate (FR) data in addition to their NPs. These data are extremely important in characterizing correctly the response of each system with respect to each target array and calculate the precise correction that connects the ranges to the center of gravity of the target spacecraft, commonly known as the “center-of-mass” correction. Examination of the tracking over the past year indicates that the tracking of targets decreased slightly by about 2.5%, with no change in the number of tracking sites (Table 1 and Figure 8). NASA is moving forward with the deployment of the first next generation Space Geodesy SLR systems (SGSLRs) at McDonald Obs., Texas, to be followed by the one at Mt. Haleakala, Hawaii, and the development of a third system for the Norwegian Mapping Agency, to be deployed at their new core site of Ny-Ålesund, Svalbard. Russia’s expansion and upgrade of their network continues, with new deployment of a system in co-location with MOBLAS 6 at Hartebeesthoek, South Africa, this year actively contributing to the ILRS. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of the ILRS SLR. This addition will eventually improve tremendously the tie between the SLR and GNSS-, VLBI-implied frames.

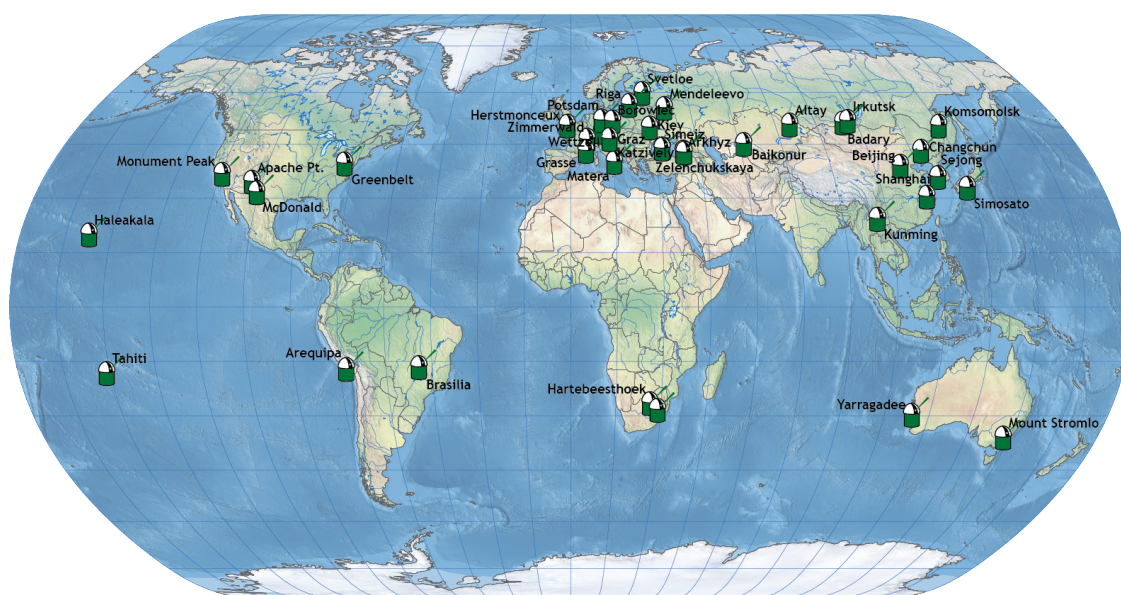
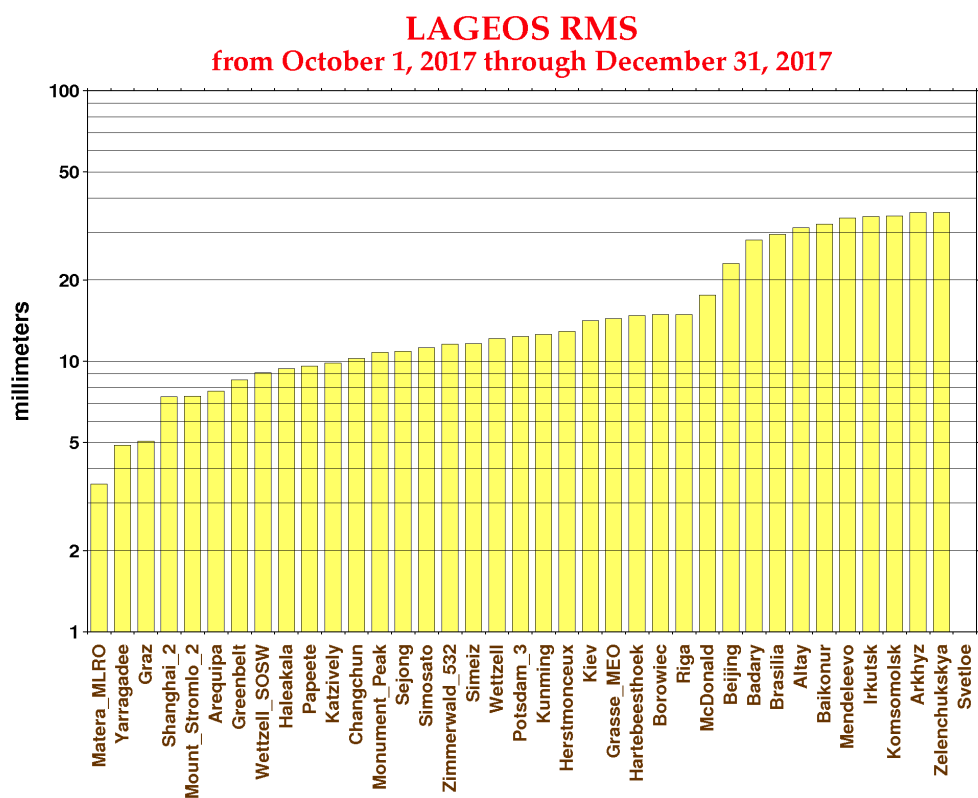


Fig. 1: The global network of SLR stations (status early 2018).



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Fig. 2: Performance of the global network of SLR stations on LAGEOS (last quarter of 2017).

Table 1: *ILRS Network Tracking Statistics for 2017*

Site Name	Station	Number of Pass Segments			
		Low	LAGEOS	High	Grand Total
Altay	1879	189	369	2,640	3,198
Arequipa	7403	2,532	217	0	2,749
Arkhyz	1886	444	215	533	1,192
Badary	1890	2,522	255	146	2,923
Baikonur	1887	63	340	1,223	1,626
Beijing	7249	1,523	358	1,365	3,246
Borowiec	7811	432	114	2	548
Brasilia	7407	544	475	1,192	2,211
Changchun	7237	9,022	1,671	6,898	17,591
Grasse	7845	249	459	544	1,252
Graz	7839	3,317	845	2,884	7,046
Greenbelt	7105	5,065	1,273	1,136	7,474
Haleakala	7119	2,435	819	1	3,255
Hartebeesthoek	7501	2,768	1,212	1,419	5,399
Hartebeesthoek	7503	38	37	38	113
Herstmonceux	7840	3,763	1,174	3,606	8,543
Irkutsk	1891	492	170	376	1,038
Katzively	1893	1,693	296	86	2,075
Kiev	1824	339	22	0	361
Komsomolsk	1868	102	201	2,018	2,321
Kunming	7819	885	227	452	1,564
Matera	7941	4,001	2,241	3,938	10,180
McDonald	7080	283	51	2	336
Mendeleevo	1874	169	85	336	590
Monument Peak	7110	5,471	966	1,537	7,974
Mount Stromlo	7825	6,439	1,955	4,259	12,653
Potsdam	7841	3,803	778	573	5,154
Riga	1884	606	109	22	737
Sejong	7394	467	85	3	555
Shanghai	7821	2,117	641	2,744	5,502
Simeiz	1873	1,736	416	181	2,333
Simosato	7838	1,467	595	26	2,088
Svetloe	1888	199	29	15	243
Tahiti	7124	1,078	311	604	1,993
Wettzell	7827	1,344	560	2,404	4,308
Wettzell	8834	3,450	851	2,709	7,010
Yarragadee	7090	22,059	6,251	15,310	43,620
Zelenchukskaya	1889	813	242	309	1,364
Zimmerwald	7810	6,141	1,699	3,725	11,565
Totals:	39 stations	100,060	28,614	65,256	193,930

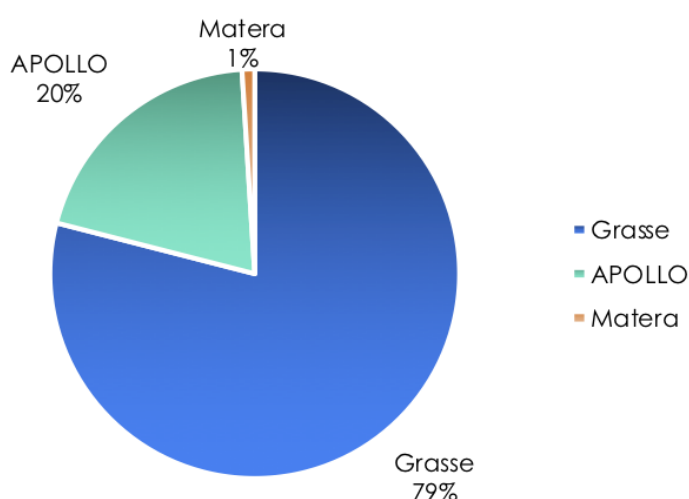


Fig. 3: Observatory statistics in 2017.

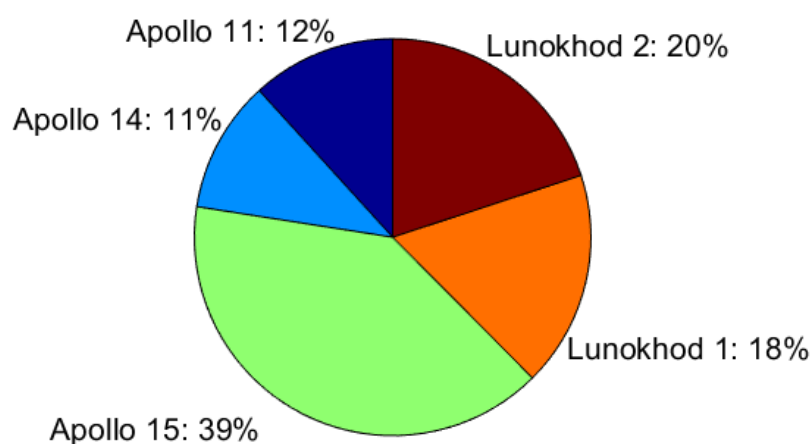


Fig. 4: Retro-reflector statistics from MeO in 2017.

Statistics of the SLR data collected as pass segments during the calendar year 2017 are summarized in Table 1. For each of the contributing stations the tracked passes are broken down in three categories of target orbits: Low Earth Orbiters (LEO), LAGEOS 1 & 2 and LARES, and the High Earth Orbiters (HEO), GPS, GLONASS, Etalon 1 & 2, GIOVE-A/B, Galileo, BeiDou, IRNSS, QZSS and the Moon.

Some of the SLR stations are technically equipped to track retro-reflector arrays placed on the surface of the Moon. Currently there are only three Lunar Laser Ranging (LLR) capable stations within the ILRS network of about 40 SLR stations. These are the MeO system of the Observatoire de la Côte d'Azur at Grasse, France, the Matera Laser Ranging Observatory (MLRO) station in Matera, Italy and the non-SLR station

Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) in New Mexico, USA. Additionally, stations Kunming in China (http://english.ynao.cas.cn/research/rp/201801/t20180123_189509.html) and Wettzell in Germany successfully detected lunar returns at the beginning of 2018. Stations in Russia, China and South Africa plan to join the LLR network over the next few years. In 2017, the largest amount of normal points came from the French station in Grasse (79 %), followed by APOLLO (19%) and 35 normal points from MLRO as illustrated in Figure 3. The number of data for 2017 was higher than in any other year of LLR observations. This is mainly due to the successful use of ranging at infrared wavelength at MeO, where most of the data collected in 2017 (~92%) were obtained with infrared instead of the usual green wavelength at 532 nm (<http://www.geoazur.fr>). Figure 4 illustrates the statistics for the observed retro-reflectors from MeO in 2017 which is representative for the whole data set (The 2017 APOLLO data is not available up to now). Nearly 40 % of the data were obtained from the Apollo 15 reflector array, the Apollo 11 and 14 arrays are measured nearly equally at ~11% and the Lunokhod arrays at ~20%.

LLR data analysis is carried out at a few LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; and the Institute of Geodesy (IfE) at the University of Hannover, Germany. Recently, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Japan, increased their LLR data analysis activities. One general objective of LLR analysis is to achieve mm-level accuracy; currently this is still at the cm level as seen in Figure 6. The various analysis centers are eager to improve their software codes, though it is a difficult task. Recent activities also comprise simulations to show the potential benefit of improved tracking from additional observatories and/or to new lunar reflectors. These activities are aiming for a better science product, as LLR belongs to the best tools to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system.

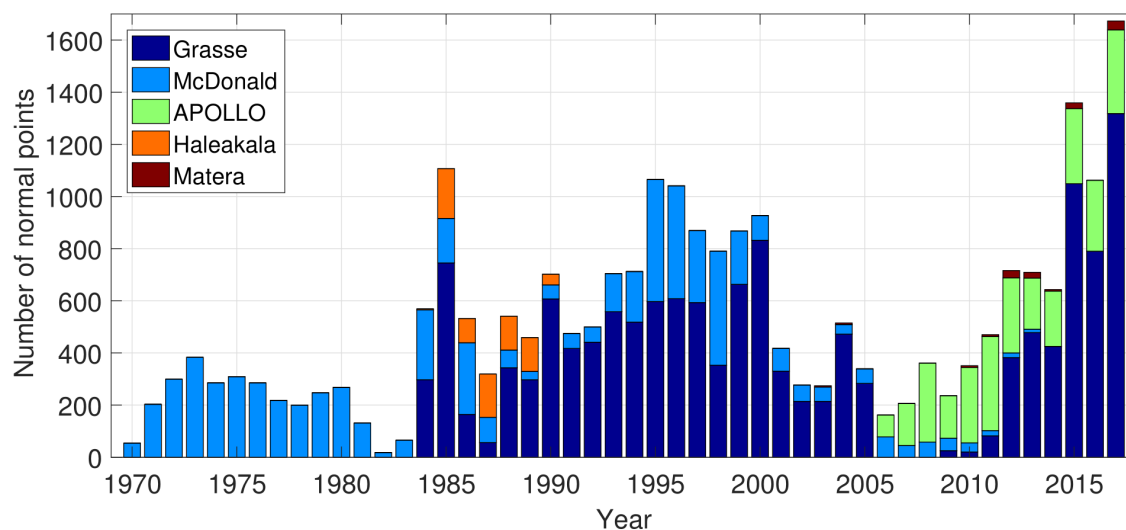


Fig. 5: Data yield of the global LLR network of stations (up to end of 2017). Note the increased contribution of Grasse's MeO system upon its return to operations in 2011, the steady yield of APOLLO, the small increase at Matera, and the absence of McDonald Obs. the last four years.

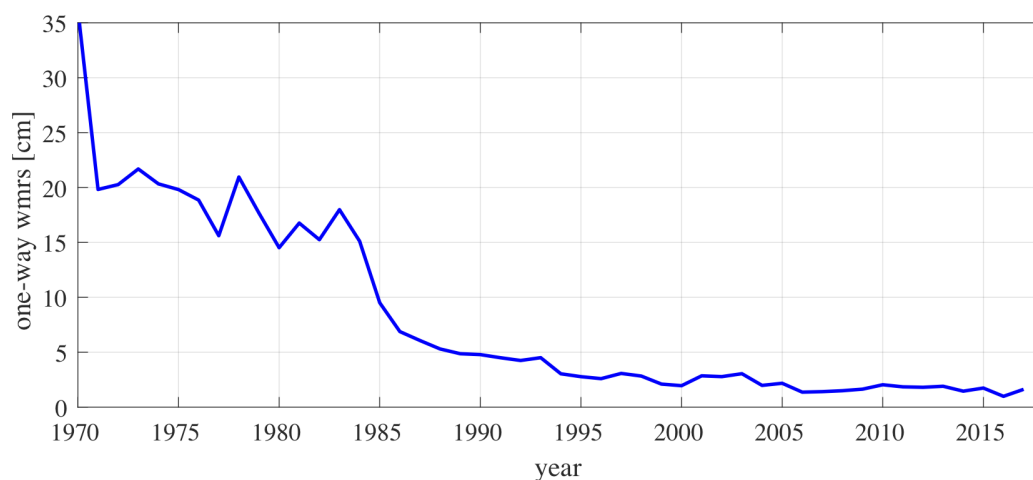


Fig. 6: LLR residuals, annual WRMS 1970 to 2017.

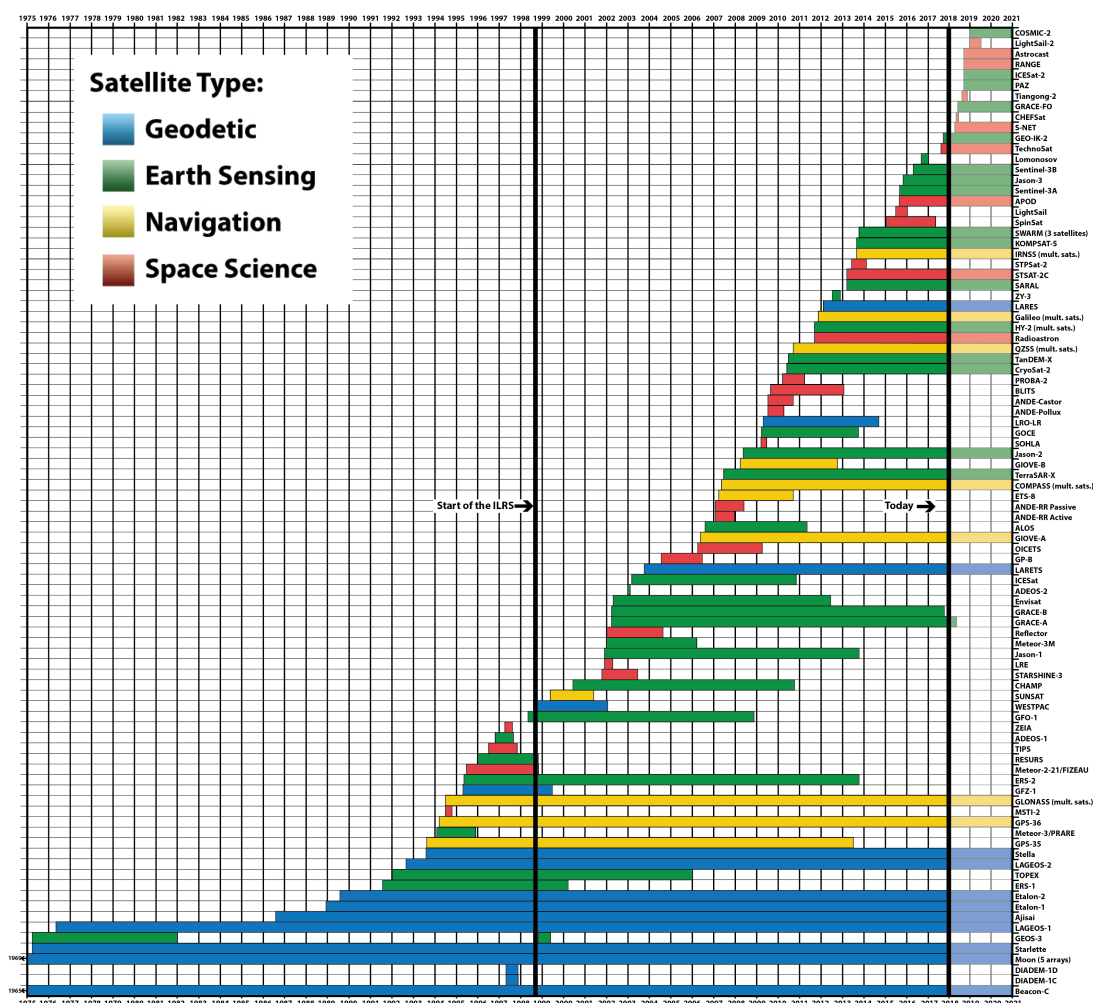


Fig. 7: *The currently tracked SLR missions (status as of late 2017).*

Missions

In 2017, a total of ~100 targets, including those on the moon, were being tracked by SLR/LLR (Figure 7). This indicates a ~42% increase in targets since the 70 missions supported in 2016! Of these, only about 1/3 are geodetic targets (cannonball satellites), about one half are navigation satellites (GNSS) and the rest are Earth Observation missions, including a small number of experimental space science missions. In 2017 the steady increase of tracking multiple GNSS targets continued for a sixth year in a row and two dedicated tracking campaigns organized through the ILRS/GGOS LARGE Working Group (LAser Ranging to GNSS s/c Experiment), resulted in a substantial increase in data yield from such missions:

- December 19, 2016–March 02, 2017 – [Galileo](#) tracking campaign
- January 15–April 15 – LARGE GLONASS tracking campaign
- March 03–April 05 – [Galileo](#) tracking campaign
- April 06–May 11 – [Galileo](#) tracking campaign

- April 24–May 15 – [IRNSS-1B](#) tracking campaign
- May 15–August 15 – LARGE GNSS tracking campaign
- August 25–September 23 – [IRNSS-1B](#) tracking campaign
- August 25, 2017–February 28, 2018 – [QZS-2](#) tracking campaign
- November 01, 2017–February 28, 2018 – [QZS-3](#) tracking campaign
- December 01–February 28, 2018 – [QZS-4](#) tracking campaign

Table 2: *ILRS Supported Missions Launched or Initiating Tracking in 2017*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (sec)	Altitude (Km)	Inclination (°)	First Data Date
Galileo-207	1606901	7207	41859	9	300	23,220	56 +/- 2 °	2017-Feb-16
Galileo-214	1606904	7214	41862	9	300	23,220	56 +/- 2 °	2017-Feb-20
Galileo-213	1606903	7213	41861	9	300	23,220	56 +/- 2 °	2017-Feb-20
Galileo-212	1606902	7212	41860	9	300	23,220	56 +/- 2 °	2017-Feb-20
QZS-2	1702801	1582	42738	9	300	32,000-40,000	45 °	2017-Jun-01
TechnoSat	1704205	6203	42829	3	15	600	97.6 - 97.9 ° +/- 7.2 '	2017-Jul-30
QZS-3	1704801	1583	42917	9	300	36,000	0 °	2017-Sep-12
QZS-4	1706201	1584	42965	9	300	32,000-40,000	45 °	2017-Oct-12
GLONASS-137	1705501	9137	42939	9	300	19,140	65 °	2017-Oct-16
Geo-IK-2	1603401	5561	41579	5	30	943.5 - 973.5	99.47 °	2017-Oct-18

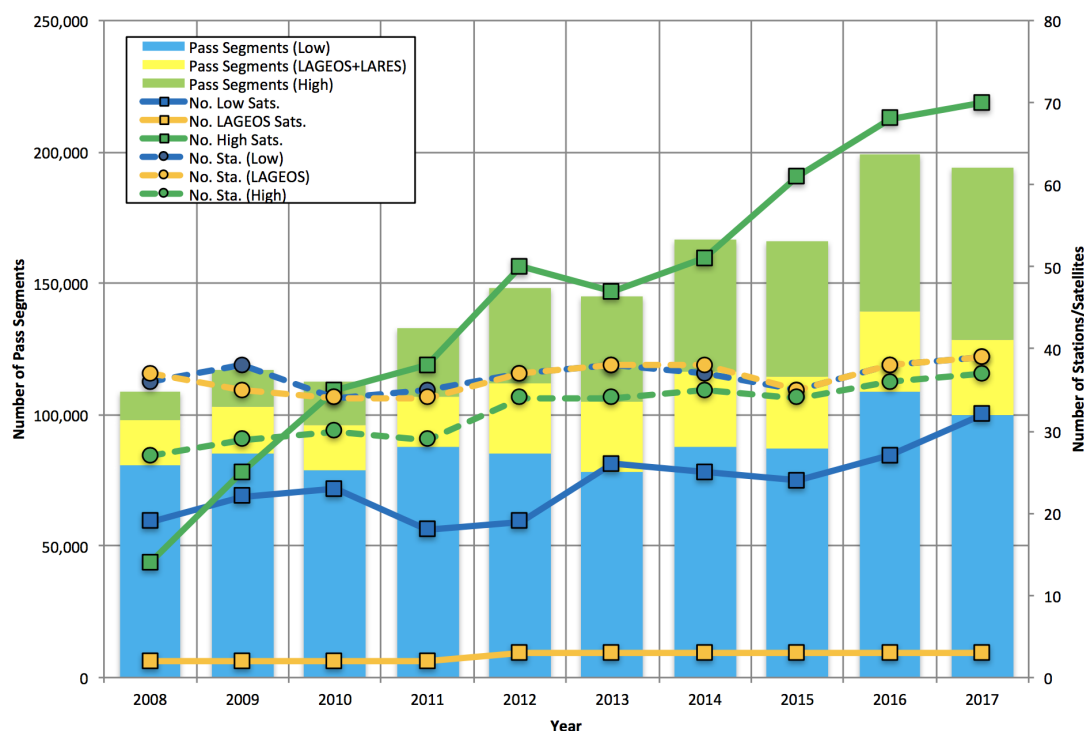


Fig. 8: ILRS network data yield by target type since 2008 and up to the end of 2017.

During 2017 the new missions that were launched are shown in Table 2. All but two were spacecraft of GNSS Constellations. We also had the end of one mission: SpinSat re-entered the Earth's atmosphere on March 11, 2017. Finally, this year, the Italian Space Agency (ASI) approved the development of the LARES-2 spacecraft, very much in shape along the lines of LARES, however, slightly larger, heavier and to be placed in orbit thanks to an offer by ESA, on the maiden launch of the extended VEGA (C) rocket sometime in late 2019 (Ciufolini et al., 2017). Despite the increase in the number of targets in 2017, the ILRS network has increased its productivity to keep pace with this increased demand for support, and kept the data yield at similar levels as in the past years (Figure 8).

Analysis and science

The effort to identify, mitigate and monitor systematic errors in the ILRS data has continued-on since several years with new initiatives and results. The Pilot Project to develop a strategy for a combined product that delivers estimates of station systematics on a regular basis led to the development of an operational tool. Initially a re-analysis of the main ILRS targets LAGEOS and LAGEOS-2 was completed, (eventually it will include Etalons and LARES), covering all SLR data from 1993 to present. The reanalysis followed the established best practice to monitor separately the systematics on each s/c and to allow for long-term averaging of the results of weekly estimates. This will now

transition to a fully operational product that will become available in 2018, once a trial period with the participation of all ILRS ACs is successfully completed. The weekly estimates from a preliminary combination at the JCET Combination Center were averaged over the 25-year period to obtain a reliable mean estimate for each target separately (Figure 9). These averaged results along with the individual AC estimates are displayed in Figures 10 (a)-(d) separated into biases above and below the 10-mm threshold.

A dedicated web-portal was developed to allow numerous ways of comparing the results between different ACs, targets and time intervals: http://geodesy.jcet.umbc.edu/BIAS_W_v221/configuration.php Example results of the reanalysis for two specific systems and all ACs for LAGEOS 1 over the period 1993-2018 are displayed in Figure 11 at Yarragadee, Australia, (a), and Matera, Italy, (b). Note that in general, the results are all very close to each other, indicating the high degree of consistency between the individual ACs' analysis.

The next phase of the project is the development of this product as a service to the network, so that stations can be notified when an abnormal estimate is obtained. The process requires careful implementation to limit false alarms and for that we first needed to develop a long history of the systematics for each station separately. This task was completed in 2017, and the operational service will be in test mode during early 2018.

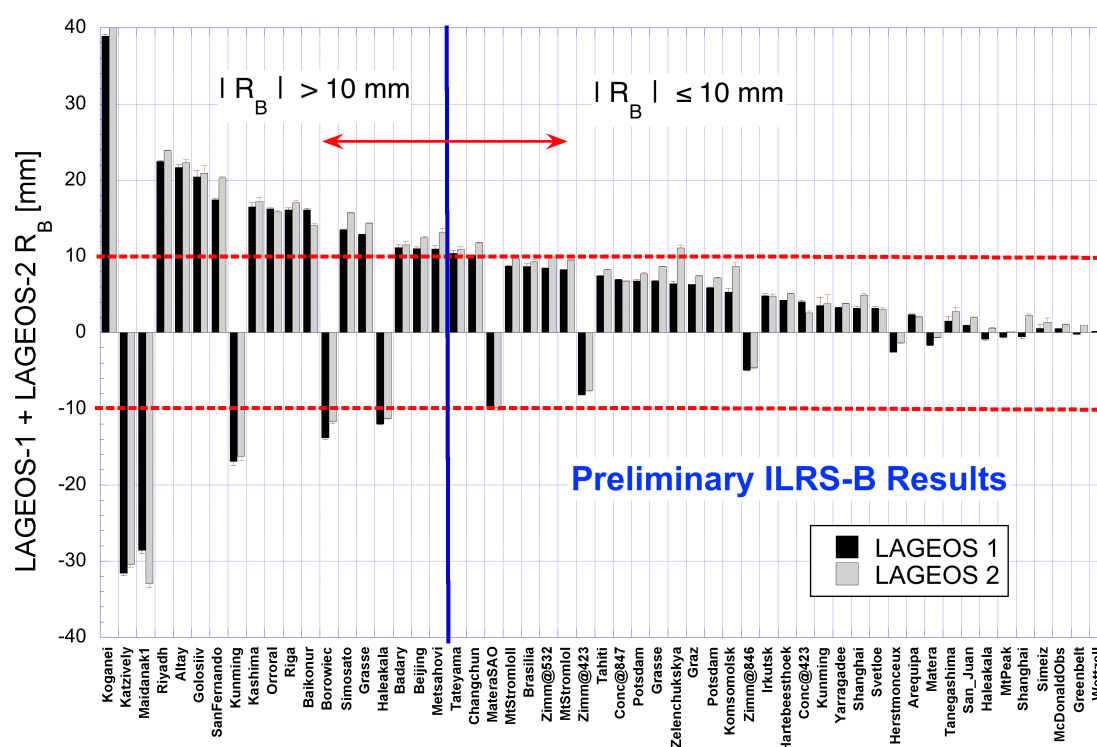
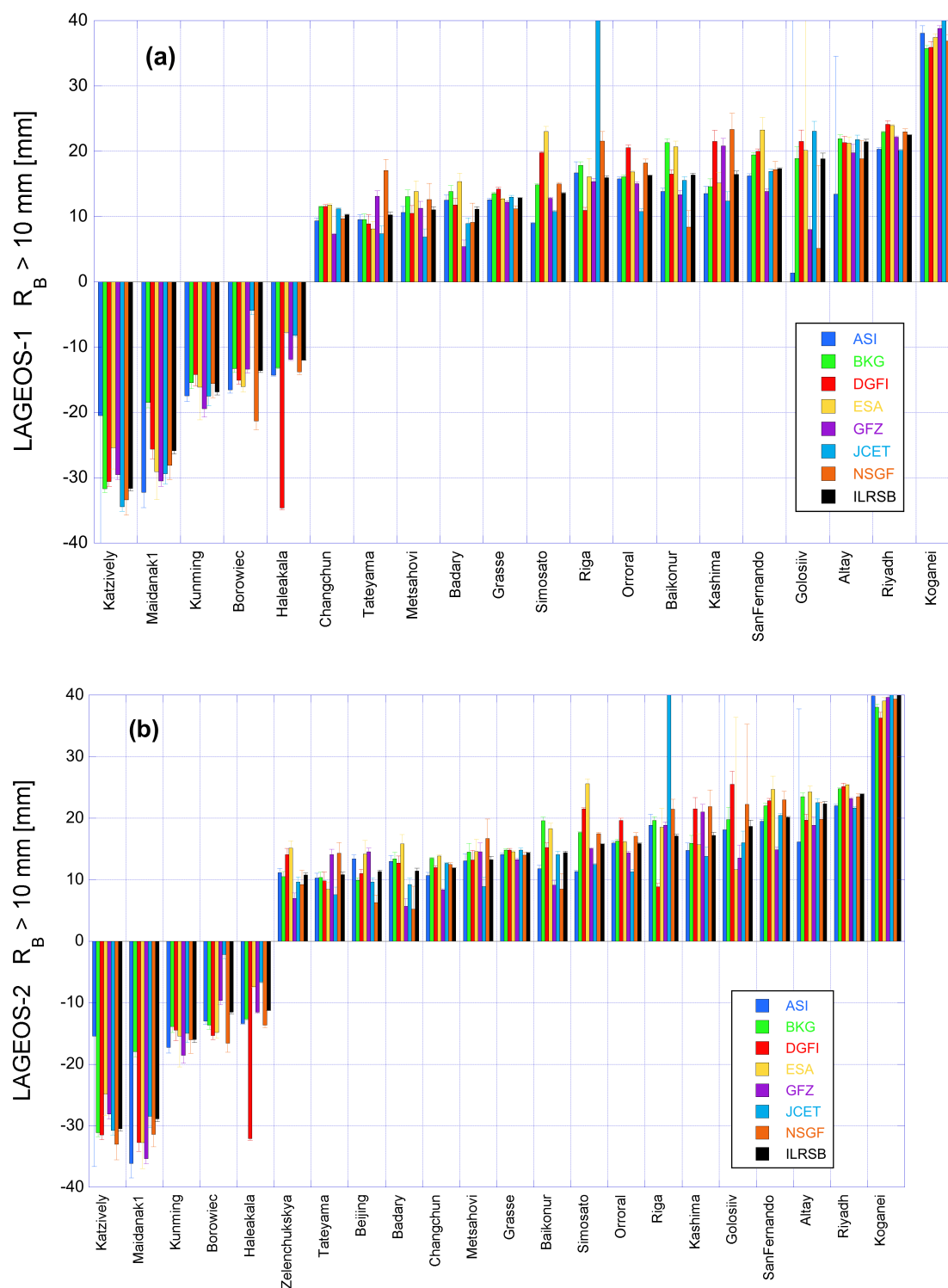


Fig. 9: Mean range bias estimates for each of the LAGEOS s/c and all ILRS stations that contributed data to the SSEM Pilot Project, averaged over the period 1993-2018 (~1305 weeks). A more detailed analysis in the final phase will separate the time interval to allow for changes in the mean bias, due to observed jumps and station position changes.



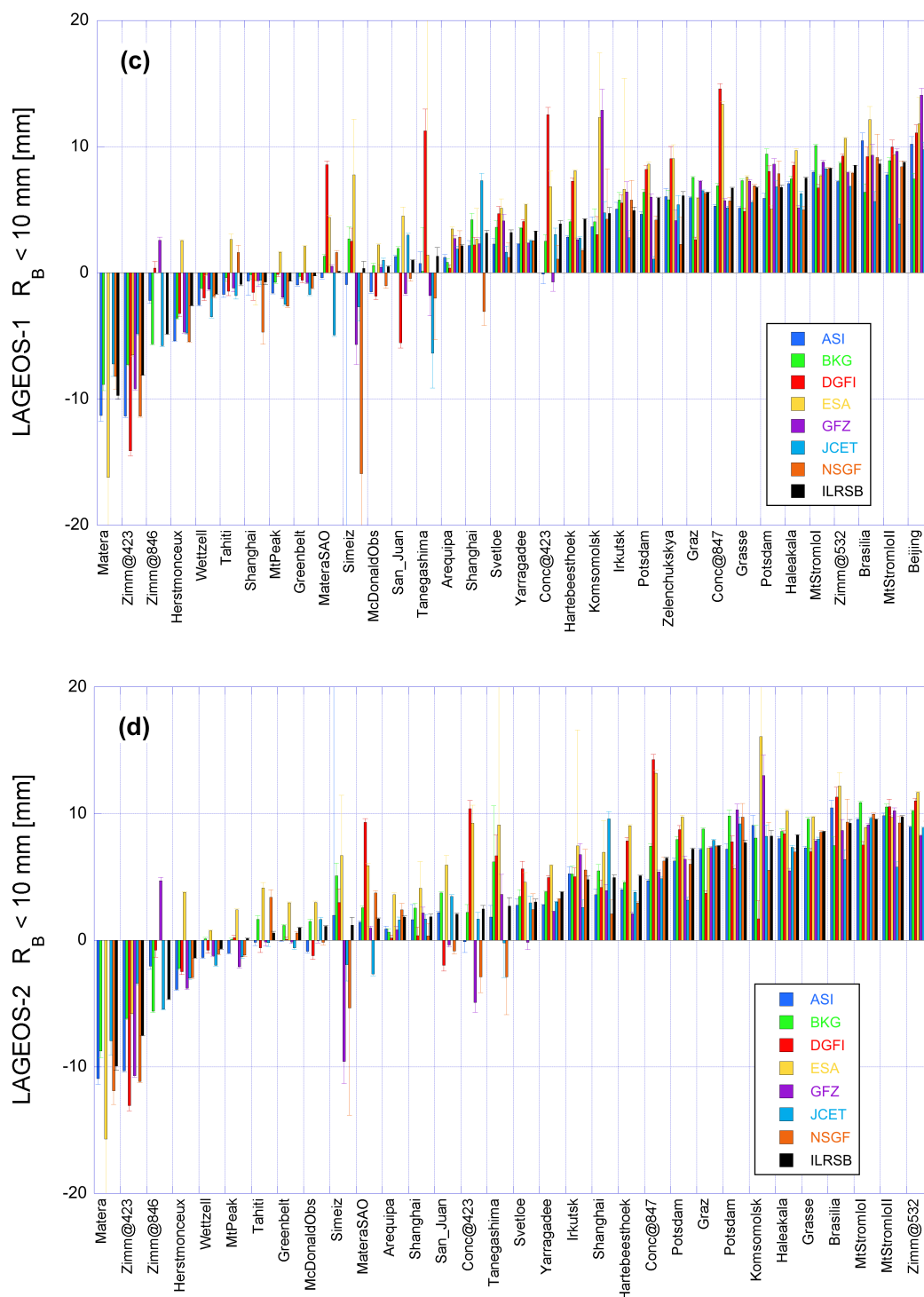


Fig. 10: The systematics for the ILRS network, averaged over the period 1993 – 2018, for each target separately, LAGEOS 1 top figures (a) and (c), and LAGEOS 2 bottom figures (b) and (d). Preliminary results from the Station Systematic Error Monitoring Pilot Project ordered by the magnitude of the combined ILRS-B estimate for each case. The results are organized in two groups for each target satellite, those with a bias magnitude over 10 mm, (a) and (b), and those with an estimate below that threshold value, (c) and (d).

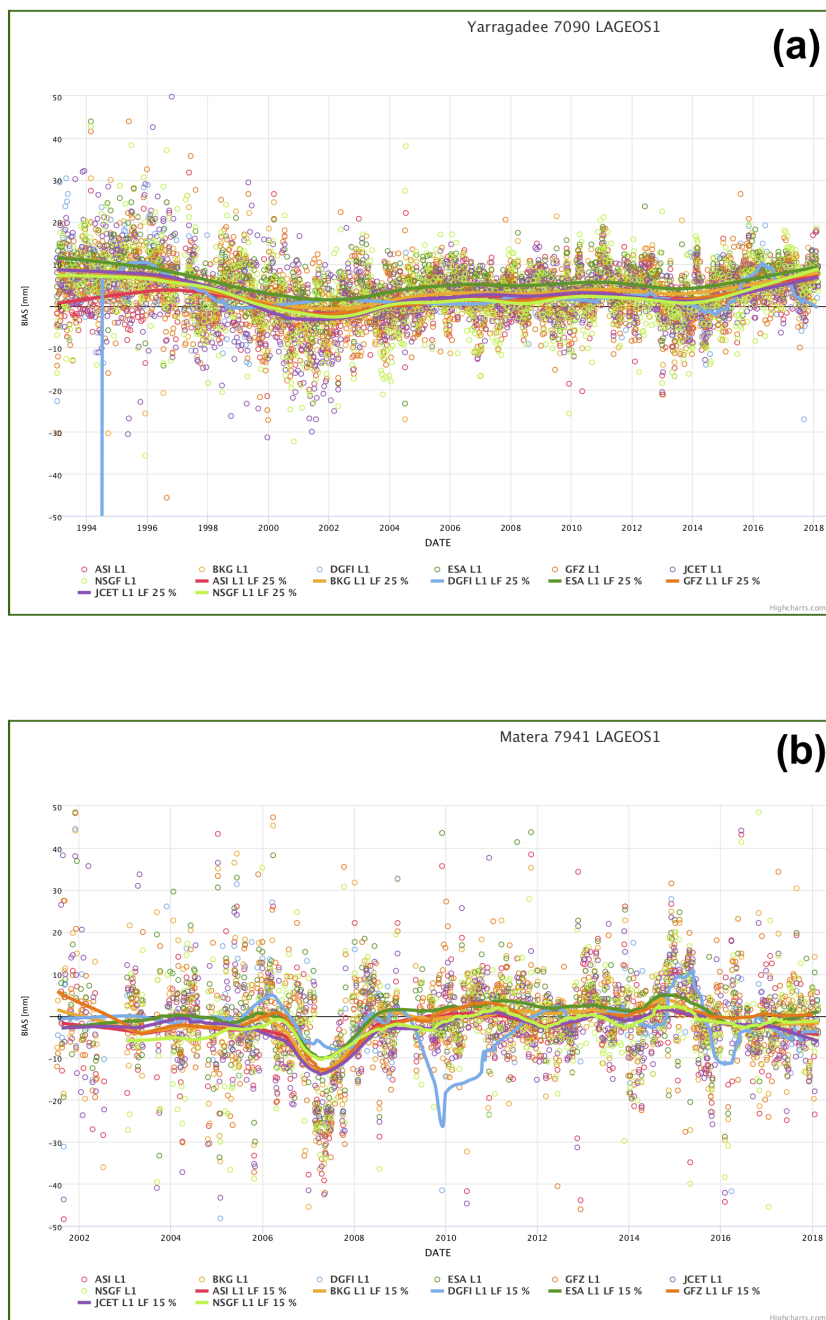


Fig. 11: Weekly estimates of the systematic error for (a), the Yarragadee, Australia, (7090) and (b), the Matera, Italy MLRO system (7941). The circles indicate the weekly results while the lines are a “moving average” LOESS estimate.

Meetings

In 2017 the ILRS held a Technical Workshop at Riga, Latvia, during the week of October 2–5, hosted by the Institute of Astronomy at the University of Latvia. The theme for this workshop was: “Improving ILRS Performance to Meet Future GGOS Requirements” and the topics that were addressed:

- What are the current and anticipated laser ranging requirements for the various satellites and have we defined them properly?
- How do we evaluate our current performance and is it adequate?
- What factors are currently limiting our network performance?
- What operational steps and tools would help us to better meet satellite ranging accuracy and scheduling requirements?
- What automation capabilities have been implemented or are planned for implementation, and what automation capabilities should stations consider?

The workshop was very well attended with over 120 participants from many countries, more than 50 oral presentations and many poster presentations. The ASC held two meetings in 2017, one during the EGU General Assembly, on April 22 (<http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html>), and one prior to the Riga Workshop, on October 1 (<http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html>). The ILRS Governing Board met once in 2017, prior to the Riga workshop on October 1 (http://ilrs.gsfc.nasa.gov/about/organization/govboard/gbmeeting_reports.html). In 2018 the ILRS will hold the 21st International Workshop on Laser Ranging that will take place in Canberra, Australia, November 5–9. For more information please see:

<http://www.iwlr2018.serc.org.au>

The topic of the 2018 Workshop is: "Laser Ranging for Sustainable Millimeter Geoscience".

Publications

Access all the presentations, posters, and proceedings papers presented at the Technical Workshop in Riga from the official ILRS page for the workshop:

https://cddis.nasa.gov/2017_Technical_Workshop

An extensive list of general publications of interest to ILRS associates can be found at the ILRS website:

<http://ilrs.gsfc.nasa.gov/about/reports/biblio/bibliography.2017.html>

References

Ciufolini, I., Paolozzi, A., Pavlis, E. C., Sindoni, G., Koenig, R., Ries, J. C., Matzner, R., Gurzadyan, V., Penrose, R., Rubincam, D., others (2017). A new laser-ranged satellite for General Relativity and space geodesy: I. An introduction to the LARES2 space experiment. *Eur. Phys. J. Plus* (2017) 132: 8, 336. [urlhttps://doi.org/10.1140/epjp/i2017-11635-1](https://doi.org/10.1140/epjp/i2017-11635-1).

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3.4.3 International VLBI Service for Geodesy and Astrometry (IVS)

IVS Organization and Activities

During 2017, the IVS continued to fulfill its role as a service within the IAG and IAU by providing necessary products for the maintenance of global reference frames: TRF, CRF, and EOP. Some highlights of the IVS organization and activities were:

- Several IVS Analysis Centers (ACs) in cooperation with the International Astronomical Union (IAU) Working Group on the third realization of the International Celestial Reference Frame (ICRF3) worked on prototype solutions and their final contributions to ICRF3. It is planned to create a combined solution based on the individual solutions of the ACs in SINEX form.
- The IVS continued an observing program to determine the alignment of the current radio frame (ICRF2) with the future *Gaia* optical frame by observing ICRF2-*Gaia* transfer sources.
- In the first quarter of 2017 the 32-m antenna at Tsukuba, Japan was dismantled. The functionality of Tsukuba, in particular the observation of the weekend Intensive sessions to determine UT1, was taken over by the 13.2-m antenna at Ishioka.
- The Onsala Twin Telescopes were inaugurated on May 18, 2017 as part of the European VLBI Group for Geodesy and Astrometry (EVGA) meeting, which was held at Chalmers University of Technology in Gothenburg, Sweden. The meeting attracted 100 participants from 20 countries.
- The IVS published three IVS Newsletters in April, August and December, keeping the community informed about IVS activities. In December 2017 the Biennial Report 2015+2016 was published.

Table 1: *IVS meetings in 2017. The EVGA and AOV are regional subgroups of the IVS organizing institutions that are active in geodetic and astrometric VLBI in Europe and Asia-Oceania.*

Event	Location	Date
9th IVS Technical Operations Workshop	Westford, MA, USA	April 30 – May 4, 2017
23rd EVGA Working Meeting	Gothenburg, Sweden	May 15–19, 2017
18th IVS Analysis Workshop	Gothenburg, Sweden	May 17, 2017
37th IVS Directing Board meeting	Gothenburg, Sweden	May 19, 2017
Detection and Measurement of RFI in RA	Yebes, Spain	June 8–9, 2017
2nd General Meeting of the AOV	Kobe, Japan	July 31 – August 1, 2017
6th Int'l VLBI Technology Workshop	Bologna, Italy	October 9–11, 2017
38th IVS Directing Board meeting	Bologna, Italy	October 12, 2017

Network Stations and observing sessions

A total of 202 geodetic/astrometric 24-hour sessions were observed during the year 2017. The number of observing sessions coordinated by IVS was about ~ 3.9 days per week; the increase of the number of sessions w.r.t. 2016 (with 190 sessions) is mostly due to the inclusion of the CONT17 campaign (see below). Beyond that, the last two observing years were very similar in its composition. In addition to the 24-hour sessions, there were 410 1-hour Intensive sessions observed for the determination of UT1–UTC. The major observing programs during 2017 were:

- IVS-R1, IVS-R4** Weekly (Mondays and Thursdays) 24-hour, rapid turnaround measurements of EOP. Databases were available no later than 15 days after each session. The NASA Goddard Space Flight Center (R1) and the U.S. Naval Observatory (R4) coordinated these sessions.

- Intensive** Daily 1-hour UT1 Intensive measurements were made on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Ishioka (Japan), and on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Ishioka (Japan).

- IVS-T2** Bi-monthly sessions coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn, Germany, with 14–16 stations per session. Seven of these sessions were observed to monitor the TRF with all IVS stations.

- IVS-CRF** The Celestial Reference Frame (CRF) sessions, coordinated by the U.S. Naval Observatory, provide astrometric observations that are required for improving the current CRF and for extending the CRF by observing ‘new’ sources. Twelve sessions were observed for the maintenance of the CRF in 2017.

- VLBA** The Very Long Baseline Array (VLBA), operated by the Long Baseline Observatory (LBO), allocated six observing days for astrometry/geodesy. These sessions included the 10 VLBA stations plus up to seven geodetic stations, providing state-of-the-art astrometry as well as information for mapping ICRF sources.

- Europe** The European geodetic network, coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn, continued with six sessions in 2017.

- IVS-OHIG** The purpose of the IVS-OHIG (Southern Terrestrial Reference Frame) sessions is to tie together optimally the sites in the southern hemisphere. In 2017 five OHIG sessions were observed.
- APSG** The Asia-Pacific Space Geodynamics (APSG) program operated two sessions in 2017.
- AUSTRAL** In 2017, 19 Austral sessions were observed. The purpose is to determine the station coordinates and their evolution in the Australia (AuScope) and New Zealand geodetic VLBI network.
- AOV** The Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) had six sessions during 2017.
- IVS-R&D** Ten research and development sessions were observed in 2017. The goals of the 2017 R&D sessions included the observation of link sources between *Gaia* and the ICRF2 and the improvement of the scheduling technique of the Intensives.
- CONT17** The IVS organized a continuous VLBI campaign (CONT17) during the period from November 28 to December 12, 2017. The campaign consisted of three separate networks: two legacy S/X networks observing for 15 consecutive days (Figure 1) and one VGOS broadband network (Figure 2) observing for five consecutive days in the middle of the CONT17 period. The use of the two legacy networks allows to study the accuracy of VLBI estimates of EOP and to investigate possible network biases. A special issue on CONT17 is planned to be published in *Journal of Geodesy*.

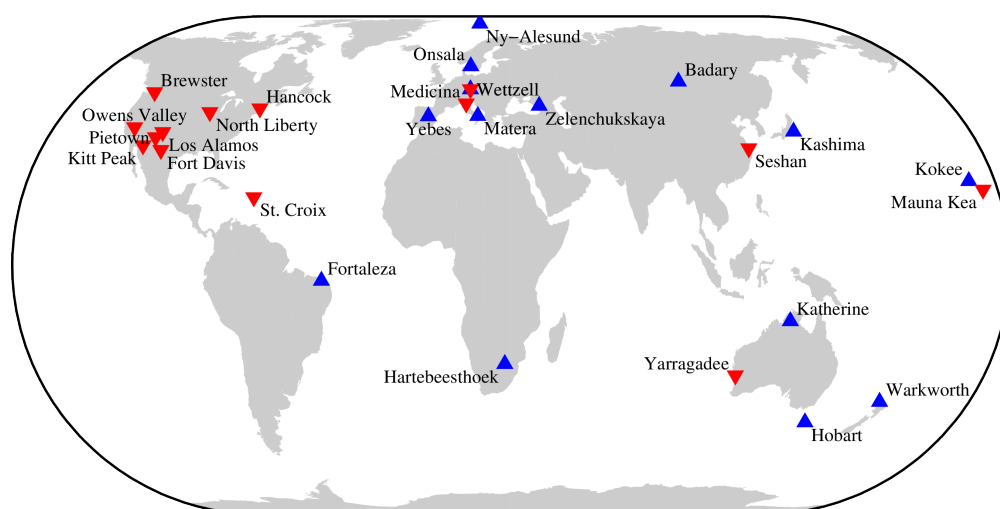


Fig. 1: The two legacy S/X networks of CONT17: the Legacy-1 network is depicted by blue triangles and the Legacy-2 network by red inverted triangles. Twenty-seven stations at 26 sites participated in the S/X portion of CONT17.

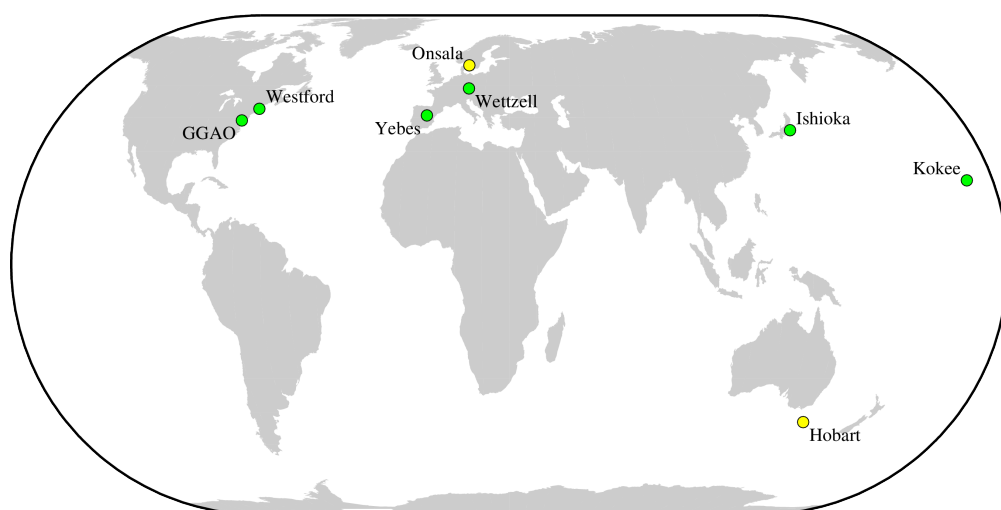


Fig. 2: The six-station VGOS demonstration network (VGOS-Demo, green circles) of CONT17. The broadband signal chain roll-out for Onsala and Hobart (yellow circles) was not completed on time for an official inclusion in the campaign.

Correlators

The correlator at Haystack Observatory (USA), the correlator at the U.S. Naval Observatory in Washington (USA), the BKG/MPIfR correlator at the Max Planck Institute for Radio Astronomy in Bonn (Germany), the correlator at the Shanghai Astronomical Observatory (China), and the correlator at the Geospatial Information Authority of Japan (GSI) in Tsukuba efficiently processed the data recorded for the IVS. The majority of the 24-hour sessions were processed by the Bonn and Washington correlators. Both correlators used the DiFX software correlator; while the Bonn correlator processed the R1, EURO, T2, Int3, and OHIG sessions, the Washington correlator was responsible for the R4, Int1, and CRF deep south sessions. The Shanghai correlator analyzed CRF, APSG, and AOV sessions. The Haystack correlator processed R&D sessions and some T2 sessions. The Int2 sessions were processed at the Tsukuba correlator.

Data Centers

The IVS Data Centers continued to receive databases throughout the year and made them available for analysis within one day of correlation. The Data Centers also continued to receive solutions from Analysis Centers. All data and results holdings are mirrored several times per day among the three primary IVS Data Centers at BKG (Germany), Paris Observatory (France), and Goddard Space Flight Center (USA).

Data Analysis

At its meeting in Gothenburg, Sweden on 19 May 2017, the Directing Board decided that the analysis work should make the switch from using the MK3 database format (and the derived NGS card files) to only using the vgosDB format by 30 September 2017. This change is needed in anticipation of VGOS; the older formats of MK3 databases

and NGS cards are not capable of storing VGOS data. Most analysis packages were upgraded to support the new format in all stages of data processing. Also the correlators updated their software suites to output vgosDB. The complete transition, however, had to be postponed to early 2018, because a few Analysis Centers were not capable to use vgosDB by the deadline and the data centers required a vetting process (e.g., security checks, metadata extraction) before placing the vgosDB files into their archives that was not completed yet.

In the context of rolling out the new format, the Analysis Centers were encouraged to start their analysis work at the Version-1 level of the database and to perform all pre-processing steps themselves (i.e., ambiguity resolution, ionospheric calibration, inclusion of weather and cable data). Thus far, many Analysis Centers started at the Version-4 level and relied on one or two main IVS Analysis Centers to do the pre-processing.

Technology Development

Progress was made in achieving operational readiness of the next-generation VLBI system, the VLBI Global Observing System (VGOS). In addition to the CONT17 VGOS campaign, a network of 5–6 stations regularly participated in 24-hour sessions about every two weeks. These sessions were used to improve the operational stability of the stations, data transport mechanisms, and the correlation and post-processing of the data. All of these were necessary steps to make the first VGOS broadband CONT campaign possible. The Onsala Twin Telescopes (Sweden) were inaugurated on May 18, 2017 as part of the European VLBI Group for Geodesy and Astrometry (EVGA) meeting. They obtained broadband fringes toward the end of 2017. With the signal chain assembly at Onsala, first experience was gained with the European digital backend DBBC3 for use in VGOS. Further work is needed to optimize its application; but it is anticipated that several European stations will utilize the DBBC3 backend in the future. The Australian AuScope antennas at Hobart, Katherine, and Yarragadee are scheduled to be upgraded to VGOS broadband systems in 2018. New VGOS stations are under construction at Ny-Ålesund (Norway), Hartebeesthoek (South Africa), Metsähovi (Finland), Shanghai (China), and Gran Canaria (Spain).

A first test experiment for distributed correlation was performed in 2017. Pieces of data of an R1 session were distributed to several branch correlators and each of these correlated one hour of the network. Later the results were gathered at the central correlator at MPIfR in Bonn and compared to a full correlation performed in Bonn. Some issues were encountered with the data transfer and the different versions of the DiFX software used at the various branch correlators. While these issues prevented us from drawing final conclusions from this test, the experience gained was very useful and distributed correlation appeared

to be a very promising approach. Further tests are planned to be performed in 2018.

Publications

K.D. Baver, D. Behrend, K. Armstrong (editors): IVS 2015+2016 Biennial Report, NASA/TP-2017-219021, Greenbelt, MD, USA, 2017, online: <https://ivscc.gsfc.nasa.gov/publications/br2015+2016/>

Dirk Behrend, Rüdiger Haas

3.4.4 International DORIS Service (IDS)

Overview The current report presents the different activities held in 2017 by the components of the International DORIS Service (IDS). In a first step, we give the current status of the DORIS system (satellites and tracking network). In a second step, we provide the latest news of the IDS (Governing Board, Central Bureau, Data Centers). Then we focus on the most recent activities conducted by the Analysis Centers and the Analysis Coordination. The report ends with information about the meetings and the publications.

DORIS system

DORIS satellites During this report period (2017), the number of DORIS satellites has remained the same as the previous year at six (see Table 1).

Table 1: *DORIS data available at IDS Data Centers. As of December 2017*

Satellite	Start	End	Mission
SPOT-2	31-MAR-90 04-NOV-92	04-JUL-90 15-JUL-09	Remote sensing
TOPEX/Poseidon	25-SEP-92	01-NOV-04	Altimetry
SPOT-3	01-FEB-94	09-NOV-96	Remote sensing
SPOT-4	01-MAY-98	24-JUN-13	Remote sensing
SPOT-5	11-JUN-02	11-DEC-15	Remote sensing
Jason-1	15-JAN-02	21-JUN-13	Altimetry
ENVISAT	13-JUN-02	08-APR-12	Altimetry, Environment
Jason-2	12-JUL-08	-	Altimetry
Cryosat-2	30-MAY-10	-	Altimetry
HY-2A	1-OCT-11	-	Altimetry
SARAL	14-MAR-13	-	Altimetry
Jason-3	17-JUN-16	-	Altimetry
SENTINEL-3A	16-FEB-16	-	Altimetry

In 2018, a new DORIS instrument came to join its fellows. It operates onboard Sentinel-3B, launched in April 2018. With Jason-2, Cryosat-2,

HY-2A, Saral, Jason-3, and Sentinel-3A, there are now seven active DORIS instruments, all the same DGXX generation.

Many future missions currently under preparation should guarantee a constellation of DORIS contributor satellites up to 2030 and beyond:

- Sentinel-3C and -3D (ESA/Copernicus) are under development and expected for 2020 and 2025.
- SWOT (Surface Water Ocean Topography), a joint project involving NASA, CNES, the Canadian Space Agency and the UK Space Agency, is planned for 2021.
- Jason-CS will ensure continuity from Jason-3 with a first launch in 2020 (Jason-CS1/ Sentinel-6A) and 2025 (Jason-CS2 / Sentinel-6B). The Jason-CS / Sentinel satellites are part of the Copernicus program and are the result of international cooperation between ESA, Eumetsat, the European Union, NOAA, CNES and NASA/JPL.
- HY2-C, HY-2D (CNSA/NSOAS), two Chinese missions flying DORIS, are planned for 2019 and 2020, respectively.

DORIS network The DORIS ground network is made up of 56 permanent stations (including 4 master beacons and 1 time beacon) well distributed over the Earth's land surface for the purposes of orbitography and altimetry. Two additional DORIS stations are used for other scientific applications: Grasse (France) and Wettzell (Germany).

Despite the extensive outage of 4 stations (Santa-Cruz, Easter, Mahé, and Cibirong), the DORIS network provided a reliable service in 2017 with an annual mean of 89% of active sites thanks to the responsiveness and the combined efforts of CNES, IGN and all agencies hosting the stations: 6 failed beacons and 2 failed antennas were replaced.

The development of the 4th DORIS beacon generation has been nominally ongoing according to the provisional schedule: after the detailed design review, a prototype was developed for testing at the end of 2017. The start of the deployment is still scheduled for mid-2019. This development is eagerly waited for the network because that will allow installation of the antenna up to 50 m from the indoor equipment: the maximum cable length currently allowed to the antenna is 15 m which often makes it difficult for the antenna to have a clear view of the sky with the proximity of the building housing the transmitting unit.

The tie vectors between successive DORIS antenna locations on the same site were reassessed and made available on the IDS data centers: ftp://ftp.ids-doris.org/pub/ids/stations/DORIS_int_ties.txt

Specifications for installing nearby DORIS and VLBI were set based on successive RF compatibility tests performed at Greenbelt, MD, USA

(2014), then at Wettzell, Germany (2015–2016) and lastly at Papenoo, French Polynesia (2017) in the framework of the future geodetic observatory of Tahiti.

Co-location with other space geodetic techniques and with tide gauges remains a major objective for the DORIS network. After the DORIS station installation at the geodetic observatory Wettzell in 2016, the IDS plans to install in April 2018 a DORIS station in Guam Island (co-location with IGS station “GUUG” and tide gauge of Pago Bay PSMSL 2130). This new site is also particularly interesting in that it offers coverage of the western North Pacific Ocean over the Micronesia and the Mariana Trench.

In 2017 the following sites were visited:

- Reconnaissance in Papenoo (French Polynesia)
- Local tie survey at Papeete (French Polynesia) and Sal (Cape Verde)

In 2018, the overall objectives are:

- New stations at Guam Island (USA) and San Juan (Argentina)
- Re-location in Rothera (Antarctica) and Easter Island (Chile)
- Restarting at Santa-Cruz (Galapagos, Ecuador) and Mahé (Seychelles)
- Reconnaissance in China and Iceland

IDS Governing Board

On January 1st, 2017, new members took up their duties within the Governing Board (GB) to serve for the period 2017–2020.

- Frank Lemoine as the Analysis Center Representative,
- Patrick Michael as the Data Center Representative,
- Denise Dettmering as a Member-at-Large.

In addition, the IAG nominated Petr Stepanek as its representative to the IDS Governing Board (GB). Petr succeeds Michiel Otten who held that post for 8 years.

Guilhem Moreaux (CLS) was confirmed as the representative of the Combination Center (CC) within the GB after CNES/CLS was selected to run the IDS CC for a new period of four years (2017–2020). In November 2016, the Board elected Frank Lemoine as the new Chairman from January 1st, 2017. The composition of the new Governing Board is given in Table 2.

At its meeting in May 2017, the GB has accepted TU Delft and the POD team of CNES as Associated Centers.

Following user requests for NRT data for assimilation in ionospheric model, the GB has decided to create a Working Group (WG) “NRT DORIS data” to:

- define the objectives and possible applications,
- identify potential users,
- define the test requirements (time, duration, ...).

The CNES will then study the feasibility and implement this test campaign. Based on the results of the Working Group, in a later stage, the possibility to operationalize this production will be evaluated. The GB appointed Denise Dettmering as chairman of this WG.

In May 2017, the GB also decided to organize a retreat in 2018 to review the activities, overall scientific direction and future of the service. A key outcome of the meeting will be a set of ideas that can contribute to the development of a strategic plan for the IDS. A survey form has been set up and put on the website to collect inputs from both inside and outside the IDS community in preparation for the retreat.

DORIS stations co-located with other IERS techniques

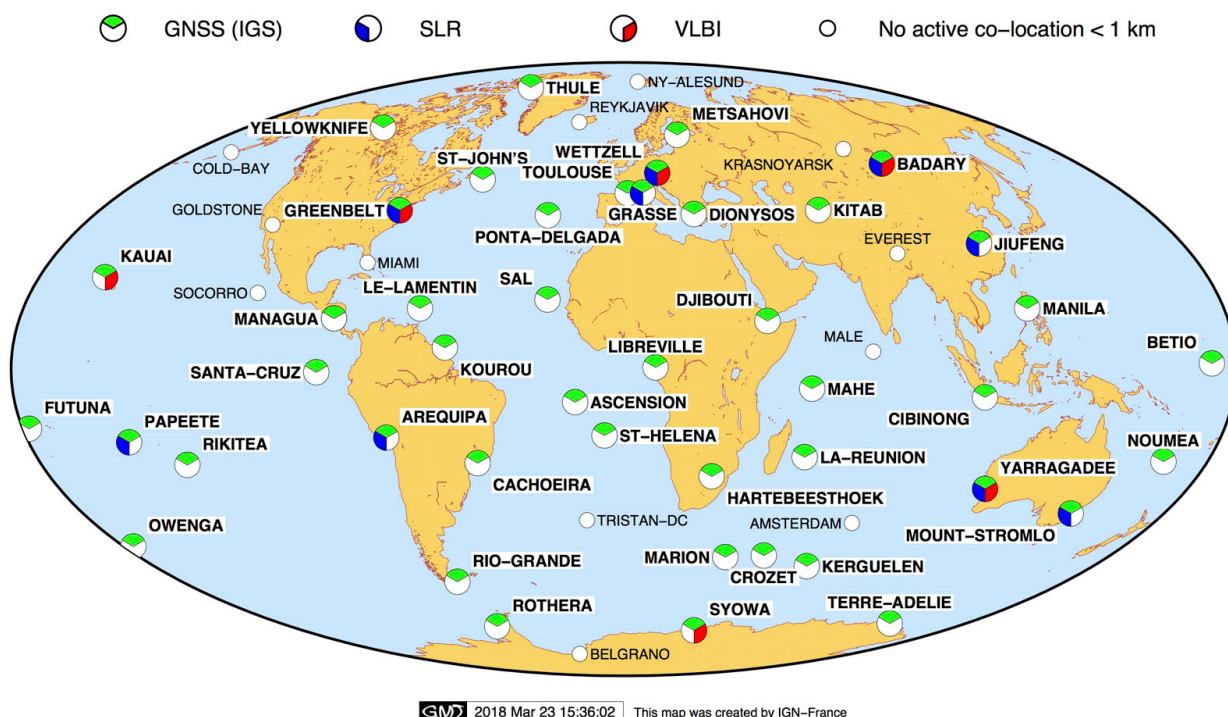


Fig. 1: The permanent DORIS network – 56 stations – and co-location with other IERS techniques (as of March 2018).

Table 2: *Composition of the IDS Governing Board (January 2017 – December 2018)*

Name	Institution	Country	Mandate
Hugues Capdeville Jean-Michel Lemoine	CLS CNES	France	Analysis Coordination
Denise Dettmering	DGFI-TUM	Germany	Member at large
Pascale Ferrage	CNES	France	System representative
Frank Lemoine (chair)	NASA/GSFC	USA	Analysis Center representative
Brian Luzum	GSFC	USA	IERS representative
Guilhem Moreaux	CLS	France	Combination Center representative
Patrick Michael	NASA/GSFC	USA	Data flow Coordinator
Michiel Otten	ESOC	Germany	IAG representative
Jérôme Saunier	IGN	France	Network representative
Laurent Soudarin	CLS	France	Director of Central Bureau
Marek Ziebart	UCL	UK	Member at large

IDS Central Bureau

In 2017, the Central Bureau participated in the organization of the AWG meeting held at University College London in London, UK, on May 22 and 23. The CB documented the GB meeting held on this occasion.

The CB managed the edition and publication of the 2016 IDS Activity Report. It also produced the IDS contribution to the 2016 IERS Annual Report.

At its meeting in Washington in October 2015, the Governing Board asked the Central Bureau to consider the publication of a newsletter. The intention was to improve the flow of information within the community of providers and users of DORIS data and products, to highlight the activities of the groups participating in the IDS, and to bring the DORIS and IDS news to a wider audience, from the host agencies to the other sister services. Three issues were published in 2016, #1 in April 2016, #2 in July, and #3 in December.

IDS Newsletter #4 was published in November 2017. It contains the following article:

- Station re-location at Kitab (Uzbekistan) to get better visibility (J. Saunier, IGN)
- Kitab: the host agency in short (D. Fazilova and S. Ehgamberdiev, UBAI)

- DPOD2014: a new DORIS extension of ITRF2014 for Precise Orbit Determination (G. Moreaux, CLS).

In addition, the section “IDS life” provides information about the service.

The issues are distributed via email to the subscribers to the DORIS-mail and several identified managers and decision-makers. They are also available on the IDS website for downloading at <https://ids-doris.org/ids/reports-mails/newsletter.html>.

Data information service

The Central Bureau works with the SSALTO multi-mission ground segment and the Data Centers to coordinate the data and products archiving and the dissemination of the related information.

In 2017, this activity focused on:

- the delivery of the CNES orbits for HY-2A in GDR-E standards (file naming, store folders, description files)

See: [ftp CDDIS or IGN] ftp://cddis.gsfc.nasa.gov/pub/doris/products/orbits/ssa/README_SP3.txt

- the update of the antex files giving the phase law to apply in DORIS processing for the ground antennas (format of the antex files revised and corrected to be in agreement with the format description; new characterization of the ALCATEL antenna based on 5 antennas)

See: ftp://ftp.ids-doris.org/pub/ids/stations/doris_phase_law_antex_readme.txt

- the change in the delivery of the DORIS/RINEX files in January: (re-)start delivering RINEX with DIODE time tagging with a latency of 1 day (instead of 3 days with SSALTO/PANDOR time tagging) and completion of missing periods (version number of the files: 001)

See for instance: [ftp CDDIS or IGN] ftp://doris.ign.fr/pub/doris/data/ja2/README_JASON2_data.txt

The Central Bureau also interfaced with the Data Centers and the Combination Center for making available the DPOD products. See [ftp CDDIS or IGN] <ftp://doris.ensg.eu/pub/doris/products/dpod/dpod.readme>

IDS web and ftp sites

The IDS Central Bureau (CB) maintains the IDS web (<https://ids-doris.org>) and ftp (<ftp://ftp.ids-doris.org/pub/ids>) sites.

A new version of the IDS website was proposed in early 2017 with an updated design and structure. The website is now accessed using the secure HTTPS protocol.

Besides the regular updates of pages and addition of documents, the website was enriched with new pages and received some changes. We can mention among others the following new features:

- The Section “Combination” has been renamed, reorganized and enriched. It is now named “Combination Center” and contains new pages about the Activity and Products of the Combination Center, the cumulative solution and the DPOD in addition to the section dedicated to the contributions to the ITRF. The map of the horizontal displacements of the DORIS stations by Moreaux et al. (2016) can be seen on the page <https://ids-doris.org/analysis-coordination/combination/activity-products.html>.
- A new page Working Groups (AWG, WG NRT DORIS data) is available at <https://ids-doris.org/ids/organization/working-groups.html>.
- The document “IDS data structure and formats” has been reviewed and completed. It is now available as a PDF file encapsulated in the web page <https://ids-doris.org/ids/data-products/data-structure-and-formats.html>.
- Two new sections added in the Gallery for the DORIS station: equipment and obstruction views. <https://ids-doris.org/ids/gallery/category/4-stations.html>

The main updates of the website, as well as the list of the new documents and files put on the ftp site, can be found in the 2017 IDS Activity Report (<https://ids-doris.org/ids/reports-mails/governing-board.html#activity>).

DOR-O-T, the IDS web service

A new version of the IDS web service (<http://ids-doris.org/webservice>) was proposed in early 2017. It is based on the latest Highcharts/Highstock library and on a new version of the network viewer. Improvements were brought to make the service more ergonomic, simpler and more practical, especially on mobile devices.

The web service is now accessed using the secure HTTPS protocol.

IDS Data Centers

The IDS data flow organization remains the same. It is based on two data centers: one on the East Coast of the U.S. (CDDIS at NASA GSFC) and one in Europe (IGN in France). They are both exact mirrors of each other, and so, are able to continue on an operational basis, even if one of them is inaccessible due to a temporary failure.

These two data centers archive the DORIS data as well as the IDS products (station coordinates and velocity, geocenter motion, earth orientation parameters, ionosphere data, etc.).

During 2017, the CDDIS developed all new software to handle the ingest of GNSS, SLR, and DORIS data. This new software allows for more automated operation, much improved quality-checks, and a new metadata extraction process and storage method all leading to improved efficiency in processing incoming data. CDDIS's goal is that all incoming files are quality-checked, metadata extracted, and processed into the archive within 30 seconds of being received.

The CDDIS provides access to two applications for querying site information or archive contents. The Site Log Viewer 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 systems having particular equipment or characteristics.

The Site Log Viewer is accessible at the CDDIS website at URL https://cddis.nasa.gov/Data_and_Derived_Products/SiteLogViewer/.

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

The CDDIS Archive Explorer application is accessible on the CDDIS website at URL: https://cddis.nasa.gov/Data_and_Derived_Products/CddisArchiveExplorer.html

IDS Analysis Centers and IDS Analysis Coordination

The activities of all the DORIS analysts of the past year 2017 have been dominated by the evaluation of the three TRFs 2014 solutions and the DPOD2014, taking into account the last DORIS satellites Jason-3 and Sentinel-3A which DORIS data are only available in RINEX format, defining a strategy to minimize the impact of the sensitivity to the South Atlantic Anomaly (SAA) effect of their Ultra Stable Oscillator (USO) and resolving the scale factor jump of the IDS solution. In 2017, the Analysis Working Group (AWG) met in London at the University College of London, from May 22 to May 23.

All the IDS Analysis Centers (AC) continue the standard routinely processing by considering the last DORIS data available. The IDS

includes six ACs and three associate analysis centers who use seven different software packages. Some ACs on a routine basis perform POD analyses of DORIS satellites using other geodetic techniques (SLR or GNSS). The multi-technique analyses are useful since they can provide an independent assessment of DORIS system performance and allow us to validate more easily model changes and the implementation of attitude laws for the different spacecraft.

An increase in the IDS scale factor was identified in 2012. This increase is mainly due to the introduction of the HY-2A satellite into the combined solution, which has a high scale factor. The increase also comes from DORIS2.2 data processing for the Jason-2 and Cryosat-2 satellites. For this part, the jump observed in the scale factor is due to the change of tropospheric model in the POD processing of the CNES team. It was then recommended to the IDS ACs to consider all the measurements in the DORIS2.2 file, even those rejected by the CNES POD team preprocessing, and therefore to do their own preprocessing. In November 2017, a new initial position of the HY-2A satellite center of mass (CoM) in the satellite reference frame was delivered to CNES by the Chinese Mission Center. This new position greatly reduces the HY-2A scale factor. The IDS Analysis Coordinators recommend to IDS ACs to use this new position of the CoM HY-2A.

The IDS performed an assessment of the three realizations of the Terrestrial Reference Frame which are the outcome of the “ITRF2014 effort”: the ITRF2014 (IGN), DTRF2014 (DGFI) and JTRF2014 (JPL). While ITRF2014 and DTRF2014 are formally similar, differing mainly by the Post Seismic Deformation model (PSD) which has been introduced in the IGN solution, the JPL solution is quite different, being a time series of weekly solutions obtained through a Kalman filter process. Due to a more aggressive data editing, the JPL solution contains less stations at a given time than the two others, particularly at the beginning of the processed period in 1993. The three TRF realizations have been evaluated in terms of DORIS and SLR observation residuals, orbit overlaps and transformation parameters of the DORIS network. All the TRF realizations represent a clear improvement post-2008 over the previous realization ITRF2008. Based on the different criteria used for the evaluation, it has been shown that it is the ITRF2014 which presents the best overall performances. It is this model that will serve as a basis for the operational processing of the future IDS products. The extension of the ITRF2014 for the DORIS network, called DPOD2014, consists in an update of the position/velocity of all the DORIS stations and aligned to the ITRF2014, leading to possible minor adjustment of older stations. Some IDS ACs have switched to ITRF2014 by using the DPOD2014 solution for their IDS operational products at the end of 2017 and others will plan to do that in 2018.

The behavior of the various DORIS on-board oscillators near the high radiation area “South Atlantic Anomaly” (SAA) has been studied. It has been shown by different ACs (and associated) that all DORIS receivers are frequency-sensitive to the crossing of the SAA, though at very different levels. For Jason-1 and SPOT-5 satellites, a corrective model has been developed and used for the realization of the ITRF2014. However, Jason-2 is also impacted, not at the same level as Jason-1 but strong enough to worsen the multi-satellite solution provided for ITRF2014 for the SAA stations. The last DORIS satellites are also impacted by the SAA effect, in particular Jason-3. While awaiting precise DORIS data corrective model for the satellites Jason-2&3, ACs have to adopt a strategy to minimize the SAA effect on the orbit and also and in particular on the station position estimation. This strategy could lead to add the single satellite solutions affected by the SAA in the multi-satellite solution as it was done for the ITRF2014 with Jason-1.

The analyses associated with ITRF2014 as well as subsequent work have demonstrated that the DORIS products contain signals at distinct tidal, TOPEX/Jason-draconitic, semi-annual, and annual periods. These signals point to potential problems in force and measurement modeling, potentially associated with the tidal EOP modelling and with the modeling of non-conservative forces on some satellites. ACs have to improve SRP modelling to reduce draconitics, in particular for Topex/Jasons satellites by using solar angle panels as done and showed by the GSFC AC.

The Jason-3 and Sentinel-3A satellites were added in the DORIS processing chain of some ACs which can process RINEX data format. The others ACs have to complete their DORIS/RINEX data processing implementation in order to take into account the data from these new satellites and in preparation to the next ITRF.

IDS Combination

In 2017, in addition to the routine evaluation and combination of the IDS AC solutions, the IDS Combination Center delivered to the IDS Data Centers its two first versions of the DPOD2014 (DORIS extension of the ITRF2014 for Precise Orbit Determination). These two solutions are based on the two DORIS cumulative position and velocity solutions of the IDS Combination Center from the IDS combined solution over the time periods 1993.0–2016.0 and 1993.0–2017.0, respectively. Both the IDS cumulative position and velocity solution and the DPOD2014 solution will be updated twice a year and freely available from the IDS Data Centers. More information on these new IDS products are accessible on the Combination Center corner of the IDS website.

Meetings

In 2017, IDS organized a meeting of the Analysis Working Group on May 22–23 at University College London (UK).

All the presentations from the meeting are made available by the Central Bureau on the IDS website at: <https://ids-doris.org/ids/reports-mails/meeting-presentations/ids-awg-05-2017.html>

In 2018, IDS organizes two events:

- a meeting of the Analysis Working Group in Toulouse (France), on Monday June 11, 2018 (hosted by CNES) followed by the Copernicus Quality Working Group Meeting on Tuesday June 12 to which IDS AWG members are invited.
- the IDS Workshop 2018, in Ponta Delgada (Azores Archipelago) (24 to 26 September 2018), Portugal, as part of the 25 Years of Progress in Radar Altimetry Symposium with the Ocean Surface Topography Science Team (OSTST) 2018.

Publications

IDS published the 2016 activity report that was broadly distributed to all DORIS participants and relevant services (see <https://ids-doris.org/ids/reports-mails/governing-board.html#activity>).

All DORIS related articles published in international peer-reviewed journals are available on the IDS Web site <https://ids-doris.org/ids/reports-mails/doris-bibliography/peer-reviewed-journals.html>.

Conclusions

2017 has been highlighted by the arrival of four new members in the Governing Board, and two new Associate Analysis Centers (CNES/POD and TU Delft), the creation of the Working Group “NRT DORIS data” and the decision to organize an IDS retreat to prepare the activities of the Service for the next years.

The IDS Combination Center delivered its two first versions of the DPOD2014 (DORIS extension of the ITRF2014 for Precise Orbit Determination).

The activities of all the DORIS analysts have been dominated by the evaluation of the three TRFs 2014 solutions and the DPOD2014, considering the last DORIS satellites Jason-3 and Sentinel-3A, defining a strategy to minimize the impact of the sensitivity to the South Atlantic Anomaly (SAA) effect of their Ultra Stable Oscillator (USO) and resolving the scale factor jump of the IDS solution.

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3.5 Product Centres

3.5.1 Earth Orientation Centre

This section presents over the year 2017 the activities and main results of the Earth Orientation Centre located at Paris Observatory.

According to the IERS Terms of Reference, this component is responsible for monitoring Earth Orientation Parameters including long term consistency, publications for time dissemination (DUT1) and leap second announcements. Earth Rotation Parameters (ERPs), i.e. Pole coordinates (x,y), Difference UT1–UTC, Length of Day variation (LOD) and Celestial pole offsets (dX, dY), are available to a broad community of users in various domains such as astronomy, geodesy, geophysics, space sciences and time. ERPs are firstly collected in the form of combined solutions derived by the Technique Centres (IGS, IVS, ILRS and IDS). Two main solutions are computed: a long-term solution (IERS C01) since 1846 until the end of the previous year and the Bulletin B / C04 given at one-day intervals, which is published monthly with a 30 day delay (Gambis, 2004; Bizouard and Gambis, 2009; Gambis and Luzum, 2011, Bizouard et al, 2018).

14 C04 solution consistent with ITRF 2014

The 14 C04 solution consistent with ITRF 2014 became operational in March 2017. During the year 2017, it was finalized and tuned up (Bizouard et al, 2018). In July 2017, discussions during the Unified Analysis Workshop held at LAREG/IGN, lead us to create and maintain an alternative solution C04 at 12hUTC. This allows a direct comparison with pole coordinate and LOD solutions provided at midday by GNSS analysis centers. The UT1 solution had been spoilt by the removal of the UT1 intensive series. Outside the R1/R4 24 hour sessions, the interpolation procedure produced much larger errors than the one associated with the intensive UT1 values. Therefore UT1 intensive have been reintroduced in the C04 solution in April 2018. Changes or updates are reported in the public file <ftp://hpiers.obspm.fr/iers/eop/eopc04/updateC04.txt>.

Web site upgrade

Upgrades to the web site pertain especially to the tool for inter-comparing ERP series (<http://hpiers.obspm.fr/eop-pc/index.php?index=operational&lang=en>). Now, this tool allows to simultaneously compare as many series as the user wants to.

Table 1: Intra-techniques solutions: averaged time sampling and standard deviation with respect to the combined solutions Bulletin B / C04 over the year 2017. Solutions contributing to Bulletin B / C04 are flagged by stars (*).

Intra-technique solutions	Estimated uncertainties				
	Time sampling	Terrestrial Pole	UT1	LOD	Celestial Pole
VLBI - 24h					
EOP(AUS)	~ 4 d	274.5	19.5		129
EOP(BKG)	~ 2 d	104.5	8.3		98.5
EOP(GSFC)	~ 2 d	79	8.4		92
EOP(IAA)	~ 3 d	101.5	8.7		102
EOP(USNO)	~ 2 d	79	8.6		77.5
EOP(IVS Comb*)	~ 4 d	63.5	8.5		61.5
VLBI - Intensive					
EOP(BKG)	~ 1 d		9.4		
EOP(GSFC)	~ 1 d		27.3		
EOP(IAA*)	~ 1 d		11.5		
EOP(PUL)	~ 1 d		11.9		
EOP(USNO*)	~ 1 d		12.4		
SLR					
EOP(MCC)	~ 1 d	128.5		201	
EOP(IAA)	~ 1 d	212.5		27	
EOP(ASI)	~ 1 d	199		55	
EOP(ILRS Comb*)	~ 1 d	135.5		24	
GPS					
EOP(CODE)	~ 1 d	40		13	
EOP(JPL)	~ 1 d	43		18	
EOP(GFZ)	~ 1 d	41		16	
EOP(ESOC)	~ 1 d	40		13	
EOP(NOAA)	~ 1 d	46		12	
EOP(SIO)	~ 1 d	72		32	
EOP(EMR)	~ 1 d	53		13	
EOP(IAA)	~ 1 d	75		25	
EOP(GRGS)	~ 1 d	39		11	
EOP(CGS)	~ 1 d	400.5		61	
EOP(IGS-R Comb*)	~ 1 d	34.5		10	
EOP(IGS-F Comb*)	~ 1 d	34.5		9	
DORIS					
EOP(INASAN)	~ 1 d	365.5			
EOP(IDS Comb*)	~ 1 d	204.5			

Statistics Statistics of 14 C04 for the year 2017 are provided in Table 1 (standard deviations of C04 – intra-techniques solutions), Table 2 (mean and standard deviations of C04 – intra-technique combined solutions) and 3 (mean and standard deviations of C04 – multi-technique combined solutions).

Table 2: Mean and standard deviations (STD) in microarcseconds of the differences between intra-techniques combined solutions entering the combination and Bulletin B / C04 over 2017.

EOP	IGS Comb - IERS 14C04		ILRS Comb - 14C04		IVS Comb - 14C04		IDS Comb - 14C04	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
x(μas)	26	35	141	131	53	78	118	211
y(μas)	-21	34	25	140	-25	80	2	198
UT1(μas)					-2.5	9.5		
LOD(μas)	-1	34	0	24				
dX(μas)					32	81		
dY(μas)					-18	42		

Table 3: Mean and standard deviations for Pole coordinates (x,y) and UT1 of the differences between combined solutions derived by both the Rapid Service/Prediction Center at USNO, the JPL and Bulletin B / C04 over 2017.

EOP	Unit	Bul A - Bul B		Comb JPL - Bul B	
		Mean	STD	Mean	STD
x	μas	21	56	25	65
y	μas	-11.6	16.8	1	48
UT1	μs	-11.6	16.8	-11.2	15.4

Earth Orientation Center staff

Christian Bizouard, Astronomer, head
 Olivier Becker, Engineer, operational work and automation
 Teddy Carlucci, Engineer, system
 Jean Yves Richard, Engineer, EOP consistency with ITRF
 Pascale Baudoin, Secretary
 Sébastien Lambert, Assistant-Astronomer, Consultant, representative of the IERS EOC

References

Bizouard C, Lambert S, Gattano C, Becker O and J Y Richard (2018), The IERS EOP 14C04 solution for Earth orientation parameters consistent with ITRF 2014, J. of Geodesy, doi:10.1007/s00190-018-1186-3

- Bizouard C and D Gambis (2009), The combined solution C04 for Earth Orientation Parameters, recent improvements, Springer Verlag series, Series International Association of Geodesy Symposia, Vol. 134, Drewes, Hermann (Ed.), pp. 265–270, doi:10.1007/978-3-642-00860-3
- Gambis D (2004), Monitoring Earth Orientation at the IERS using space-geodetic observations. J. of Geodesy 78, pp. 295–303
- Gambis D and B Luzum (2011), Earth rotation monitoring, UT1 determination and prediction, Metrologia 48, pp. S165–S170

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3.5.2 Rapid Service/Prediction Centre

Introduction

This section provides a discussion and summary of the Earth orientation parameter (EOP) results produced by the IERS Rapid Service / Prediction Center (RS/PC) for the calendar year 2017. The accuracies of both the inputs used and the subsequent EOP combination and prediction results produced by the IERS RS/PC are provided. The combination and prediction comprise the Bulletin A results and are published in several human and machine readable formats. In addition, a plot of the polar motion path for the year, a summary of the expected times during each day at which inputs are provided to the IERS RS/PC solution, a low precision table of predictions of TT–UT1, and a comprehensive list of the inputs to the IERS RS/PC combination and prediction process are provided. This section also contains an overview of the combination processing techniques, the prediction processing techniques, the centre activities that include developmental work to improve EOP results, and the web and FTP locations available to users for obtaining results. Lastly, detailed analyses and discussions regarding results may not, in general, be discussed in this section, but may be presented at upcoming conferences and meetings.

Combination Processing Techniques and Results

In combining the contributed observational data to generate the quick-look EOP results, the IERS/PC employs a smoothing cubic spline that weights each of the input data series based on its reported observational errors, which is referred to as a “weighted smoothing cubic spline” (WSCS) (McCarthy and Luzum, 1991a). Observational data contributions are corrected for possible systematic differences in the form of offsets and rates computed with respect to the C04 series of the IERS Earth Orientation Centre (EOC) at the Paris Observatory; to this end, a robust linear estimator is employed which ameliorates the effect of outliers on the computed offsets and rates. The statistical weights used in the spline are proportional to the inverse square of the estimated accuracy of the individual techniques computed over the past several years. Minimal smoothing is applied, consistent with the estimated accuracy of the observational data.

Weights for each contributor in the algorithm may be either a priori values estimated by determining the standard deviation of a long history of residuals or values based on the internal precision reported by contributors. The estimated accuracies for each of the IERS RS/PC contributors to the EOP combination solutions for 2017 are provided in Table 1. The estimates are based on the residuals between the contributor series and the IERS RS/PC (USNO) EOP solution (contained in the file `finals.data`) for all the epochs in 2017.

On 23 March 2017, the EOP solution for UT1–UTC and Polar Motion was adjusted to an updated set of systematic corrections that had been computed based on the residuals of the observational inputs versus the ITRF 2014 series. Normally, the systematic corrections would be based on the C04 reference series. However, since the 14 C04 was in the process of being refined and since the IERS Directing Board had wanted the RS/PC to use an updated reference series, we thought it best to use the ITRF 2014 series as the reference series. In addition the celestial pole offsets (CPOs) were adjusted to be consistent with the IVS combined VLBI solution, as the ITRF 2014 does not contain CPO results.

Some of the EOPs are measured directly while others are a hybrid of direct measurements and related quantities. For polar motion (x and y) and the CPOs, all the contributors (which have associated statistics in Table 1) provide direct measurements of these quantities. The IERS RS/PC published CPOs are either $d\psi$, $d\epsilon$, consistent with the 1976 precession and 1980 nutation series, or dX and dY , consistent with the IERS Conventions 2010 and IAU 2006 precession and 2000A nutation models. For UT1–UTC, some contributors provide direct measurements and others provide estimates based on the derivative of UT1.

All of the Very Long Baseline Interferometry (VLBI) contributors provide direct measurements of UT1; the International GNSS Service (IGS) ultra-rapid observations (IGS ultras) provide a length-of-day (LOD) type input, which is a derivative of UT1; and the USNO GPS UT provides a UT1-like estimate based on GPS orbit modeling. The VLBI-based results have been used to correct for the LOD bias in the IGS ultras and to minimize drifts in UT estimates in both the IGS ultras and USNO GPS UT (“UTGPS”). The corresponding statistics shown for the IGS ultras and UTGPS are computed after the bias corrections are applied. Although the Atmospheric Angular Momentum (AAM) inputs may be added to the EOP combination in the future, currently the AAM inputs do not contribute to the EOP combination solution, but provide inputs to the EOP UT1–UTC predictions out to seven days into the future; therefore, there is no mention of AAM results in Table 1. The combination refers to solutions of past EOP results; whereas, predictions refer to the current and future EOP look-ahead solutions, which are discussed later in the chapter.

Operationally, the following inputs are provided to the WSCS: the epoch of observation, the observed EOP value, and the corresponding weight. The software computes the spline coefficients for every data point, which are then used to interpolate the Earth orientation parameter time series so that x , y , UT1–UTC, $d\psi$, and $d\epsilon$ values are computed for the midnight (00:00) UTC epoch for each day. While the celestial pole offset combination software can combine either $d\psi$ and $d\epsilon$ or dX

and dY , it uses $d\psi$ and $d\epsilon$ for historical reasons. Therefore, the Institute of Applied Astronomy (IAA) and the International VLBI Service (IVS) VLBI dX and dY values are converted (for 2017) to $d\psi$ and $d\epsilon$ in the combination process.

Table 1: *Estimated accuracies of the contributions to the IERS RS/PC combination results for 2017 with respect to the IERS RS/PC EOP series. Units are milliseconds of arc for x , y , $d\psi$, $d\epsilon$, dX , and dY and milliseconds of time for UT1–UTC. (All acronyms used in this table are defined in the Acronyms section of the Appendix of this report.)*

Contributor information		Estimated accuracy			
Name, Type	x	y	UT1–UTC	$d\psi$ (dX)	$d\epsilon$ (dY)
ILRS SLR	0.14	0.17	–	–	–
IAA SLR	0.19	0.22	–	–	–
MCC SLR	0.17	0.17	–	–	–
GSFC VLBI Intensive	–	–	0.017	–	–
USNO VLBI Intensives	–	–	0.017	–	–
GSI Intensives	–	–	0.015	–	–
GSFC VLBI	0.12	0.10	0.006	0.14	0.06
IAA ⁺ VLBI	0.20	0.24	0.009	(0.08)	(0.15)
IVS ⁺ VLBI	0.15	0.26	0.003	(0.06)	(0.06)
USNO VLBI	0.11	0.09	0.004	0.08	0.05
IGS Final	0.01	0.01	–	–	–
IGS Rapid	0.04	0.06	–	–	–
IGS Ultra*	0.04	0.06	0.051*	–	–
USNO GPS UT*	–	–	0.042*	–	–

⁺ IAA and IVS VLBI nutation values are in terms of dX/dY using IAU 2000A Nutation Theory (see Petit and Luzum, 2010).

* All satellite techniques provide information on the rate of change of Universal Time contaminated by effects due to un-modeled orbit node motion. VLBI-based results have been used to correct for LOD biases and to minimize drifts in UT estimates.

Additionally, LOD and estimated error results are published along with the EOP combination results. The LOD results for the combination are

derived directly from the UT1–UTC data. The analytical expression for the first derivative of a cubic spline passing through the UT1–UTC data (after leap second discontinuities are removed) is used to estimate the LOD at the epoch of the UT1–UTC data. The uncertainties in the daily values (listed in Bulletin A) are derived from the quality of the spline fit in the neighborhood of the day in question.

Two groups of data points are excluded from the combination process. One group are those EOP inputs that have contributor reported errors (sometimes called formal errors) greater than three times their average reported precision. The other data excluded are those inputs that have a residual that is more than four times the associated a priori error estimate. Also, note that since all of the observations are reported to the IERS RS/PC with the effects of sub-daily variations already removed, the input data do not need to be corrected for these effects (see IERS Gazette No. 13, 30 January 1997).

Table 2: Mean and standard deviation of the differences between the Rapid Service/Prediction Center combination solutions and the 14 C04 EOP solutions for 2017. Polar motion x and y values are in milliseconds of arc and UT1–UTC values are in units of milliseconds of time.

Bulletin A – C04		
	Mean	Std. Deviation
Bulletin A Rapid Solution (finals.data)		
x	0.01	0.06
y	0.02	0.05
UT1–UTC	-0.011	0.018
Bulletin A Weekly Solution (finals.data) ¹		
x	0.01	0.08
y	0.01	0.07
UT1–UTC	-0.019	0.029
Bulletin A Daily Solution (finals.daily)		
x	0.00	0.07
y	0.01	0.07
UT1–UTC	-0.027	0.058

¹ Statistics computed over the 7-day combination solution period prior to solution epoch.

When comparing the integrated IGS Ultra LODs (IIUL) RMS value provided in Table 1 to that shown in Table 1 in the IERS RS/PC section from 2016, one can see over a 95% decrease (0.051 for 2017 vs 0.103 milliseconds (msec) for 2016). The RMS provided is computed using the first IIUL residual for that solution if any IIULs were used in the combination for that day. The exact causes for the change are being considered; however, reasons for the change could be affected by the manner in which the following were computed: a) the RMS statistics and b) the IIUL constants of integration for each day.

For each day, only the IIULs that are beyond the last VLBI intensive are used in the UT1–UTC combination. For most weekends each year and on some Mondays, GSI rapid turn-around intensives are observed, fringed, analyzed and published on the same day; consequently, these GSI intensives are often used in the combination on the same day that they are observed. On those days, no IIULs are used in the combination since the last observed IIUL was further in the past than the GSI intensive. Conversely, for several days during the year, there are potential gaps of several days between the last VLBI observation and when that data is available in the combination. For those days, there are several IIULs used in the combination. Each successive IIUL is 6 hours into the future, and its residual will be increased relative to the last one. Statistics that would be computed based on successive IIULs would be highly influenced by the number of successive IIULs used in the set. Therefore, to avoid this issue, statistics were based only on the first available (if any) IIUL for each day. However, this choice may also cause the statistics to vary from year-to-year depending on how many days have zero or several used IIULs for each year.

Since the IIULs are integrated to form a UT1 input, there must be a constant of integration used as a type of initial condition. The UTGPS input and the VLBI 24-hour and intensive series are both partially used to determine this constant of integration. It was mentioned in the 2016 IERS Section 3.5.2 that there was an apparent error in the UTGPS input series that had developed over the previous few years. The influence of this error was reduced after 30 March 2017 by deweighting the UTGPS input to the WSCS. Thus, the reduced IIUL 2017 RMS residual value compared to the 2016 value may have been due in part to the effect of the de-weighting of the UTGPS input on the UT1–UTC solution.

Table 2 shows the accuracies of Rapid Service/Prediction Center's combination solution for the running, weekly, and daily products compared to the 14 C04 series maintained by the IERS EOC for 2017; the latter series uses somewhat different data inputs and a different combination algorithm, which makes it suitable for comparison. Nominally,

each Thursday, the IERS RS/PC produces a weekly EOP solution in two general file formats – “finals.data” and the “ser7.dat” files. The finals.data solution contains EOP data in a tabular, machine-readable form, for each day from 1992 to one year into the future from the Thursday updated solution date. At the same time, the results are published in the ser7.dat file, which is more in a human readable format. Formats for each can be found at <http://maia.usno.navy.mil/ser7/readme.finals> and [ser7/readme.bulla](http://maia.usno.navy.mil/ser7/readme.bulla). In addition, each day, the IERS RS/PC computes and publishes an EOP solution in the file “finals.daily”. This file has the same format as the finals.data file; however, it only contains the current day, three prior months, and three future months of EOP results.

Figure 1 contains plots of the 2017 residuals between the daily rapid and the 14 C04 solutions, and the corresponding statistical results are listed in Table 2 under “Bulletin A Daily Solution (finals.daily).” These daily rapid solutions are considered the last combination or 0-day prediction results. As shown in Figure 1 and Table 2, Bulletin A Daily Solution (finals.daily) section, the UT1–UTC residuals for 2017 were smaller in both mean and standard deviation than those computed for 2016 -0.027 versus -0.034 in mean and 0.058 versus 0.078 milliseconds in standard deviation (STD) for 2017 compared to 2016. In addition, the first epoch of 2017 had a clear outlier as shown in the UT1–UTC plot of Figure 1 and as documented in the archive notes kept at USNO. (On that date, there was a network outage at USNO DC and USNO Flagstaff that caused missed input series updates and delayed solution generation and publication.) With this outlier removed, the mean and STD of the residuals would have been -0.028 and 0.049 milliseconds, respectively, for 2017.

The statistics for the daily solution, shown under the “Bulletin A Daily solution (finals.daily)” heading in Table 2, are the differences between the EOP solution, updated daily and at each corresponding daily epoch for 2017, versus the respective 14 C04 series solution for that epoch when it becomes available. (An example of the method used to compute the Bulletin A Daily solution (finals.daily) statistics is provided in the RS/PC section of the IERS Annual Report 2015 on pages 82 and 83.)

One likely cause for the decrease was the reduction in weighting of the UTGPS input to the WSCS, since, as mentioned previously, there was a degradation in the UTGPS solution over the past several years. The weighting decrease was implemented on 30 March 2017. However, even with the outlier mentioned above removed, the mean and STD for UT1–UTC for 2017 are higher than that obtained in 2013, the last year there was no noticeable drop in UTGPS performance and no additional latency in electronic VLBI transfer (e-VLBI) of VLBI intensives. It was hypothesized that by reducing the current UTGPS weighting (because of poor performance of that input series in recent years) and the full

restoration of e-VLBI over the past several years, the 2017 performance would be on a par with that of 2013. However, in 2013, the mean and STD were 0.002 and 0.037 milliseconds, respectively, which had clearly lower mean and STD than that obtained in 2017 even with outliers removed (-0.028 and 0.049 milliseconds, respectively). Resources permitting, it is hoped that some kind of investigation will reveal why the mean and STD remained higher than in 2013; and then corrective action could be applied if possible in subsequent EOP solutions.

The RMS of the polar motion residuals for 2017 are also shown in Table 2, under the heading “Bulletin A Daily Solution (finals.daily)”; these results are similar in mean, yet somewhat higher in STD than those determined in previous years. The potential reasons for the increases in STD are being considered.

The running solution statistics, shown under the label “Bulletin A Rapid Solution (finals.data),” are the residuals of the combination solution, contained in finals.data, versus the 14 C04 series over the 365-day period covering 2017. The finals.data file used in computing these statistics was computed on January 14, 2018 (and also archived). Nominally, the last observational input data for the year (in this case, 2017) is processed and provided to the IERS RS/PC by January 14 of the following year (in this case, 2018); the last observational data are usually the 24-hour VLBI input series. Thus, the running solution includes the effects of any late-submitted, but highly accurate data.

While the UT1–UTC STDs obtained in 2017 and 2016 were almost identical, as shown in the Table 1 Bulletin A Rapid Solution (finals.data) for both years, the mean was higher for 2017 compared to 2016. The mean was -0.011 for 2017 versus 0.001 milliseconds for 2016. The reason for the change in mean is not understood at this time, and if any reasons are determined, the IERS RS/PC will archive the reason and provide the information to the IERS community.

The “Bulletin A Weekly Solution” results shown in Table 2 are the statistics of the residuals obtained from the Bulletin A combination values, contained in the ser7.dat format, for 2017 versus the 14 C04 series. These combination values for 2017 are the concatenation of all 52 Bulletin A, 7-day EOP combination results. For each Bulletin A, there is a set of 7-day EOP combination results listed prior to the solution epoch. (For example, the Bulletin A solution computed on January 12, 2017 has EOP combination results from January 6 through January 12, 2017.)

Prediction Techniques and Results

In 2007, the algorithm for polar motion predictions was changed to incorporate the least-squares, autoregressive (LS+AR) method created by W. Kosek and improved by T. Johnson (personal communication, 2006). This method solves for a linear, annual, semiannual, 1/3 annual, 1/4

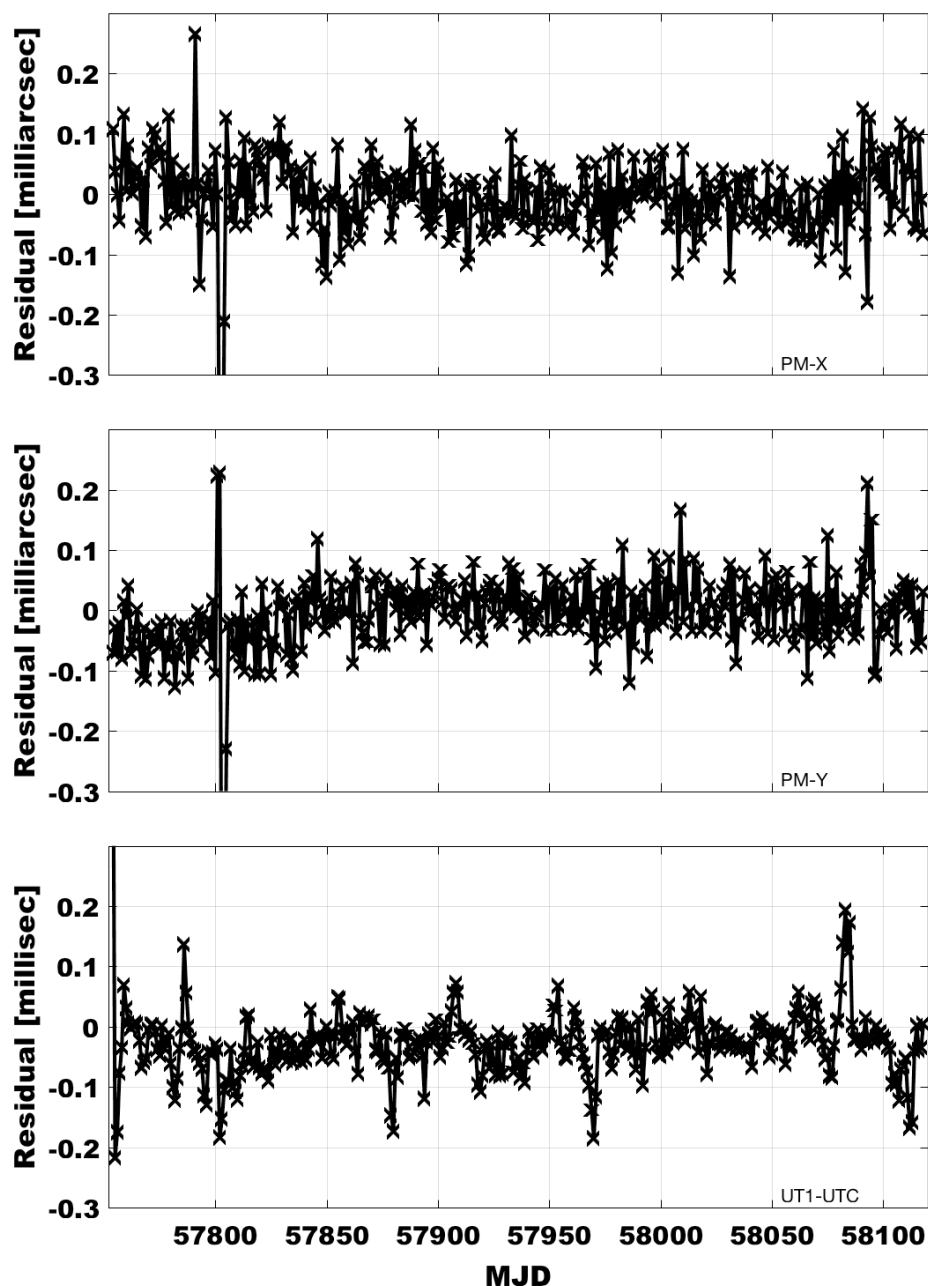


Fig. 1: Differences for 2017 between the daily updated EOP solution at the day of the solution update and the respective 14 C04 series combination solution. (The day of the solution is also known as the last combination or 0-day prediction epoch.) Earth Orientation Parameters shown are: a) Polar Motion X; b) Polar Motion Y; and c) UT1–UTC. The two large (off-the-scale) outliers in PM X that occurred on MJDs 57802 and 57803 had residual values of -0.55 and -0.77 msec, respectively. The two large outliers in PM Y that occurred on MJDs 57803 and 57804 had residual values of -0.74 and -0.59 msec, respectively. The large outlier in UT1–UTC that occurred on MJD 57754 had a residual value of 0.56 msec.

annual, and Chandler periods fit to the previous 400 days of observed values for x and y . This deterministic model is subtracted from the polar motion values to create residuals that are more stochastic in nature. The AR algorithm is then used to predict the stochastic process while a deterministic model consisting of the linear, annual, semiannual, and Chandler terms is used to predict the deterministic process. The polar motion prediction is the addition of the deterministic and stochastic predictions. The additional unused terms in the deterministic solution help to absorb errors in the deterministic model caused by the variable amplitude and phase of the deterministic components (T. Johnson, personal communication, 2006). For more information on the implementation of the LS+AR model, see Stamatakos *et al.* (2008). A deficiency with the current implementation of this algorithm occasionally causes poor quality short-term polar motion predictions. Mitigation strategies are being investigated.

The UT1–UTC prediction makes use of a UT1-like data product derived from a combination of the operational National Centers for Environmental Prediction (NCEP) and U.S. Navy’s Global Environmental Model (NAVGEM) Atmospheric Angular Momentum (AAM) analysis and forecast data (UTAAM). AAM-based predictions are used to determine the UT1 predictions out to a prediction length of 7.5 days (Johnson *et al.*, 2005). For longer predictions, the LOD excitations are combined smoothly with the longer-term UT1 predictions described below. For more information on the use of the UTAAM data, see Stamatakos *et al.* (2008).

The procedure for generating UT1–UTC predictions after 7.5 days involves a simple technique of differencing (McCarthy and Luzum, 1991b). All known effects such as leap seconds, solid Earth zonal tides, and seasonal effects are first removed from the observed values of UT1–UTC, resulting in a quantity called UT2R–TAI. (UT2R is a smoothed version of UT1, removing periodic seasonal and long period variations due to tides.) Then, to create the prediction of $(UT2R - TAI)_N$ N days into the future, the smoothed time value from N days in the past, $(UT2R - TAI)_{-N}$, is subtracted from 2-times the most recent value, $2(UT2R - TAI)_0$ to yield:

$$(UT2R - TAI)_N = 2(UT2R - TAI)_0 - (UT2R - TAI)_{-N}.$$

The amount of smoothing used in this procedure depends on the length of the forecast. Short-term predictions with small values of N make use of less smoothing than long-term predictions. Once this value is obtained, it is possible to restore the known effects in order to obtain the prediction of UT1–UTC. This process is repeated for each day’s prediction.

The UT1–UTC prediction out to a few days is also influenced by UTGPS, the observed daily Universal Time estimates derived at USNO from the motions of the GPS orbit planes reported by the IGS Rapid service (Kammeyer, 2000). The IGS estimates for LOD are combined with the UTGPS estimates to constrain the UT1 rate of change for the most recent observation.

Errors of the prediction estimates are derived from analyses of the past differences between observations and the published predictions. Formulas published in Bulletin A can be used to extend the Bulletin A tabular data, but predictions derived from these formulas are significantly less accurate than the tabular predictions and are not recommended for operational use. The predictions of $d\psi$ and $d\epsilon$ are based on the IERS Conventions (McCarthy, 1996; McCarthy and Petit, 2004).

For several representative prediction days, the RMS of the residuals between USNO produced polar motion and UT1–UTC solutions and the 14 C04 series values for 2017 are shown in Tables 3a through 3d. Prediction day “N” is defined as “N” days into the future from the current day for which the EOP solution was updated. For example, prediction day 10 for the EOP solution that was updated on MJD 57027 (October 1, 2017) is MJD 57037 (October 11, 2017). Table 3a provides the RMS prediction errors for EOP solutions updated at 17:00 UTC; Tables 3b, 3c, and 3d provide RMS prediction errors for solutions updated at 21:10, 03:10, and 09:10 UTC, respectively.

As Table 3a shows, in 2017, there was a noticeable improvement in the RMS of the residuals for the UT1–UTC 1-day predictions when compared to 2016; for 2016 the RMS was 0.131 and for 2017 it was 0.088 milliseconds. However, as was noted for the 0-day prediction, the value for 2017 remains high when compared to the 2014 results which was 0.056 milliseconds. (Again, as noted earlier, the 2014 result is considered one of the best years for EOP UT1–UTC results. For that year, the UTGPS and e-VLBI intensives were both performing well with low latency.) No explanation can be provided at this time; although it is worth noting that for some reason the corresponding mean of the 1-day UT1–UTC prediction residuals is -0.035 microseconds. That offset partially explains the high RMS. However, the STD is 0.073 which is still well above even the RMS of 0.056 milliseconds from 2014.

In annual reports up through 2013, the prediction length (as shown in Tables 3a) was determined from the epoch of the last known VLBI or IGS observation, and not based on the date of the solution epoch. It has been determined that many EOP users base their inputs on the prediction from the date of the solution epoch, and also using this new paradigm simplifies the comparison of results among the 17:00 UTC EOP solution and the 21:10, 03:10 and 09:10 UTC solutions (which are discussed below). In general, the results are very similar since on

most days an observation is made either on the solution day or the day before. The statistics based upon the older paradigm could be made available upon request from navobsy_eop.fct@navy.mil.

Table 3a: *RMS of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14 C04 combination solutions for 2017. Note that the prediction length starts counting from the day after the date of the solution epoch.*

Days in future	PMx masec	PMy masec	UT1–UTC msec
0	0.075	0.072	0.063
1	0.348	0.260	0.088
5	2.08	1.36	0.206
10	4.04	2.42	0.622
20	7.18	4.15	1.920
40	11.96	7.87	5.550
90	23.22	17.00	16.172

Table 3b: *RMS of the differences between the EOP time series predictions produced by the 21:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2017.*

Days in future	PMx masec	PMy masec	UT1–UTC msec
0	0.059	0.052	0.056
1	0.291	0.201	0.082
5	1.99	1.24	0.203
10	3.97	2.31	0.622
20	7.13	4.06	1.92
40	11.95	7.79	5.55
90	23.2	16.9	16.18

Table 3c: *RMS of the differences between the EOP time series predictions produced by the 03:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2017.*

Days in future	PMx masec	PMy masec	UT1–UTC msec
0	0.065	0.055	0.054
1	0.13	0.092	0.079
5	1.78	1.15	0.204
10	3.76	2.28	0.626
20	6.98	4.06	1.919
40	11.79	7.78	5.555
90	23.01	16.84	16.180

Table 3d: *RMS of the differences between the EOP time series predictions produced by the 09:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2017.*

Days in future	PMx masec	PMy masec	UT1–UTC msec
0	0.066	0.056	0.053
1	0.083	0.086	0.078
5	1.71	1.18	0.204
10	3.71	2.31	0.627
20	6.91	4.09	1.921
40	11.7	7.83	5.561
90	22.9	16.9	16.188

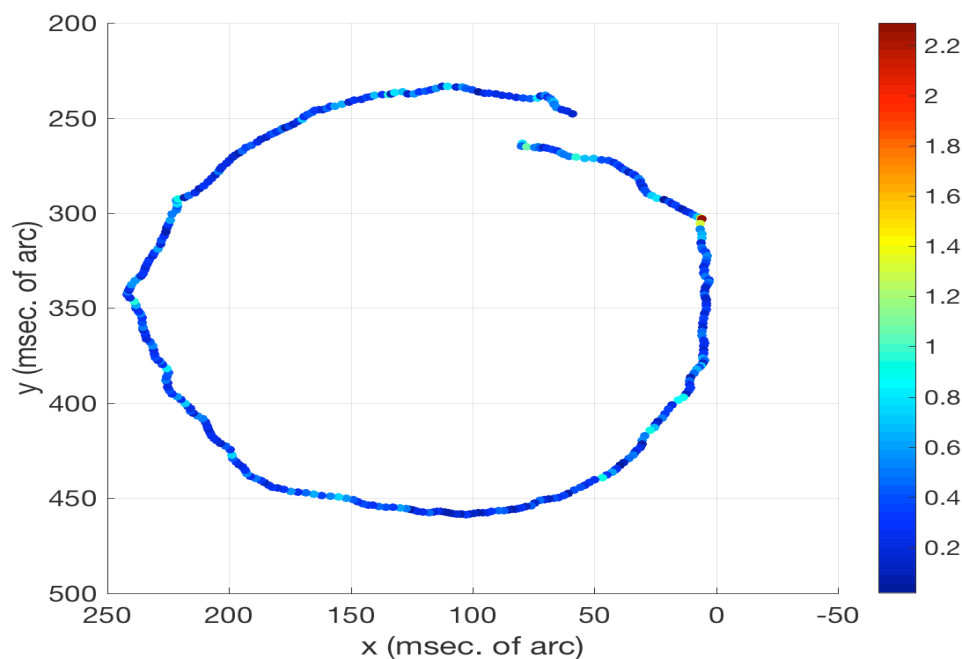


Fig. 2: Plot of the polar motion path for 2017 with corresponding 1-day prediction residual values. The residual is the RMS of the combined polar motion x and y residual values and is in units of msec and corresponds to the color-coded vertical bar at the right ranging from less than 0.1 (dark blue) to greater than 2.2 (dark red) msec.

In addition to the 17:00 UTC EOP solution, three additional EOP solutions are computed each day – new solutions are computed at 21:10, 03:10, and 09:10 UTC. These four solutions are collectively referred to as the Nxdaily solutions. At these solution times, the EOP results are recomputed and made available to users. The original solution at 17:00 UTC has been produced by the IERS RS/PC each day for over 15 years. The additional solutions are part of an ongoing effort to improve the accuracy of the EOP results by updating EOP solutions soon after new observational data are available, thereby reducing the latency between observations and EOP solution updates. Examples of these new observational input data are e-VLBI intensives and the IGS ultras. Tables 4a and 4b illustrate the relationship between the EOP solution times and these input data.

At each Nxdaily UTC solution time listed in Tables 4a and 4b, major contributors, whose latencies between observations to availability for the EOP solution are under a few days, are listed with an associated “epoch at midpoint.” IGS and VLBI solutions are determined from a span

of observations and the EOP estimate is provided at the midpoint of this span. Typically IGS orbits are determined over a 24-hour period and VLBI intensives sessions span a 1-hour period. The “Contributor” column contains the most recently available input at the time of each UTC solution. Although major contributors, the 24-hr VLBI solutions are not shown in the table since the time between observations and availability to the EOP solutions is generally greater than 7 days. Table 4a lists the most recent major input contributors for each polar motion Nxdaily solution. For example, by the polar motion 17:00 UTC <MJD> solution time, the most recently computed IGS rapid observation solution (IGS rapid), which has an epoch at midpoint of 12:00 UTC noon from the previous day, <MJD-1>, is available. In addition, there are two IGS ultras available that contain an epoch at midpoint after the IGS rapid. By 21:10 UTC <MJD>, the IGS has produced an updated IGS ultra, the 18-hr solution, and the corresponding EOP solution will use this latest data. Similarly, the 03:10 UTC and 09:10 UTC solutions will have later IGS ultra data available as shown in the table. Finally, for the next day, <MJD+1>, the sequence of IGS Rapids and Ultras will repeat – the 17:00 UTC <MJD+1> solution will have the next IGS rapid solution whose midpoint was at 12:00 UTC <MJD> along with the next 6-hr and 12-hr Ultras.

In Table 4b, there is a pattern for UT1–UTC that is similar to that described above for polar motion. In addition to the IGS contributions, the VLBI intensives series are included. While the IGS contributions have a consistent update time, the VLBI intensives updates are not as regular as the IGS updates. For example, new IGS ultra rapid observations are regularly provided every 6 hours with only a handful of missed or late solutions each year; whereas, a few VLBI intensives could be late or missing each month. So, the contributors shown for each solution are only an ideal case that occurs less than 100% of the time. There are 3 sets of VLBI intensives that are used in the EOP RS/PC UT1–UTC solution – called INT1, INT2, and INT3 intensives. The INT1 intensives are typically only observed on weekdays, the INT2 intensives on weekends, and the INT3 intensives on Mondays. For more information about the relation of the INT1, INT2, and INT3 VLBI intensives observation times to the EOP solution see Stamatakos *et al.* (2012).

Each Nxdaily EOP solution file (which are located in separate sub-directories) has an identical format to the original 17:00 UTC solution. As shown in Figure 3, the 1-day EOP prediction from the 17:00 UTC <MJD> EOP solution will make a prediction of the EOP for 00:00 UTC <MJD+1>; the 1-day EOP prediction from the 09:10 UTC <MJD+1> EOP solution will also make an estimate of the EOP value for the same

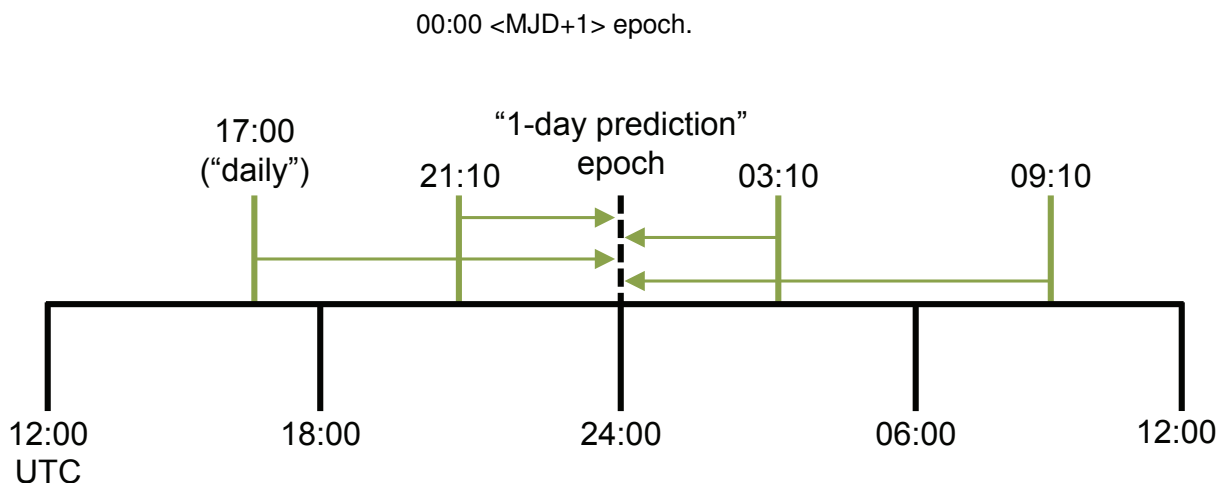


Fig. 3: Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP “daily” solution produced at 17:00 UTC. Each EOP solution update time is shown by the vertical green lines at 17:00, 21:10, 03:10 and 09:10 UTC, respectively. At each of these times, the latest observations are obtained. For example, at 03:10 UTC, the latest IGS ultra rapid observation, the 0-hour solution, is obtained (at the vertical black line labeled 24:00), and so the EOP solution for the “1-day prediction epoch” should be improved from that determined earlier at 17:00 and 21:10 UTC because of this additional, more recent, input observation.

The 0 and 1-day UT1–UTC RMS residuals shown in Tables 3a, 3b, 3c, and 3d follow an expected pattern – as more observations become available (as shown in Figure 3 and Table 4b), the RMS values are lower; thus, the Table 3d values are slightly lower than the Table 3c values, which in turn, are lower than the Table 3b values, and so on. For the 5-day RMS residuals, there is hardly any change among Tables 3a through 3d. It is worth pointing out that the 2017 results are significantly improved over the 2016 results for the 0, 1 and 5-day UT1–UTC RMS residuals. For the prediction days 10, 20, 40, and 90, there is no noticeable pattern among Tables 3a through 3d; at these prediction days, the results are becoming more influenced by the chaotic nature of physics of the Earth rotation. Thus, there is less of an expectation that increasing observations 10+ days in the past would significantly influence such distant predictions.

The 0, 1, and 5-day polar motion RMS residuals shown in Tables 3a, 3b, 3c, and 3d generally follow the expected pattern – as more observations become available (as shown in Figure 3 and Table 4a), the RMS values are lower. Thus, Table 3d values are lower than Table 3c values; Table 3c values are lower than 3b, and so forth. For the prediction days 10, 20, 40, and 90, there is no noticeable pattern among Tables 3a through 3d, since observations obtained 10+ days in the past would not significantly influence such distant predictions.

The predictions of celestial pole offsets (both dX/dY and $d\psi / d\epsilon$ representations) are produced through the use of the KSV1996 model

(McCarthy, 1996). In addition, a bias, based on several years of past observations compared to the 14 C04 solution, is computed and applied to ensure consistency with the 14 C04 solution. Since celestial pole offsets are based solely on VLBI data, if no new VLBI 24-hour session observations are available, a new rapid combination/prediction of these angles is not determined. Therefore, the predictions of celestial pole offsets start before the solution epoch and the length of the prediction into the future can and does vary in the daily solution files. The RMS differences between the daily predictions and the 14 C04 for 2017 are provided in Table 5.

Starting mid-2018 (after the 2017 year range covered by this report), the predicted dX and dY CPOs are based on an autoregressive process. A model based on free core, 9.3 year, annual, semi-annual, and 28-day nutation corrections are determined, and the results of this model are subtracted from the CPO observations to produce stochastic residuals. An autoregressive model is fit to these residuals and used to predict based on these stochastic values; deterministic predictions based on the nutation corrections are added to the autoregressive results to obtain CPO prediction values.

Predictions of TT–UT1, up to 1 October 2028, are given in Table 6. They are derived using a prediction algorithm similar to that employed in the Bulletin A predictions of UT1–UTC. Up to twenty years of past observations of TT–UT1 are used. Estimates of the expected one-sigma error for each of the predicted values are also given. These errors are based on analyses of the past performance of the model with respect to the observations.

Additional information on improvements to IERS Bulletin A and the significance for predictions of GPS orbits for real-time users is available (Luzum *et al.*, 2001; Wooden *et al.*, 2005; Stamatakos *et al.*, 2008; Stamatakos *et al.*, 2009; Stamatakos *et al.*, 2011).

Table 4: Available data for each Nxdaily solution is listed in Table 4a) for Polar Motion and Table 4b) for UT1–UTC. The 24 hr VLBI contributors are not included due to a > 7 day latency between observation and EOP solution integration.

(a) Major contributors to the Polar Motion EOP solution for each Nxdaily solution.

1700 UTC Solution		2110 UTC Solution		0310 UTC Solution		0910 UTC Solution	
Contributor	Epoch at Midpoint*	Contributor	Epoch at Midpoint*	Contributor	Epoch at Midpoint*	Contributor	Epoch at Midpoint*
IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	IGS 0 hr Ultra	+12:00	IGS 6 hr Ultra	+18:00
IGS 6 hr Ultra	-06:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	IGS 0 hr Ultra	+12:00
IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00
		IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	IGS 12 hr Ultra	00:00
				IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00
						IGS Rapid	-12:00

(b) Major contributors to the UT1–UTC EOP solution for each Nxdaily solution.

1700 UTC Solution		2110 UTC Solution		0310 UTC Solution		0910 UTC Solution	
Contributor	Epoch at Midpoint*	Contributor	Epoch at Midpoint*	Contributor	Epoch at Midpoint*	Contributor	Epoch at Midpoint*
AAM LOD ¹	—	AAM LOD ¹	—	AAM LOD ¹	—	AAM LOD ¹	—
INT2/3 VLBI ²	+08:00	INT2/3 VLBI ²	+08:00	IGS 0 hr Ultra	+12:00	IGS 6 hr Ultra	+18:00
IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	INT2/3 VLBI ²	+08:00	IGS 0 hr Ultra	+12:00
INT1 VLBI ³	-05:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	INT2/3 VLBI ²	+08:00
IGS 6 hr Ultra	-06:00	INT1 VLBI ³	-05:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00
IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	INT1 VLBI ³	-05:00	IGS 12 hr Ultra	00:00
		IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	INT1 VLBI ³	-05:00
				IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00
						IGS Rapid	-12:00

* IGS and VLBI solutions are determined by integrating a period of observation times. The reported EOP is the observation midpoint.

¹ The AAM LOD inputs contain 7.5 days of hourly forecast data from 00:00 to 18:00 hours.

² INT2 Intensives are observed Saturday and Sunday and INT3 Intensives are observed on Monday. Both sets of Intensives have an epoch midpoint of approximately 08:00 UTC.

³ INT1 Intensives are observed Monday through Friday with a midpoint epoch of approximately 19:00 UTC. The “Epoch and Midpoint” value of -05:00 is an idealized scenario.

Table 5: *RMS of the differences between the nutation prediction (also known as celestial pole offset) series produced by the daily solutions and the 14 C04 combination solutions for 2017.*

Days in Future	dX mas	dY mas	d ψ mas	d ϵ mas
0	0.11	0.11	0.27	0.11
1	0.11	0.11	0.27	0.11
5	0.11	0.12	0.28	0.12
10	0.12	0.13	0.31	0.13
20	0.14	0.14	0.34	0.15
40	0.16	0.18	0.41	0.19

Table 6: *Predicted values of TT–UT1, 2018–2028. Note that UT1–TAI can be obtained from this table using the expression $UT1-TAI = 32.184s - (TT-UT1)$.*

DATE	TT–UT1 (s)	Uncertainty (s)
2018 Jan 1	68.917	0.016
2018 Apr 1	69.039	0.01
2018 Jul 1	69.152	0.01
2018 Oct 1	69.27	0.03
2019 Jan 1	69.39	0.07
2019 Apr 1	69.5	0.1
2019 Jul 1	69.6	0.2
2019 Oct 1	69.7	0.2
2020 Jan 1	69.9	0.3
2020 Apr 1	70.0	0.4
2020 Jul 1	70.1	0.5
2020 Oct 1	70.2	0.6
2021 Jan 1	70.3	0.8
2021 Apr 1	70.4	0.9
2021 Jul 1	70.5	1.0
2021 Oct 1	71.0	1.0
2022 Jan 1	71.0	1.0
2022 Apr 1	71.0	1.0
2022 Jul 1	71.0	1.0
2022 Oct 1	71.0	2.0
2023 Jan 1	71.0	2.0
2023 Apr 1	71.0	2.0

Table 6 (cont...)

2023 Jul 1	72.0	2.
2023 Oct 1	72.0	2.
2024 Jan 1	72.0	2.
2024 Apr 1	72.0	2.
2024 Jul 1	72.0	3.
2024 Oct 1	72.0	3.
2025 Jan 1	72.0	3.
2025 Apr 1	72.0	3.
2025 Jul 1	73.0	3.
2025 Oct 1	73.0	3.
2026 Jan 1	73.0	4.
2026 Apr 1	73.0	4.
2026 Jul 1	73.0	4.
2026 Oct 1	73.0	4.
2027 Jan 1	73.0	4.
2027 Apr 1	74.0	4.
2027 Jul 1	74.0	5.
2027 Oct 1	74.0	5.
2028 Jan 1	74.0	5.

Center Activities for 2017

On 23 March 2017, the IERS RS/PC Bulletin A solutions for UT1–UTC, Polar Motion, and LOD were transitioned to be consistent with the ITRF 2014 series. Small adjustments to celestial pole offsets were also made in order to be more consistent with the IVS VLBI combined series solution.

During 2017, several changes to or to the usage of input data series were made. A list of these upgrades is as follows:

- a) On 30 March 2017, the UTGPS contribution to the IERS RS/PC Bulletin A solutions was deweighted to better reflect the degraded accuracy of the UTGPS solution over time;
- b) On 18 May 2017, the USNO VLBI 24-hour and intensive data series were upgraded from the usno2016a to usno2017a series; and
- c) On 21 September 2017, the USNO VLBI 24-hour and intensive data series were upgraded from the usno2017a to usno2017b series.

Efforts continued in the following areas as well:

- a) Studying combined U.S. Navy AAM and OAM inputs to improve polar motion predictions (Stamatakis *et al.*, 2016; Stamatakis *et al.*, 2017; Stamatakis *et al.*, 2018);
- b) Studying methods to better optimize the use of the UTGPS and IGS Ultra-rapid observations for LOD inputs to the EOP solution;
- c) Upgrading the *DataSim* simulation environment to test changes to codes, input data series, and configurations to the EOP software and processing;
- d) Creating code to combine CPO using the dX and dY formulation rather than $d\psi$ and $d\epsilon$ (which is based the older 1980 precession and nutation formulations.) In mid 2018, this code using the dX and dY formulation was made operational.;
- e) Developing new code for another web-based, interactive EO matrix calculator that computes rotation matrices based on the celestial intermediate origin (CIO) and pole (CIP) and terrestrial intermediate origin (TIO) formulation (In mid 2018, this code was made operational.);
- f) Starting efforts to test other optimal estimation techniques to replace the WSCS in the EOP combination. (These new optimal estimation techniques would stack and combine normal

equations, which is the desired future methodology for combining EOPs as stated by the IERS.);

g) Using the Very Long Baseline Array (VLBA) estimates as additional UT1–UTC inputs to the EOP solution (Stamatakis *et al.*, 2012, AGU poster G51A-1084); and

h) Looking at publishing EOP data on Navy public portals.

The existing web-based, interactive EO matrix calculator¹ was maintained throughout the year. The calculator can produce rotation matrix elements calculated using the IERS Technical Note 36 equinox-based algorithm (Petit and Luzum, 2010). This web-based product provides both the transformation matrices as well as quaternion representations of the rotations between terrestrial and celestial reference frames.

Rapid Service Input Data Contributors and Products

A list of the inputs to the EOP combination and prediction solutions are provided in Table 7; in addition, this table indicates which EOPs are provided by each contributor.

Other data sets are available and are listed below; however, they are not used in the EOP combination and prediction solutions. They include: UT from Natural Resources Canada GPS; UT0–UTC from University of Texas at Austin Lunar Laser Ranging (LLR); UT0–UTC from JPL LLR; UT0–UTC from the Centre de Recherches en Géodynamique et Astrométrie (CERGA) LLR; UT0–UTC from JPL VLBI; latitude and UT0–UTC from Washington, DC, Photographic Zenith Tubes (PZTs) 1,3,7; latitude and UT0–UTC from Richmond, Florida PZTs 2,6; LOD from ILRS 1-day SLR; x , y , UT1–UTC from Center for Space Research (CSR) UT at Austin LAGEOS 3-day SLR; x and y from CSR LAGEOS 5-day SLR; x and y from Delft, Netherlands 1-, 3- and 5-day SLR; and x , y , UT1–UTC, $d\psi$ and $d\epsilon$ from International Radio Interferometric Surveying (IRIS) VLBI.

Daily and Bulletin A weekly EOP solutions can be obtained from the primary Earth Orientation (EO) server at <http://maia.usno.navy.mil> and <ftp://maia.usno.navy.mil>, and from the backup EO server at <http://toshi.nofs.navy.mil> and <ftp://toshi.nofs.navy.mil>. An additional backup mirror of the daily and Bulletin A EOP data is now hosted by NASA's Archive of Space Geodesy Data server at <ftp://cddis.gsfc.nasa.gov/pub/products/iers>. Users may also request a weekly machine-readable version of the IERS Bulletin A containing the current 365 days' worth of predictions via the document request form at <http://maia.usno.navy.mil/docrequest.html>.

¹<http://maia.usno.navy.mil/t2c36e/t2c36e.html>

Table 7: Input data available from contributors to the IERS Bulletin A EOP solution.

Contributor	PM-x	PM-y	UT1–UTC	LOD	$d\psi$	$d\epsilon$	dX	dY
IAA VLBI	✓	✓	✓				✓	✓
GSFC VLBI	✓	✓	✓		✓	✓		
USNO VLBI	✓	✓	✓		✓	✓		
IVS VLBI	✓	✓	✓				✓	✓
GSFC Int. ^a			✓					
USNO Int.			✓					
GSI ^b Int.			✓					
ILRS ^c	✓	✓						
IAA ^d ILRS ^e	✓	✓						
MCC ^f SLR	✓	✓						
IGS	✓	✓		✓				
UTGPS			✓					
NCEP AAM			✓					
NAVGEM AAM			✓					
IERS EOC	✓	✓	✓		✓	✓	✓	✓
IERS RS/PC ^g	✓	✓	✓		✓	✓	✓	✓

^a The word “Int” is an abbreviation of the word Intensive.^{b, c, d, e, f} Defined in the Acronyms of the Appendix of this report.^g Both combination and prediction values are available.

Table 8 lists the locations and update times of several of the EOP solutions discussed in this report. The first column lists the EOP solution time in UTC. These are the approximate times when an EOP result is computed; if a problem occurs, the solution may actually become available as much as one hour later than what is listed. The second column contains the subdirectory under each FTP or web address listed in the above paragraph where an EOP solution resides. For example, at <http://maia.usno.navy.mil> there exists a subdirectory called “ser7” (i.e., <http://maia.usno.navy.mil/ser7>) where the daily EOP solution computed at 17:00 UTC will be updated each day. Similarly, at <ftp://cddis.gsfc.nasa.gov>, there exists a subdirectory called “eop0300utc” (i.e., <ftp://cddis.gsfc.nasa.gov/pub/products/iers/eop0300utc>), where

an EOP solution update computed at approximately 03:10 UTC will be uploaded each day.

Table 8: *EOP solution locations and update times.*

EOP solution Time (UTC)¹	Subdirectory location	Approximate time solution is posted ²
17:00	ser7	17:15
21:10	eop2100utc	21:15
03:10	eop0300utc	03:15
09:10	eop0900utc	09:15

¹ Solution times are the approximate times when an EOP result is computed; actual solution time may occur as much as one hour later than what is listed.

² At <http://maia.usno.navy.mil>, <ftp://maia.usno.navy.mil>, <http://toshi.nofs.navy.mil>, and <ftp://toshi.nofs.navy.mil>, this time represents the approximate time an updated EOP solution will be available. For <ftp://cddis.gsfc.nasa.gov/pub/products/iers>, the solution is posted shortly after 18:00 UTC, which is approximately 45 minutes after the “maia” and “toshi” servers have data posted. The additional time is needed to allow the EOP solution to finish at USNO and to be verified by EOP personnel before the mirroring is performed to post the solution to CDDIS.

Center Staff The Rapid Service/Prediction Center staff (at the USNO EO Department) consisted of the following members:

Dr. Christine Hackman	Director; Head, Earth Orientation (EO) Department
Mr. Nick Stamatakis	Project Director and Lead Scientist; Chief, EOP Combination and Prediction (EOP C/P) Division
Ms. Merri Sue Carter	Assists in daily operations and support; Research Astronomer, EOP C/P Division
Mr. Nathan Shumate	Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division
Ms. Maria Davis	Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division

References

- Davis, M., Stamatakos, N., 2017, "Improving the IERS Rapid Service / Prediction Center UT1–UTC 0-day Solution," Journées 2017 des Systèmes de Référence et la Rotation Terrestre, Alicante, Spain, 25–27 September, 2017.
- Johnson, T.J., Luzum, B.J., and Ray, J.R., 2005, Improved Near- Term Earth Rotation Predictions Using Atmospheric Angular Momentum Analysis and Forecasts, *J. Geodynamics*, **39**(3), 209–221.
- Kammeyer, P., 2000, A UT1-like Quantity from Analysis of GPS Orbit Planes, *Celest. Mech. Dyn. Astr.*, **77**, 241–272.
- Luzum, B.J., Ray, J.R., Carter, M.S., and Josties, F.J., 2001, Recent Improvements to IERS Bulletin A Combination and Prediction, *GPS Solutions*, **4**(3), 34–40.
- McCarthy, D.D. and Luzum, B.J., 1991a, Combination of Precise Observations of the Orientation of the Earth, *Bulletin Geodesique*, **65**, 22–27.
- McCarthy, D.D. and Luzum, B.J., 1991b, Prediction of Earth Orientation, *Bulletin Geodesique*, **65**, 18–21.
- McCarthy, D.D. (ed.), 1996, IERS Conventions (1996), IERS Technical Note No. 21, Paris Observatory, France.
- McCarthy, D.D. and G. Petit (eds.), 2004, IERS Conventions (2003), IERS Technical Note No. 32, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany.
- McCarthy, D. and Stamatakos, N., "A Conventional Mean Pole," G41A-1002 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2016.
- Petit, G. and Luzum (eds.), 2010, IERS Conventions (2010), IERS Technical Note No. 36, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany.
- Salstein, D., Stamatakos, N., "New Atmospheric and Oceanic Angular Momentum Datasets for Predictions of Earth Rotation/Polar Motion," G13A-0521 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2014.
- Stamatakos, N., Luzum, B., Wooden, W., 2008, "Recent Improvements in IERS Rapid Service/Prediction Center Products," in Proc. Journées Systèmes de Référence Spatio-Temporels, Paris, 17–19 Sept. 2007, 163–166.
- Stamatakos, N., Luzum, B., Stetzler, B., Wooden, W., and Schultz, E., 2009, "Recent Improvements in IERS Rapid Service/Prediction Center Products," in Proc. Journées Systèmes de Référence Spatio-Temporels, Dresden, 22–24 Sept. 2008, 160–163.
- Stamatakos, N., Luzum, B., Stetzler, B., Shumate, N., and Carter, M.S., 2011, "Recent Improvements in IERS Rapid Service/ Prediction

- Center Products,” in Proc. Journées Systèmes de Référence Spatio-Temporels, Paris, 20–22 Sept. 2010, 184–187.
- Stamatakis, N., Luzum, B., Stetzler, B., Shumate, N., Carter, M.S., and Tracey, J., 2012, “Recent Improvements in IERS Rapid Service/Prediction Center Products for 2010 and 2011,” in Proc. Journées Systèmes de Référence Spatio-Temporels, Vienna, 19–21 Sept. 2011, 125–129.
- Stamatakis, N., Luzum, B., Zhu, S., and Boboltz, D., 2012, “Further Analysis of a New Geodetic VLBI Data Source and its Applications,” G51A-1084, AGU Fall Meeting, San Francisco, 3–7 Dec. 2012.
- Stamatakis, N., Eubanks, T. M., McCarthy, D., Salstein, D., “Using Atmospheric and Oceanic Angular Momentum to Improve Earth Orientation Products,” EGU2016-8556 POSTER at the European Geophysical Union Meeting, Vienna, Austria, April 2016.
- Stamatakis, N., Eubanks, T. M., McCarthy, D., Salstein, D., “Ongoing Efforts to Analyze and Use U.S. Navy provided Angular Momentum Datasets for Predictions of Earth Orientation,” G41A-1003 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2016.
- Stamatakis, N., McCarthy, D., Salstein, D., “Earth Orientation from the IERS Rapid Service / Prediction Center: Improvements with the use of atmospheric and ocean angular momentum data,” EGU2018-10589 POSTER at the European Geophysical Union Meeting, Vienna, Austria, April 2017.
- Stamatakis, N., “IERS Rapid Service / Prediction Center Products and Services: Improvements, Changes, and Challenges, 2012 to 2017,” Journées 2017, des Systèmes de Référence et la Rotation Terrestre, Alicante, Spain, 25–27 Sept., 2017.
- Stamatakis, N., McCarthy, D., Salstein, D., “Enhancements and Improvements to USNO-produced Earth Orientation Results Using Navy or US-only Produced Atmospheric and Oceanic Angular Efforts,” Presented at the Institute of Navigation, Joint Navigation Conference, Long Beach, California, July 2018.
- Wooden, W.H., Johnson, T.J., Kammeyer, P.C., Carter, M.S., and Myers, A.E., 2005, Determination and Prediction of UT1 at the IERS Rapid Service/Prediction Center, Proc. Journées Systèmes de Référence Spatio-Temporels, Paris, 20–22 Sept. 2004, 260–264.

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3.5.3 Conventions Centre

Introduction

The Conventions Centre is operated jointly by L'Observatoire de Paris (OP) and the U.S. Naval Observatory (USNO). It provides updated versions of the IERS Conventions in electronic form following their approval by the IERS Directing Board (DB). In addition to the electronic releases, printed versions will be provided at less frequent intervals or when major changes are introduced.

IERS Conventions web and ftp sites that were redesigned in 2017 are located at: a) <http://iers-conventions.obspm.fr/>, b) <http://maia.usno.navy.mil/conventions/>, and c) <ftp://maia.usno.navy.mil/conventions>. The printed IERS Conventions (2010), IERS Technical Note 36, is available in electronic form at these URLs and at <https://www.iers.org/IERS/EN/Publications/TechnicalNotes/TechnicalNotes.html>. Updates continue to be provided in electronic form and can be found at:

- <http://iers-conventions.obspm.fr/updates/2010updatesinfo.php> and
- <http://maia.usno.navy.mil/conventions/updates/2010updatesinfo.php>

The IERS Conventions Center continues to work with the IAU Division A Commission on Fundamental Standards that deals with celestial and terrestrial reference systems/frames and the transformations among them, time scales, precession-nutation models, Earth rotation and polar motion, including physical models (e.g., Earth's gravity field, solid Earth-tide modeling), star catalogues, ephemerides of Solar System bodies, special and general relativistic models for time and space.

Technical Content of the IERS Conventions

Recent changes in the technical content included the following:

- A revised value of the potential of the geoid, W_0 , in Table 1.1 in accord with Resolution (1) of the International Association of Geodesy (2015) for the definition and realization of an International Height Reference System (IHRS) and
- Section 7.1.4 of the IERS Conventions was rewritten to provide the definition and realization of a secular (linear) pole to replace the previous mean pole.

After considerable discussion, the IERS decided to adopt the usage of a conventional secular pole to represent the low-frequency motion of the Earth's rotation axis with respect to the terrestrial reference system. Previous discussion in that section regarding a "mean pole" was deleted. In addition to the change in Chapter 7, revisions of text in Section 6.1 regarding gravitational potential coefficients were also made necessary to be consistent with the change in Chapter 7. Corresponding changes to the Glossary section are being considered.

Table 1: *Status of participation in the IERS Conventions major update.*

#	Chapter Title	Position	Applicant
1	General Definitions and Numerical Standards	Chapter Editor-in-Chief	Y
		Chapter Expert	N
		Assistant Chapter Expert	N
2	General Relativistic Models for Space-Time Coordinates and Equations of Motion	Chapter Editor-in-Chief	N
		Chapter Expert	Y
		Assistant Chapter Expert	N
3	Celestial Reference System and Frame	Chapter Editor-in-Chief	Y
		Chapter Expert	N
		Assistant Chapter Expert	Y
4	Terrestrial Reference Systems and Frames	Chapter Editor-in-Chief	N*
		Chapter Expert	N
		Assistant Chapter Expert	N
5	Transformation Between the International Terrestrial Reference System and the Geocentric Celestial Reference System	Chapter Editor-in-Chief	Y
		Chapter Expert	N
		Assistant Chapter Expert	Y
6	Geopotential	Chapter Editor-in-Chief	Y
		Chapter Expert	Y
		Assistant Chapter Expert	Y
7	Displacement of Reference Points	Chapter Editor-in-Chief	Y
		Chapter Expert	Y
		Assistant Chapter Expert	Y
8	Tidal Variations in the Earth's Rotation	Chapter Editor-in-Chief	N
		Chapter Expert	N
		Assistant Chapter Expert	Y
9	Models for Atmospheric Propagation Delays	Chapter Editor-in-Chief	N
		Chapter Expert	N
		Assistant Chapter Expert	N
10	General Relativistic Models for Propagation	Chapter Editor-in-Chief	N
		Chapter Expert	Y
		Assistant Chapter Expert	N
	Software Associated with Chapters 1 through 10	Software Editor-in-Chief	Y

* A person has possibly expressed verbal interest in being an Editor-in-Chief or Expert for Chapter 4, however, a written request to participate has not been received. Consequently, it is unknown to which position the person is considering.

Conventions Software Software recommended for use in connection with the IERS Conventions consists largely of the library maintained by the IAU Standards of Fundamental Astronomy (SOFA) available at www.iausofa.org. The 14th release of this library was made available recently. This release implements two new sections entitled Horizon/Equatorial Coordinates and Gnomonic (tangent plane) Projections. Three routines were added covering transformations between Astrometry Tools Cookbook, test programs and supporting files. This release implements two new sections entitled Horizon/Equatorial Coordinates and Gnomonic (tangent plane) Projections. Three routines were added covering transformations between the azimuth and altitude angles and the hour and declination angles. Six routines were added regarding the determination of the tangent point and transformations of star positions to and from celestial and tangent plane coordinates.

Major Conventions Update In anticipation of the possible publication of a new printed edition of the IERS Conventions, the IERS requested volunteer participants as Chapter Editor-in-chief, Chapter/Assistant Experts, and Software Editor. Interested candidates submitted their curricula vitae along with a possible letter of support from their sponsoring agency. Table 1 lists the Conventions Major Revision Chapters along with a list of positions for which there are applicants as of the writing of this report (September 2018).

Acknowledgements The Conventions web pages at OP <http://iers-conventions.obspm.fr/> and USNO <http://maia.usno.navy.mil/conventions/> were maintained and improved. The IERS Conventions Centre would like to acknowledge the work of Maria Davis from USNO and Teddy Carlucci from OP for their work on the updated IERS web and ftp sites.

Conventions Center Staff Christian Bizouard (OP), co-director since 1 September 2016 (and current representative to the IERS Directing Board)
 Nick Stamatakos (USNO), co-director since 1 January 2016. (Per existing agreement between the IERS DB and the IERS Conventions, the USNO co-director will become the representative to the IERS Directing Board on 1 January 2019.)
 Sébastien Lambert (OP)
 Maria Davis (USNO)
 Dennis McCarthy (USNO, retired)

Nick Stamatakos, Christian Bizouard

3.5.4 ICRS Centre

Maintenance of the International Celestial Reference Frame Construction of the ICRF3

Part of the activities of the ICRS Centre team at Paris Observatory have been related to the construction of the third realization of the International Celestial Reference Frame (ICRF3). These activities are a contribution to the Working Group on ICRF3 created at the XXVIII IAU General Assembly in 2012. The mission of the WG-ICRF3 is to propose to the XXX IAU General Assembly in 2018 a catalogue of radio source positions to realize the ICRS, which would include a larger interval of observation than that of ICRF2 for the computation of precise coordinates, assuring the representation of the axes of ICRS through a set of position-stable radio sources, namely defining sources. Objects in the new frame should allow the orientation of the Gaia catalogue onto ICRS.

The contribution to this task focused on (a) the comparison and analysis of different VLBI prototype solutions for a study of systematic effects and deformations, (b) the analysis of positional stability and statistics for improving the set of defining sources of the frame, (c) the implementation of a strategy for selecting stable sources respecting a homogeneous special distribution.

An important improvement with respect to ICRF2 has been the possibility of providing a multi-frequency catalogue. With this aim, prototype solutions on S/X, K, and X/Ka bands were included in the analysis. The ICRF2 (Fey et al., 2015) and the Gaia catalogue issued for the Data Release 2 (GDR2; Prusti et al., 2016; Brown et al., 2016, 2018; Mignard et al., 2018) were used as references for catalogue comparisons. The model used for the catalogue comparisons is that adopted since 2016 at Paris Observatory, which includes the three classical rotation angles, three deformation (glide) parameters and ten quadrupole parameters (see Section 3 of this report for the formulae and a discussion). Eight analysis centres produced prototype solutions for testing various effects, included the Galactic aberration correction. Complete independence between solutions had not been possible due to the use of common software for some. In all cases the no-net-rotation condition was imposed to the ICRF2 defining sources. Results of these comparisons will be available in Charlot et al. (2018). The three final ICRF3 catalogs at S/X, K, and X/Ka bands are publicly available at the ICRS Centre web site at <http://iers.obspm.fr/iers-pc/newwww/icrf>.

Monitoring of the ICRS

One mission of the IERS ICRS Centre is the monitoring of the ICRS, which includes verifications of the stability of the axes of the system materialized through the frame, the possible deformations of the frame and the astrometric evolution of its defining sources. The comparisons realized as a contribution to the WG on the ICRF3 gave indication of the

existence of deformations in the ICRF2 depending on the declination, mostly visible for sources at high south declination. This could be confirmed by the comparison with the Gaia DR2 catalogue, under the hypothesis that the Gaia frame is not subject to any significant deformation.

The IERS ICRS Centre at Paris Observatory developed the tools for analyzing the astrometric quality of radio source positions (Lambert, 2014). These analyses focused on the monitoring of the defining sources in ICRF2, and on the detection of possible candidates for defining sources in ICRF3. Coordinate time series for a number of sources have been analyzed, ranking them according to their statistical behavior. We used as indicators the weighted root-mean-square of the time series in the direction of the maximum variance (computed from the major axis of the error ellipses), and the chi-square computed along this direction. Also, a visual inspection of the time series was made to detect special features (noise level, slopes, etc.). Structure indices had also been considered, but a formal inspection by the Bordeaux team completed the evaluation. These analyses were also performed on the so called “special handling sources” of the ICRF2. These are 39 sources which had been detected unstable at the elaboration of the ICRF2, and consequently treated as arc parameters in the VLBI solutions. The ensemble of analyses gave the following results:

- A number of ICRF2 defining sources presents positional instability and should be excluded from this category;
- There is no clear evidence of significant instability in the position time series of the special handling sources, suggesting that they could be resolved as global parameters in the VLBI solutions.

Based on these results, it is clear that a major revision is necessary on the set of defining sources of the new frame. The criteria adopted in the elaboration of the previous versions of the celestial reference frame focused on the position stability without considering the spatial distribution of objects. This could be one of the reasons for the deformations present in the ICRF2. The sources observed by the VLBI programs has increased in number, but a big progress happened with the observation of objects south from the equator. With this improved distribution it is possible to design a method privileging a homogeneous spatial distribution. The method retained consisted on dividing the celestial sphere into 324 equal sectors, and in each one to select the best source, considering positional stability shown in the time series and radio structure. This resulted on only two empty sectors. The classification of sources in the sectors permitted to retain a list of 303 sources qualified to be defining sources in ICRF3; 54% of them are defining sources of ICRF2, 83% are in Gaia DR2.

**Analysis of recent
VLBI catalogs**
Data

We analyzed three catalogs submitted to the International VLBI Service (IVS) in 2017. One catalog was submitted by the Italian Space Agency (ASI; solution asi2017a); one catalog was submitted by Geoscience Australia (aus2017b); one catalog was submitted by BKG (bkg2017a). The aus2017b catalog was obtained with the OCCAM geodetic VLBI analysis software package (Titov et al., 2004), whereas the other two catalogs were obtained with Calc/Solve (Ma et al., 1986). As reference catalogs, we considered the current reference recommended by the International Astronomical Union (IAU), i.e., the second realization of the International Celestial Reference Frame (ICRF2; Fey et al., 2015) and the second data release of Gaia (DR2; Prusti et al., 2016; Brown et al., 2016, 2018; Mignard et al., 2018). These two reference catalogs, that were obtained by independent techniques and analyses, are of comparable accuracy but, though the former provides positions measured at the standard VLBI S/X frequency, the latter gives the positions of the same objects in the optical domain.

Overview of the catalogs

The distribution on the sky of the radio sources in each catalog is plotted in Figure 1 together with the distribution of the standard errors. In the sky maps, the color indicates the overall error computed as the major axis of the error ellipse, calculated using the correlation information between the coordinates as provided in the catalogs. The number of sources in each catalog, the mean epoch of the observations, and the median positional errors are reported in Table 1.

The ASI solution contains a smaller number of sources than the other two catalogs. However, these are sources that have the best positional errors, so that the median error is neatly lower than for other catalogs. The comparison, restrained to 920 sources that are common to all three catalogs and to the two references, shows that ASI and BKG have similar accuracy while standard errors of AUS are larger by a factor of two. Over this common sample, the median error of the ICRF2 is a bit larger than that of AUS while the median error of Gaia DR2 is larger than that of the ICRF2 by a factor of 1.3.

An overall comparison of the error distribution with that of the reference catalogs as well as the dependence of the error on the declination are displayed in Figure 1, for which we took the running median error within windows of 15 degrees. Note that the ICRF2 standard errors were inflated and a noise floor of 0.04 mas was imposed a posteriori, whereas the initial values of the standard errors could be much lower than this threshold, as they are for the three analyzed catalogs of this report.

The declination-dependent error in Figure 1 reflects the results of Table 1 with an additional aspect: both AUS and ASI solutions show larger errors at mid-latitudes in the southern hemisphere, likely in association

with the network asymmetry and the lower number of observations in the south. This feature does not show up clearly for BKG. The Gaia DR2 solution does not show such systematic effects (the Gaia scanning law allows to cover both hemispheres symmetrically).

Comparison with ICRF2 and Gaia DR2

Figure 3 displays the differences in declination between the catalogs and the references averaged within bins of 15 degrees. All three catalogs share the common feature of large (0.1-mas level) zonal differences with the ICRF2. A similar comparison with Gaia DR2 reveals that the zonal deformation is much smaller, concluding that recent VLBI catalogs are closer to Gaia than to the ICRF2. Since Gaia DR2 is not expected to present zonal deformations, Figure 3 suggests that recent VLBI catalogs are less deformed than ICRF2.

Table 1: *Statistics of the catalogs, including the two references (ICRF2 and Gaia DR2) used in this report. N is the number of sources. The mean epoch corresponds to the average of the mean observational epochs of each source. Unit is μas .*

	N	Mean Epoch	Median Error		
			RA*	Dec	EEMA
ICRF2	3414	2001.41	396.7	739.0	756.9
Gaia DR2	2820	2015.50	233.1	211.0	263.7
asi2017a	1406	2007.53	53.2	88.3	92.5
aus2017b	4166	2009.41	313.7	551.0	579.1
bkg2017a	3606	2005.17	238.1	428.3	450.9
920 common sources					
ICRF2	920	2001.06	119.7	147.5	185.3
Gaia DR2	920	2015.50	207.5	189.0	232.9
asi2017a	920	2007.42	42.7	66.1	67.2
aus2017b	920	2008.53	114.0	147.5	154.0
bkg2017a	920	2006.48	48.2	68.5	71.2

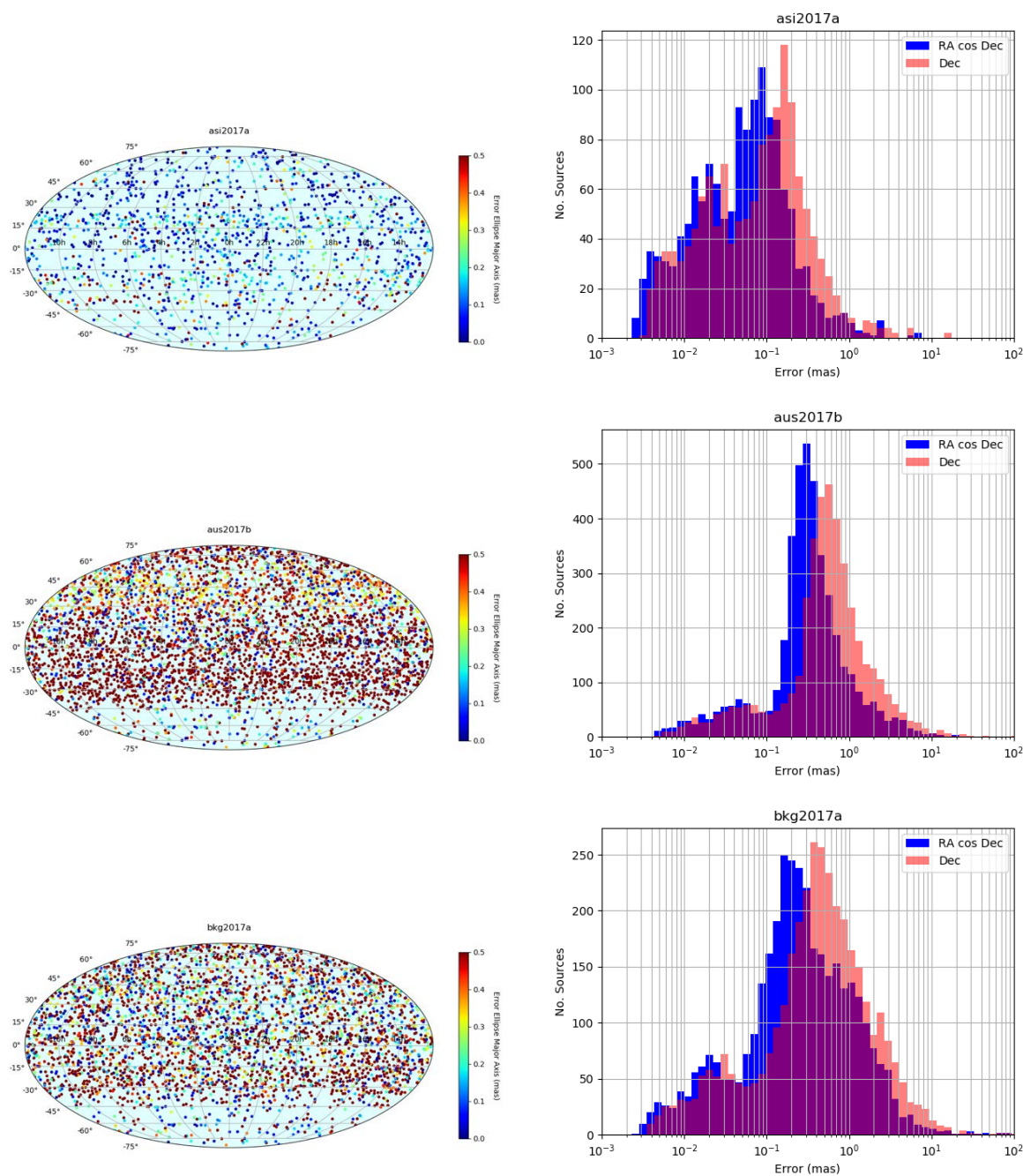


Fig. 1: Left: sky distribution of the catalogs highlighting the overall positional error computed as the major axis of the error ellipse. Right: distribution of the standard errors on source position.

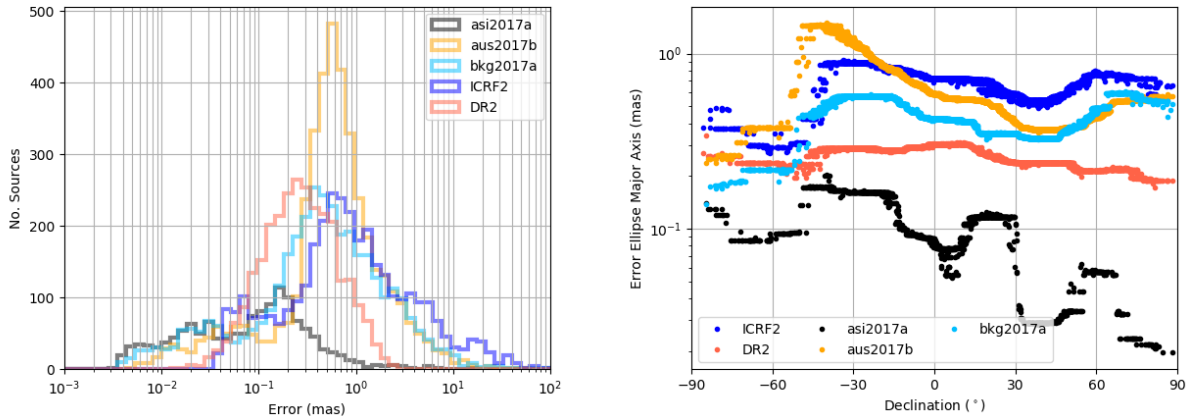


Fig. 2: Left: overall comparison of the standard error distribution. Right: standard errors in source positions as a function of the declination smoothed by taking the running median within bins of 15 degrees.

Before further comparison, we removed sources that have (i) less than three observations in one catalog, or (ii) an error ellipse major axis larger than 5 mas in one catalog, or (iii) a normalized separation between catalogs larger than 5.

To model large-scale systematics, we used a 16-parameter transformation accounting for rotations around the three axes, a glide, and degree-2 electric- and magnetic-type deformations (see, e.g., Mignard and Klioner, 2012). With respect to earlier works, we added therefore ten parameters mainly because the examination of the coordinate differences as a function of the declination revealed a $\sin 2\delta$ pattern that was not accountable by the glide alone. The coordinate differences $\Delta\alpha$ and $\Delta\delta$ between a catalog and a reference catalog read

$$\begin{aligned}
 \Delta\alpha \cos \delta &= R_1 \cos \alpha \sin \delta + R_2 \sin \alpha \sin \delta - R_3 \cos \delta - D_1 \sin \alpha + D_2 \cos \alpha + M_{20} \sin 2\delta \\
 &+ (E_{21}^{\text{Re}} \sin \alpha + E_{21}^{\text{Im}} \cos \alpha) \sin \delta - (M_{21}^{\text{Re}} \cos \alpha - M_{21}^{\text{Im}} \sin \alpha) \cos 2\delta \\
 &- 2(E_{22}^{\text{Re}} \sin 2\alpha + E_{22}^{\text{Im}} \cos 2\alpha) \cos \delta - (M_{22}^{\text{Re}} \cos 2\alpha - M_{22}^{\text{Im}} \sin 2\alpha) \sin 2\delta, \\
 \Delta\delta &= -R_1 \sin \alpha + R_2 \cos \alpha - D_1 \cos \alpha \sin \delta - D_2 \sin \alpha \sin \delta + D_3 \cos \delta + E_{20} \sin 2\delta \\
 &- (E_{21}^{\text{Re}} \cos \alpha - E_{21}^{\text{Im}} \sin \alpha) \cos 2\delta - (M_{21}^{\text{Re}} \sin \alpha + M_{21}^{\text{Im}} \cos \alpha) \sin \delta \\
 &- (E_{22}^{\text{Re}} \cos 2\alpha - E_{22}^{\text{Im}} \sin 2\alpha) \sin 2\delta + 2(M_{22}^{\text{Re}} \sin 2\alpha + M_{22}^{\text{Im}} \cos 2\alpha) \cos \delta,
 \end{aligned}$$

where α and δ are the coordinates of the object in the reference catalog. We used weighted least-squares to solve the system, with weights computed using the available covariance information (i.e., the standard errors on individual source coordinates and their correlation). The values of transformation parameters adjusted to the catalogs compared to the ICRF2 and Gaia DR2 and their standard errors are reported in Figure 4. The resulting statistics corresponding to that of Table 2 after removal of systematics are reported in Table 3. Figure 5 clearly reveals that the only really significant deformations between the catalogs and the ICRF2 lie in the D_3 and E_{20} parameters, that are associated to

the purely zonal deformations in $\cos \delta$ and $\sin 2\delta$, respectively, along the polar axis of the celestial frame. Such deformations show up in all three catalogs at comparable levels of about $100 \mu\text{as}$. No significant deformations are seen with respect to Gaia DR2. A part of the detected zonal differences between ICRF2 and the three analyzed catalogs is imputable to the uncorrected Galactic aberration that moves sources towards the Galactic centre following a glide of amplitude close to $5 \mu\text{as/yr}$ (e.g., Kovalevsky, 2003; Titov et al., 2011). Nevertheless, given the median epochs of the catalogs, this effect is expected to be of 20 to $40 \mu\text{as}$ in D_2 and D_3 so that it cannot explain all the present results. Another part of the zonal differences is likely an evidence that the VLBI network has improved since the construction of the ICRF2 (and, especially, it was enforced in the southern hemisphere).

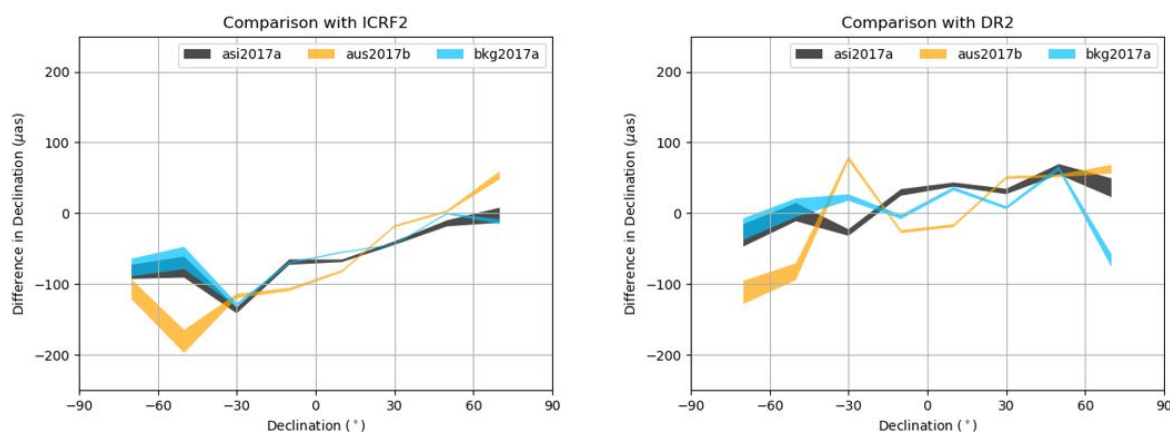


Fig. 3: Differences in declination between the catalogs and the references (ICRF2: left; Gaia DR2: right) averaged in bins of declination of width 15° .

Conclusions and recommendations

Three catalogs were submitted in 2017. They are all consistent with ICRF2 at the level of $30 \mu\text{as}$ except for zonal deformations in $\cos \delta$ and $\sin 2\delta$ for which the amplitude of the difference reaches about $100 \mu\text{as}$ (likely a combination of effects including the Galactic aberration and a network improvement). All three catalogs are consistent with Gaia DR2 within $50 \mu\text{as}$.

For a better evaluation of the consistency of the VLBI products and a better maintenance of the reference frame, especially in the frame of the next realization (ICRF3, Charlot et al., 2018) that will replace the ICRF2 as of 1 January 2019, we encourage analysis centres to submit catalogs. These catalogs should be as complete as possible, i.e., processing as much VLBI sessions as possible since 1979. Analysis strategies should be rigorously documented and motivated (e.g., why estimating some source coordinates as session parameters instead of global parameters?). The main points that will be scrutinized in the next

Table 2: Statistics of the differences of the catalogs to ICRF2 (top) and Gaia DR2 (bottom) before and after removal of large-scale systematics. N represents the number of sources used in the comparison. Unit is μas .

Before						After					
-----						-----					
		Wrms		χ^2				Wrms		χ^2	
		-----	-----	-----	-----			-----	-----	-----	-----
	N	RA*	Dec	RA*	Dec	N	RA*	Dec	RA*	Dec	

With respect to ICRF2											

asi2017a	1367	82.4	101.8	0.8	0.9	1264	79.3	93.4	0.8	0.8	
aus2017b	3282	121.1	153.5	0.6	0.7	2780	120.2	142.2	0.6	0.6	
bkg2017a	3133	86.0	109.3	0.4	0.5	2782	83.7	100.9	0.4	0.4	

With respect to Gaia DR2											

asi2017a	1048	231.4	244.5	2.4	2.6	856	229.0	240.8	2.4	2.6	
aus2017b	2696	320.8	336.1	1.8	1.6	2375	318.3	334.0	1.8	1.5	
bkg2017a	2454	317.3	337.4	2.1	2.1	2089	315.9	335.1	2.1	2.0	

reports will be the 100- μas level zonal systematics, their relation with the Galactic aberration, and the agreement with the current (DR2) and future releases of Gaia.

Photometric follow-up of quasars

As in the radio domain, it can be reasonably postulated that quasar optical flux variations can alert us to potential changes in the source structure. These changes could have important implications for the position of the target photocenters (together with the evolution in time of these centers) and in parallel have consequences for the link of the reference systems. In the continuity of what was done in the preceding years, a set of nine optical telescopes was used to monitor the magnitude variations, often at the same time as Gaia, thanks to the Gaia Observation Forecast Tool. In 2017, the Allan variances, which are statistical tools widely encountered in the atomic time and frequency community, were used to quantify the stability of the magnitude time series previously obtained.

A study concluded by a paper (Taris et al., 2017) describes the magnitude variations of 47 targets that are suitable for the link between reference systems. In this paper, we also report on some implications for the Gaia catalog. For 95% of the observed targets, new information about their variability is reported. In the case of some targets that are well observed by the TAROT telescopes, the Allan time variance shows that the longest averaging period of the magnitudes is in the range 20–70 d. The observation period by Gaia for a single target largely exceeds these values, which might be a problem when the magnitude variations

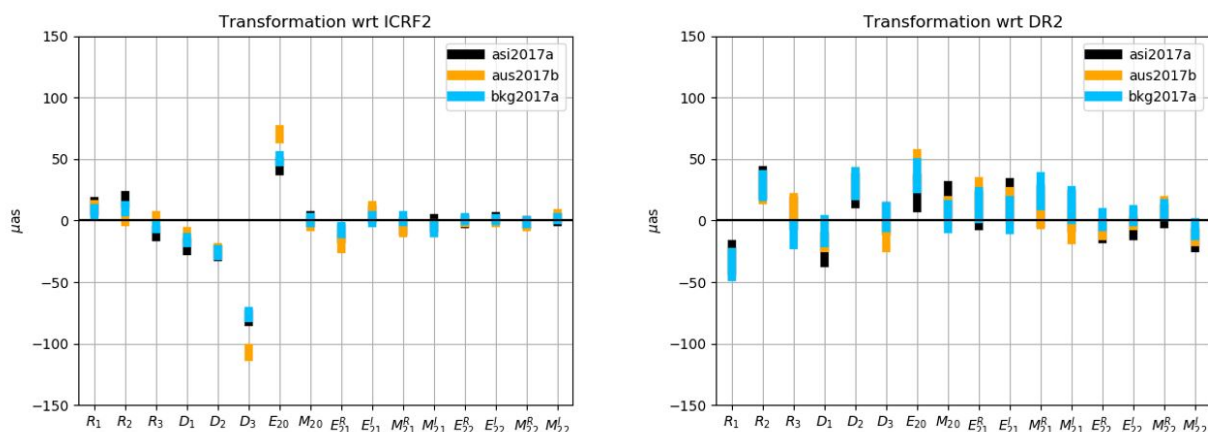


Fig. 4: Transformation parameters between the catalogs and the references (ICRF2: left; Gaia DR2: right).

exhibit flicker or random walk noises. Preliminary computations show that if the coordinates of the targets studied in this paper were affected by a white-phase noise with a formal uncertainty of about 1 mas (due to astrophysical processes that are put in evidence by the magnitude variations of the sources), it would affect the precision of the link at the level of 50 μ as.

Construction of a robotic telescope

The SyRTE department of Paris Observatory plan to build a robotic telescope dedicated to the monitoring of QSO magnitudes. The first part of this project began in 2015 by the choice of a site with a good atmosphere, characterized by its seeing. Saint-Véran (alt. 3000m), in the French Alps, near the Italian border, was chosen to implement a site seeing monitoring campaign (<http://stveran.obspm.fr/index.php?page=statistiques>). It has been demonstrated in 2016 that the median value of the seeing is 1" (mode seeing is 0.7") which made this site a very good one, probably one of the best in Europe. In the second step of this project, the SyRTE laboratory proposed to robotize a test telescope (0.50m) already on site since 2015. This part of the project has been achieved in 2017. The first images are scheduled to be obtained by the test telescope at the beginning of 2018. During 2018 it is also planned to observe intranight magnitude variations of quasars suitable for the link between reference frames and to begin to start building the telescope's shelter.

Validation of the Gaia catalogue in the CU9

The Gaia mission goal is to create an extraordinarily precise three-dimensional map of about one billion stars throughout our Galaxy and beyond. The Gaia mission through its successive releases delivers an astronomical catalogue and data archive of unprecedented scope, accuracy and completeness. A large pan-European team of expert scientists and software developers known as DPAC (Data Processing and

Analysis Consortium) is responsible for the processing of Gaia's data with the final objective of producing the Gaia Catalogue. Coordinated by the DPAC Executive, the consortium is sub-divided into nine smaller, specialist units known as Coordination Units, or CUs, with each unit being assigned a unique set of data processing tasks.

Some members of the ICRS Centre belong to the CU9 / WP944 group, responsible for validation of Gaia Catalogue Data Release with the validation Test Report. The aim of these tests is to check that Gaia data is coherent compared to other known catalogues, so to accept or not them for publication. This year, we have written tests code and reports (VTS 060) to validate quasars included in Gaia Catalogue Data Release DR2. These tests include rotation, crossmatching and completeness of these sources compared with quasars from external catalogues as ICRF2, LQAC4, GIQC and SDSS DR12Q.

Here are some results of our VTS :

LQAC4GMAG crossmatched with GAIA DR2 (VTS_060_01):

```
Crossmatch radius:      1.0 arcsec
Crossmatched size and
percentage:             323 774 / 443 725 : 73%
Not found in Gaia:      127 238 / 443 725 : 29%
Multiple cross matches: 7 230 / 323 774 : 2 %
NonDuplicated Sources: 309 257/443 725 : 70%
NaN or 0 values in Gaia data need
for VTS: 0/323774 : 0.0%
```

Rotation between ICRF3 and GAIA DR2 (VTS_060_04) :

Rotation angles R1 R2 R3, Deformation D1 D2 D3,
with respective errors, in μ as

R1	R2	R3	D1	D2	D3
13.18	-7.94	0.23	62.42	-69.84	-147.31
σ R1	σ R2	σ R3	σ D1	σ D2	σ D3
26.92	25.79	23.98	25.73	24.51	25.71

Study of the quasars with the Gaia DR2

The Gaia Data Release 2 (GDR2) contains more than 550,000 quasars (Liao et al., 2018). This number comes from the cross matching to bona fide quasars repositories as allWISEagn (Assef et al., 2017) and the LQAC4 (Souchay et al., 2017), providing that the matched sources have zero proper motion and parallax as computed from Gaia sequence of measurements. And yet the direct comparison of the GDR2 to other, denser quasar repositories, as the Gaia Initial Quasar Catalog (Andrei et al., 2014) and the MilliQuas (Flesh, 2017), leaves out as many as 50% of that number (Liao et al., 2018b) or more, within the range of Gaia observable magnitudes. The discrepancy arguably arises because of morphological issues as optical jets and emitting blobs along the jets, or magnitude variability which can be associated to transient changes

of the photocenter or simply deterioration of its determination due to photon noise. As a result spurious proper motion or even parallax can turn up, and the quasar would not at principle be shorthanded as such.

Liu et al. (2018) investigate the systematic errors in the very long baseline interferometry (VLBI) positions of extragalactic sources (quasars) and the global differences between Gaia and VLBI catalogs, using the GDR1 positions as the reference and study the positional offsets of the second realization of the International Celestial Reference Frame (ICRF2). They select a sample of 1032 common sources among the catalogs and adopt two methods to represent the systematics: considering the differential orientation (offset) and declination bias; analyzing with the vector spherical harmonics (VSH) functions. They find that: the significant declination bias between Gaia DR1 and ICRF2 catalogs reported in previous studies is possibly attributed to the systematic errors of ICRF2 in the southern hemisphere. Declination-dependent systematics may exist in the VLBI positions and need further investigations in the future Gaia data release and the next generation of ICRF.

Also, there is great interest in building unbiased catalogues of quasars for a range of important astrophysical questions. These include understanding the quasar phenomenon itself and the growth and occurrence of supermassive black holes through cosmic time, the use of quasars as probes of intervening material and their role in re-ionisation of both hydrogen and helium, and for the UV background levels throughout the universe. Thus the more diverse are the ways to assert a quasar amid the Gaia data releases, the less biased is the approach to those astrophysical questions. Conversely, the most varied are the means employed for the analysis, the largest is the sureness on the answers and the best becomes the chance to spot interesting objects or spurious detections.

Andrei and colleagues (2018, submitted) used observational data to check the power of the Maximum Entropy Principle on finding the behavior of the luminosity function of quasars. They carry out statistical tests showing the evaluation of the results. Even from limited observational information, over the number of quasars with a certain magnitude, at a given redshift, they find the probability for all values of the luminosity in that redshift from the principle. In this work it is not assumed any form of the luminosity function of the quasars. The research concludes that the approach from the Maximum Entropy Principle can be used to make estimates outside observational limits. The method therefore is promising when applied on large scale over the Gaia quasars data releases, either to check the luminosity function itself and its extension beyond the Gaia range of magnitudes, as well as an auxiliary form to spot outliers.

Construction of the LQAC-4 catalogue

During the whole year 2017 we constructed the fourth release of the Large Quasar astrometric Catalogue. Since the previous release LQAC-3 (Souhay et al., 2015), a large number of quasars have been discovered, in particular those coming from the DR12Q release of the SDSS. Moreover, for cross-matched objects, we have taken advantage of the very accurate determinations of the quasars identified within the recent Gaia DR1 catalogue. Following the same procedure as in the three previous releases of the LQAC, we have compiled the large majority of all the quasars recorded so far. Our goal was to record their best coordinates and substantial information concerning their physical properties such as the redshift as well as multi-bands apparent and absolute magnitudes. Emphasis was given to the results of the cross-matches with the recent Gaia DR1 catalogue.

New quasars coming from the DR12Q release were cross-matched with the precedent LQAC-3 compilation with a 1" search radius, in order to add the objects without counterpart to the LQAC-4 compilation. A similar cross-match was done with Gaia DR1 to identify the known quasars detected by Gaia. Thus we could improve significantly the positioning of these objects, and in parallel we could study the astrometric performance of the individual catalogues of the LQAC-4 compilation. Finally, a new method was used to determine absolute magnitudes.

The LQAC-4 contains 443 725 objects. This is roughly 37.82% more than the number of objects recorded in the LQAC-3. Among them, 249 071 were found in common with the Gaia DR1, with a 1" search radius. That corresponds to 56.13% of the whole population in the compilation. The LQAC-4 delivers to the astronomical community a nearly complete catalogue of spectroscopically confirmed quasars (including a small proportion of compact AGNs), with the aim of giving their best equatorial coordinates with respect to the ICRF2 and with exhaustive additional information. For more than 50% of the sample, these coordinates come from the very recent Gaia DR1. The LQAC-4 catalog is only available at the CDS via anonymous ftp to <http://cdsarc.u-strasbg.fr>.

USNO IERS ICRS Center Activities During 2017

USNO concentrated on four primary areas of work in support of maintenance and improvement of the Celestial Reference Frame: (1) support to the International Celestial Reference Frame-3 (ICRF3) working group, (2) generating new proper motions based on USNO CCD Astrograph Catalog (UCAC) and Gaia Data Release 1 (DR1) data, (3) operation of the USNO Bright Star Astrometry Database (UBAD) program in the Northern and USNO Robotic Astrometric Telescope (URAT) in the Southern Hemisphere to collect bright star data, and (4) partnering in operations of the Very Long Baseline Array (VLBA).

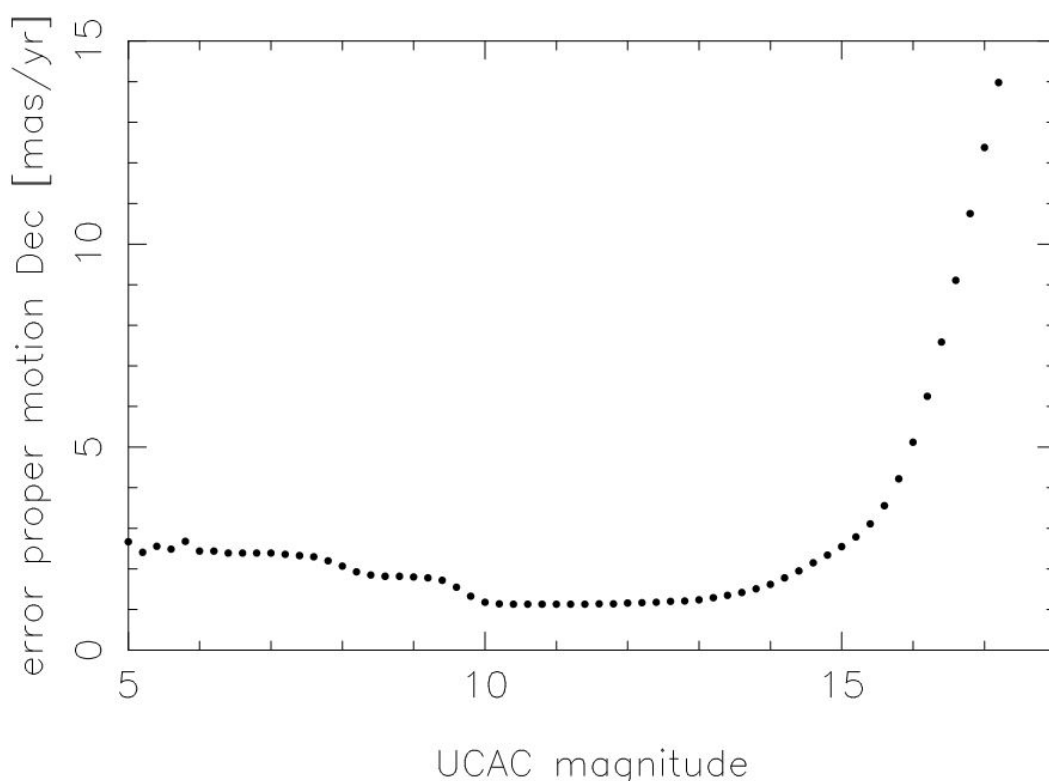


Fig. 5: Formal errors of proper motions of UCAC5 as a function of magnitude. Results are shown for declination, while results for RA are very similar.

ICRF3 USNO participated as a member of the IAU-sanctioned ICRF3 Working Group. Work included support for the execution and analysis of VLBA Calibrator Survey (VCS)-type Very Long Baseline Array (VLBA) S/X-band observing sessions under USNO's 50% timeshare agreement with the National Radio Astronomy Observatory and support for VLBA K-band and X/Ka band observations as candidates for inclusion in ICRF3. Work also included generation and analysis of numerous ICRF3 prototype global VLBI solutions for comparison with those generated by other ICRF3 Working Group members at different Very Long Baseline Interferometry (VLBI) analysis centers. The USNO continues to host the Radio Reference Frame Image Database (RRFID), a Web accessible database of radio frequency images of ICRF sources, at <http://rorf.usno.navy.mil/rrfid.shtml>.

UCAC5: New Proper Motions

The Gaia DR1 contains full astrometric parameters (including proper motions and parallaxes) for only about 2 million of the Hipparcos-Tycho stars from the Tycho Gaia Astrometric Solution (TGAS). The remaining ~billion stars in DR1 have accurate positions at the mean Gaia epoch (2015.0) but no proper motions. As shown in Figure 5, these position data were combined with a new reduction of the UCAC observations (all sky) with mean epoch of between 1997 and 2003 to derive new,

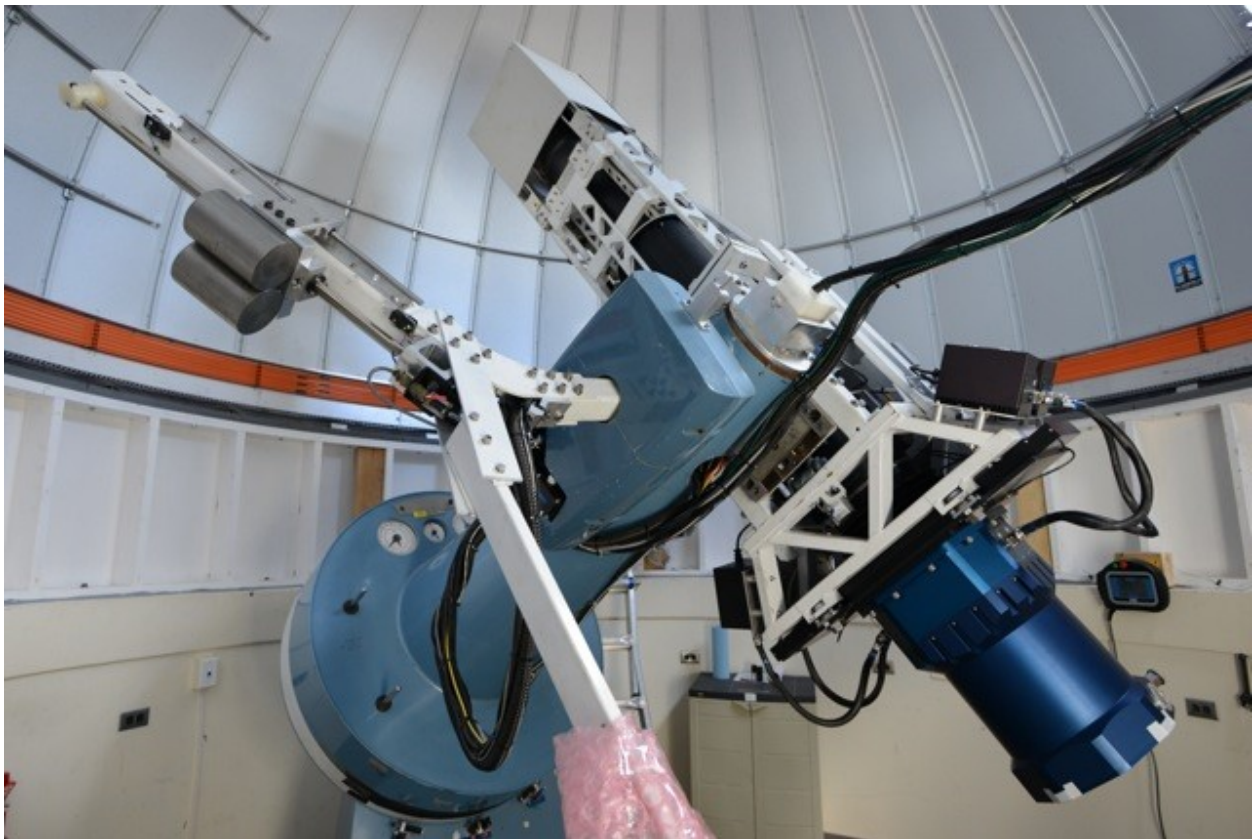


Fig. 6: *USNO Robotic Astrometric Telescope (URAT) deployed to and operating at Cerro Tololo Interamerican Observatory (CTIO) during 2017. URAT is being operating with both a full aperture grating and a neutral density spot that allows it to observe all the brightest stars in the Southern Hemisphere, up to a declination of $\sim +25^\circ$*

accurate proper motions of about 107 million stars with typical errors in the 1 to 2 mas/yr range for $R = 10$ to 15 mag, and about 5 mas/yr at $R = 16$, the limiting magnitude of the UCAC data (Zacharias, Finch & Frouard, 2017). External comparisons for selected open clusters show an improvement over currently best proper motion data in this magnitude range. The data were made public as catalog I/340 on the VizieR system at the CDS, Strasbourg and its mirror sites.

Compared to UCAC data, the TGAS data is nearly error (specifically, random and systematic) free, and was used as reference star catalog in the UCAC5 reductions. This allowed for an external error estimate of the UCAC x, y data (image centers). The UCAC data error floor thus was shown to be better than 1/100 pixel for well exposed stars.

The slight increase in errors for stars brighter than about magnitude 10 shown in the figure is due to the fact that UCAC long exposures saturate and results for those bright stars are drawn only from the short exposures. Between about magnitude 10 and 14.5 both long and short exposures contribute to the derived proper motions.

**URAT Southern Hemisphere
Bright Star Survey**

While the core of optical astrometric data for the next few decades is expected to come from the Gaia data, there are limitations with Gaia. Specifically, the Gaia focal plane physically saturates at $G=12$ under normal observing conditions. The Gaia focal plane includes “bright star modes” that allow it to get up to $G \sim 5-6$ before these modes are saturated. The Gaia DR1 results show large levels of “astrometric noise” for sources brighter than about $G=6$. The Gaia data processing team is looking at approaches to extending the Gaia results to the brightest stars in the sky, but there is currently no clear method for delivering high accuracy results for the brightest stars in the sky.

In order to address this gap in the optical reference frame, USNO has been operating the UBAD survey on its 61” (1.55 m) Strand astrometric telescope located at Flagstaff Station in Arizona for the Northern Hemisphere, and deployed the URAT 8” telescope to Cerro Tololo Inter-American Observatory (CTIO) in October 2015 (see Figure 6). URAT was modified from its Northern Hemisphere configuration by adding an ND +4.5 spot to one of the detectors, and operating in aperture grating mode (another 4.5 magnitudes of attenuation) for the entire year. Both systems (UBAD and URAT configured for bright stars) are able to observe the brightest stars in the sky (on the bright end), and Gaia stars on the faint end. During data processing and reduction, Gaia results will be used for the reference frame against which the UBAD and URAT data are located with high accuracy. In 2017 URAT observed during 293 nights. About 25 nights were lost due to a hardware issue. During 2017 a total of 64,914 exposures were taken by URAT, each about 0.9 GB (445 million pixels) in size.

It is anticipated that the bright star work will conclude in 2018 in time to supplement the Gaia DR2 catalog. At that point, an assessment will be made as to the availability of quality of the Gaia bright star data (and thus, the necessity for USNO to continue to observe and process bright stars for astrometry and photometry).

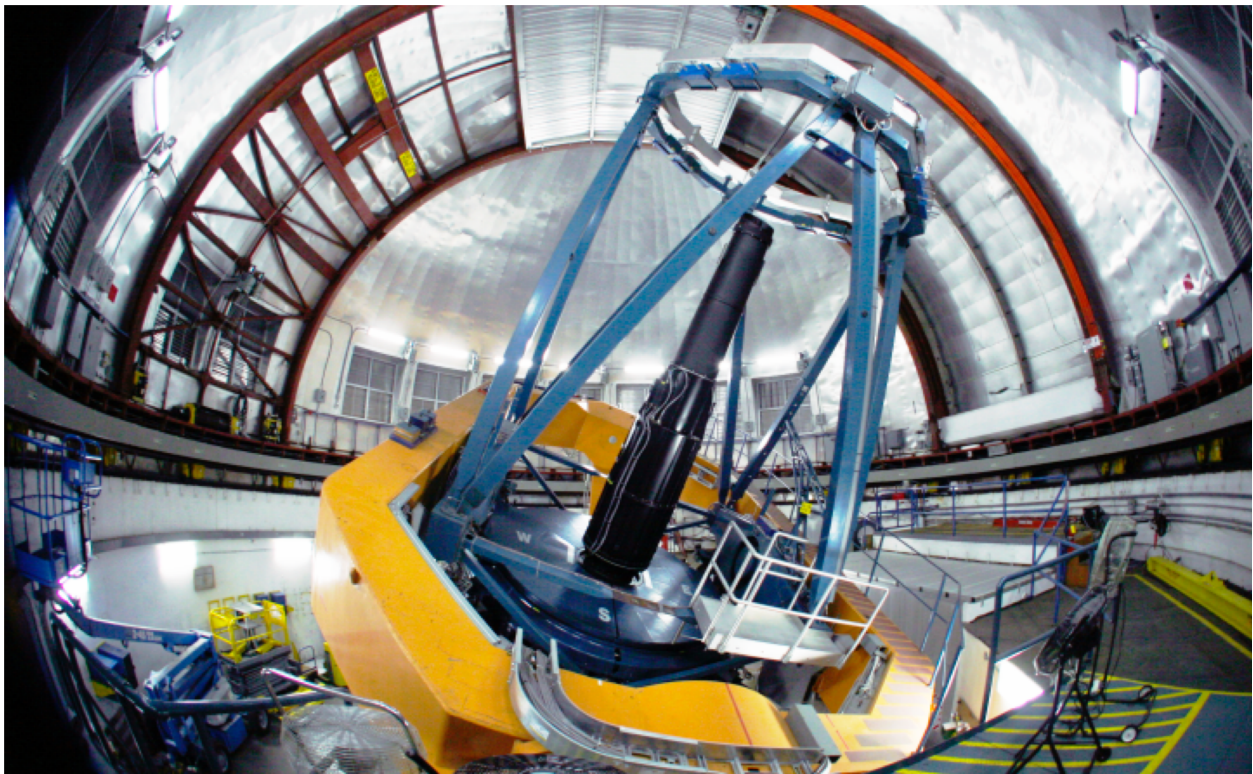


Fig. 7: An image of the 3.8m UKIRT with WFCAM installed at the forward Cassegrain focus. UKIRT, with WFCAM installed, is optimal for large area infrared surveys, yielding an impressive entendue of $\sim 2.4\text{m}^2\text{deg}^2$

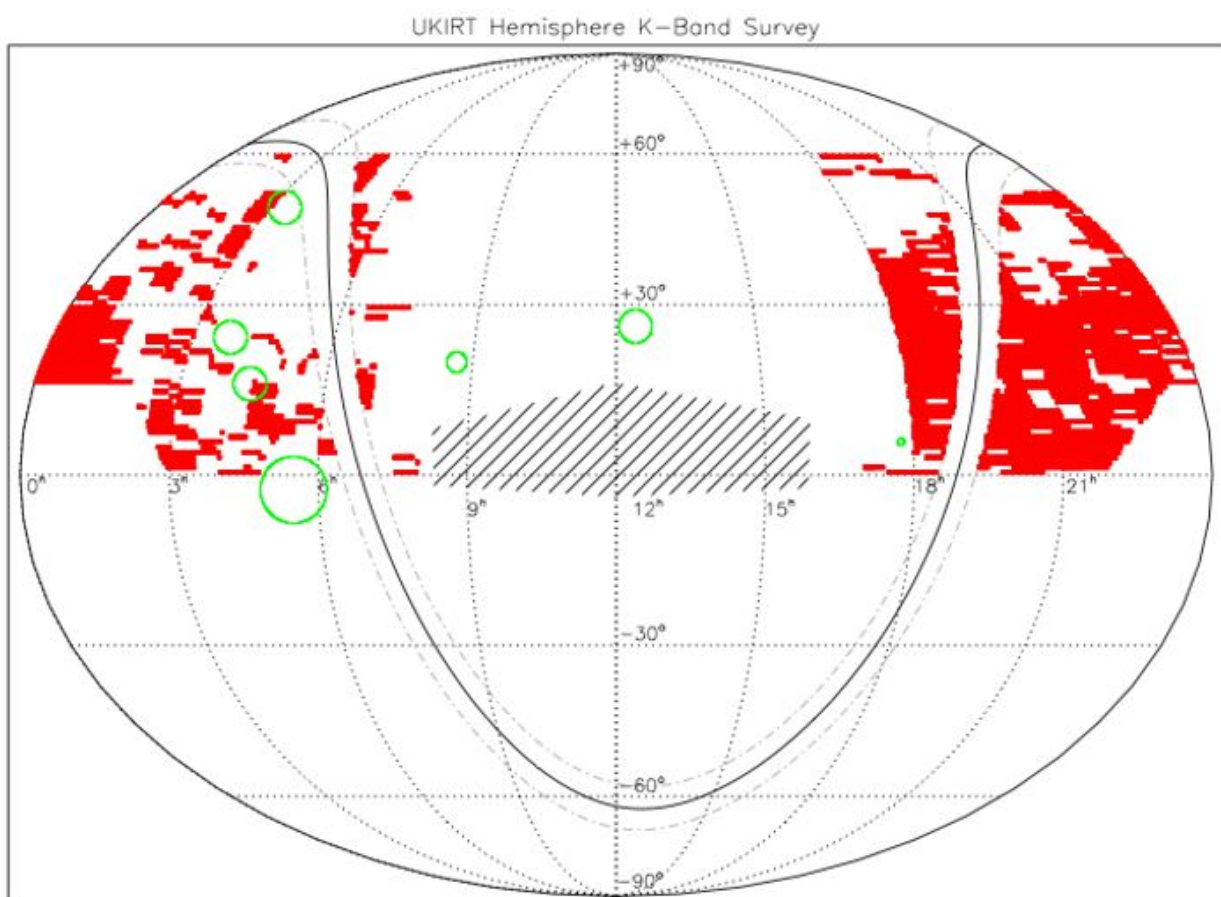


Fig. 8: UKIRT K-band survey coverage through November 2017.

USNO UKIRT K-Band Hemispherical Survey

USNO, in collaboration with the Institute for Astronomy at the University of Hawaii; the School of Physics and Astronomy, Nottingham University; Institute of Astronomy, University of Cambridge; and the Institute for Astronomy, University of Edinburgh, began a multi-year, northern hemisphere K-band survey using the UKIRT telescope, located in Hawaii on the summit of Mauna Kea (see Figure 7). When completed in the 2019/2020 timeframe, this K-band survey will provide a catalog down to below 18th magnitude that complements the VISTA Hemisphere Survey in the southern hemisphere (McMahon, 2013). When combined with the H-band UKIRT survey (Dye, 2018), the K-band data will provide deep photometric and astrometric data for two of the three standard Near IR (NIR) astronomical photometry bands. Figure 8 shows the progress of the survey through November 2017. When incorporating K-band data from earlier, directed surveys, approximately 30% of the northern sky had been completed through the end of 2017.

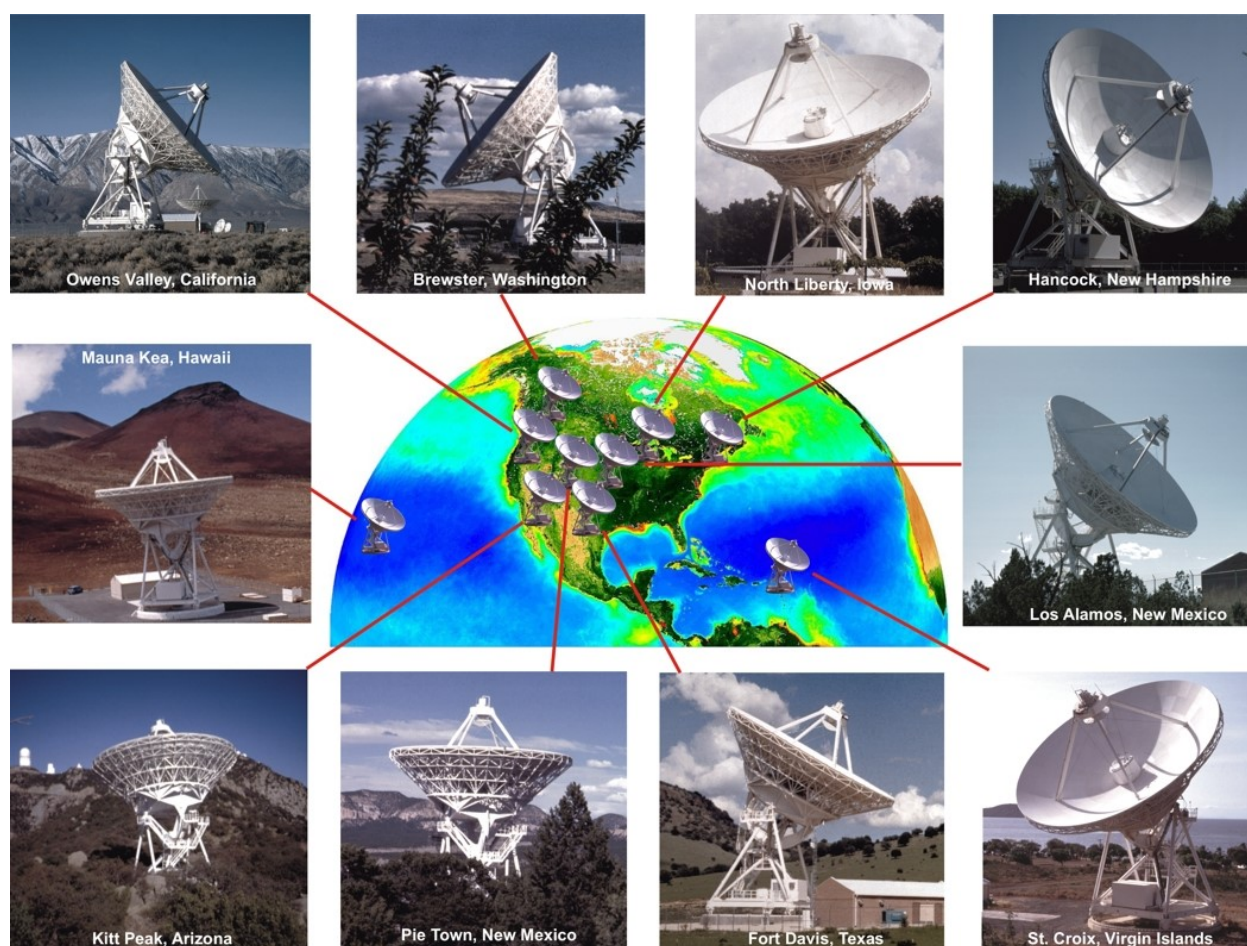


Fig. 9: The Very Long Baseline Array (VLBA) sites span the US from Hawaii in the west to the Virgin Islands in the East.

USNO 50% timeshare of the Very Long Baseline Array (VLBA)

Beginning in 2017, USNO provided funding for and was allocated 50% of the observing time on the Very Long Baseline Array (VLBA) (see Figure 9). The VLBA is an array of ten homogenous 25 m radio telescopes deployed across the United States from Hawaii in the west, to the Virgin Islands in the east, that are operated as an interferometric array. VLBA is operated by the Long Baseline Observatory (LBO) under cooperative agreement with the National Science Foundation (NSF). Working directly with LBO personnel, USNO provided monthly scheduling requests for VLBA time to support a wide variety of USNO mission and research areas. These included geodesy, Earth orientation parameter and celestial reference frame observations and measurements. Specifically, over the course of the year, USNO allocated significant S/X observing and K-band observing time to support development of the ICRF3, and also supported CONT17, an intensive geodesy observing campaign involving numerous radio telescopes around the world. It is expected that VLBA observing time scheduled via USNO will enable significant enhancements to the accuracy, the anticipated multi-wavelength nature, and the total number of sources for the ICRF3 when released in 2018.

References

- Andrei, A.H., Antón, S., Taris, F., Bourda, G., Souchay, J., Bouquillon, J., et al., 2014, The Gaia Initial Quasar Catalog, Proc. of the Journées 2013: “Systèmes de référence spatio-temporels”, Obs. de Paris, Nicole Capitaine (ed.), p. 84–87
- Andrei, A.H., Coelho, B., Guedes, L., Lyra, A., 2018, The Principle of Maximum Entropy and the Luminosity Function of Quasars, Monthly Notices of the Royal Astronomical Society, submitted
- Assef, R.J., Stern, D., Noirot, G., Jun, H.D., Cutri, R.M., Eisenhardt, P.R.M., 2018, The WISE AGN catalog, ApJS, 234:23
- Brown, A.G.A., Vallenari, A., Prusti, T., et al., 2016, Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties. Astronomy & Astrophysics, 595:A2
- Brown, A.G.A., Vallenari, A., Prusti, T., et al., 2018, Gaia Data Release 2. Summary of the contents and survey properties. Astronomy & Astrophysics, 616:A1
- Charlot, P., Jacobs, C.S., Gordon, D., Lambert, S.B. et al., 2018, The third realization of the International Celestial Reference Frame by very long baseline interferometry. Astronomy & Astrophysics, (in preparation)
- Dye, S., Lawrence, A., Read, M.A., et al., 2018, The UKIRT Hemisphere Survey: definition and J-band data release, Monthly Notices of the Royal Astronomical Society, 473:5113.

- Fey, A.L., Gordon, D., Jacobs, C.S., et al., 2015, The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry. *Astronomical Journal*, 150:58
- Flesch, E. W., 2017, CDS VizieR yCat.7280
- Gattano, C., Andrei, A. H., Coelho, B., Souchay, J., Barache, C., Taris, F., 2018, LQAC-4: Fourth release of the Large Quasar Astrometric Catalogue. Compilation of 443 725 objects including cross-identifications with Gaia DR1, *Astronomy & Astrophysics*, 614:A140
- Kovalevsky J., 2003, Aberration in proper motions. *Astronomy & Astrophysics*, 404:743–747
- Lambert, S.B., 2013, Time stability of the ICRF2 axes. *Astronomy & Astrophysics*, 553:A122,
- Liao, S., Bucciarelli, B., Qi, Z., Guo, S., Cao, Z., Tang, Z., 2018, eprint arXiv:1805.02194
- Liao, S., Qi, Z., et al., 2018b, arXiv180408821
- Liu, N., Zhu, Z., Liu, J.-C., 2018, Possible systematics in the VLBI catalogs as seen from Gaia, *Astronomy & Astrophysics*, 609:A19
- Ma, C., Clark, T.A., Ryan, J.W., et al., 1986, Radio-source positions from VLBI. *Astronomical Journal*, 92:1020–1029
- McMahon, R.G., Banerji, M., Gonzalez, E., et al., 2013, First Scientific Results from the VISTA Hemisphere Survey (VHS), *The Messenger*, 154:35
- Mignard, F. and Klioner, S., 2012, Analysis of astrometric catalogues with vector spherical harmonics. *Astronomy & Astrophysics*, 547:A59
- Mignard, F., Klioner, S., Lindegren, L., et al., 2016, Gaia Data Release 1. Reference frame and optical properties of ICRF sources. *Astronomy & Astrophysics*, 595:A5
- Mignard, F., Klioner, S., Lindegren, L., et al., 2018, Gaia Data Release 2. The celestial reference frame (Gaia-CRF2). *Astronomy & Astrophysics*, 616:A14
- Prusti, T., de Bruijne, J.H., Brown, A.G.A, et al., 2016, The Gaia mission. *Astronomy & Astrophysics*, 595:A1
- Souchay, J., Andrei, A.H., Barache, C., et al., 2015, The third release of the Large Quasar Astrometric Catalog (LQAC-3): a compilation of 321 957 objects, *Astronomy & Astrophysics*, 583:A75
- Titov, O., Tesmer, V., and J. Boehm, 2004, OCCAM v.6.0 Software for VLBI Data Analysis. In N. R. Vandenberg and K. D. Baver, editors, *International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings*, p. 267
- Titov, O., Lambert, S.B., and Gontier, A.M., 2011, VLBI measurement of the secular aberration drift. *Astronomy & Astrophysics*, 529:A91

Zacharias, N., Finch, C., Frouard, J., 2017, UCAC5: New Proper Motions Using Gaia DR1, AJ, 153:166

Zacharias, N., Finch, C., Frouard, J., 2017, VizieR Online Data Catalog I/340: UCAC5

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3.5.5 ITRS Centre

This report summarizes the activities of the IERS ITRS Centre during the year 2017.

IGS Workshop 2017

The ITRS Centre hosted the IGS Workshop 2017 in Paris, during the week July 3–7, 2017. 275 participants from 32 countries attend the workshop. All the details are available at: <http://igsworkshop2017.ign.fr/>

Unified Analysis Workshop 2017

The ITRS Centre has also hosted the Unified Analysis Workshop 2017 in Paris, during July 10–12, 2017. 42 participants attended, representing the 4 Technique Centres and the IERS. The main focus of the UAW was to discuss technique systematic errors, their handling and impact on the geodetic products and in particular the IERS combined products.

IERS Technical Note 39 on IGN best practice for surveying instrument reference points at ITRF co-location sites

The IERS ITRS Centre has published a specific Technical Note on the IGN best practice for surveying instrument reference points at ITRF co-location sites. The document aims at summarizing the IGN best practice to perform local tie survey measurements and to process and archive associated data and results. Indeed, IGN surveyors have been involved in local tie measurements at many multi-technique co-location sites during the last two decades. In charge of performing local tie surveys at DORIS stations since the nineties, IGN benefited from NASA experience thanks to joint surveys at Hartebeesthoek and Sheshan in 2003. Since that time, nine other specific surveys involving more than 3 different technique instruments have been carried out in addition to other DORIS/GNSS co-located sites. This document was initially written for IGN internal use but has been reorganized to be available to any person or group who wish to learn from IGN experience in surveying multi-technique sites.

Maintenance of the IERS network

The ITRS Centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments.

The IERS network database, which contains the descriptions of the sites and points, is continuously updated as DOMES numbers are assigned. DOMES number request form can be found on the ITRF web site <http://itrf.ign.fr>, and should be sent to domes@ign.fr. An updated list of all available DOMES number is available at http://itrf.ign.fr/doc_ITRF/iers_sta_list.txt. The IERS site information is available to the users through the ITRF website interface (see below).

Several new stations, mainly GNSS permanent stations were added to the ITRF network and database.

ITRF web site

The ITRF web site, available at <http://itrf.ign.fr>, provides an interface to consult the IERS network database. Site and point information can be requested on line; it contains approximate coordinates of the sites, the list of their points as well as their descriptions, their DOMES numbers and the list of ITRF versions in which they have been computed. Subsets of points can be selected and their ITRF coordinates can be requested at any epoch in any ITRF version if their coordinates are provided in the requested ITRF version.

The maps of the ITRF networks can be displayed depending of the measurement techniques and of the ITRF realization. Velocity vectors can be displayed as well as tectonic plates. The dynamical map can help users to familiarize with ITRF products and can be used for educational purpose. It can also be an interesting tool to select IERS sub-network depending on the measurement techniques, co-located hosted instruments or ITRF versions. ITRF94, ITRF96, ITRF97, ITRF2000, ITRF2005, ITRF2008 and ITRF2014 solutions are available for download.

Preparation for a new ITRF web site

The ITRS Centre has started an initial study analysis and preparation for a new design of the ITRF web site. It will be designed to provide more ITRF-related information to the users using more user-friendly interfaces. The new web site which was expected to be operational beginning 2016 experienced some delay, unfortunately, and will hopefully be available by the end of 2018, beginning 2019.

Local ties of ITRF co-location sites

The ITRS Centre collects all new surveys operated by either IGN or the hosting agencies of ITRF co-location sites. The reports of these surveys are posted at the ITRF web site and are available to users at http://itrf.ign.fr/local_surveys.php. The local ties SINEX files used in the ITRF combinations are also available on that web site.

At the occasion of the ITRF2014 analysis, several new local tie SINEX files and corresponding reports were submitted to the ITRS Centre. All past and new local surveys used in the ITRF2014 computation are now available via the ITRF web site: http://itrf.ign.fr/local_surveys.php.

The operational entity of the ITRS Centre at the IGN Survey department prepared a document describing the IGN current practice of local survey that could help surveyors who do not know how to proceed and are not used with mm precision. The document was published in 2017 in a dedicated IERS Technical Note (see above).

Other activities

- Participation in most meetings of the analysis working groups of the Technique Centres (in 2017: IDS, IGS, ILRS and IVS);
- Convening and organizing EGU and AGU sessions on reference frames and ITRF;
- Participation in the UN-GGIM related meetings, and contribution to the implementation plan of the Roadmap on the Global Geodetic Reference Frame for Sustainable Development, following the UN GA resolution adopted February 26, 2015.

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3.5.6 Global Geophysical Fluids Centre

The Global Geophysical Fluid Center (GGFC) <http://loading.u-strasbg.fr/GGFC> of the International Earth Rotation and Reference Systems Service (IERS) provides the community with models of geodetic effects (Earth rotation, gravity and deformation) due to the temporal redistribution of the Earth geophysical fluids. These include fluid motions within the solid Earth (core and mantle) as well as motions at the Earth's surface (ocean, atmosphere and continental hydrology). The GGFC is composed of four operational entities: the Special Bureau for the Atmosphere (SBA, chair: D. Salstein), the Special Bureau for the Oceans (SBO, chair: R. Gross), the Special Bureau for Hydrology (SBH, chair: J.-L. Chen) and the Special Bureau for the Combination Products (SBCP, chair: T. van Dam). The Atmosphere, Hydrology and Ocean SBs have been firmly established since the creation of the GGFC in 1998. The operational Combination Products SB was established in 2009 to host new datasets that model the mass movement of combined environmental fluids such as atmosphere + ocean. There is finally a non-operational component of the GGFC, the GGFC Science and Support Products, serving as a repository for models and data used regularly in data processing, but that do not change often. The GGFC is still actively searching for a chair for this component. Since 2016, J.-P. Boy acts as the chair of GGFC, with T. van Dam as a co-chair.

Special Bureau for the Atmosphere

The Special Bureau for the Atmosphere (SBA) is concerned with the atmospheric information that is needed for a number of geodetic issues. The SBA was an outgrowth of the earlier Sub-bureau for Atmospheric Angular Momentum prior to the creation of the GGFC, and can be accessed at <http://www.aer.com/science-research/earth/earth-mass-and-rotation/special-bureau-atmosphere>.

Calculations of atmospheric angular momentum (AAM) are made from a number of global meteorological operational analyses and re-analyses, and are archived at the SBA. Long-term archives are at Atmospheric and Environmental Research in the file <http://files.aer.com/aerweb/AAM/>. It should be noted that these have different file names from previous versions, because the host institution changed from an ftp to a different server.

AAM from analyses and forecasts are updated daily at NOAA on <http://ftp.cpc.ncep.noaa.gov/long/aam/>. On-line readme files on these two sites are useful in documenting the data sets.

Operational atmospheric analyses are fields determined from observations during the epoch they are valid from the resident atmospheric analysis system in use at that time. Thus the systems, the main components of which are atmospheric forecast models and data assimilation

systems, have changed over the years. In contrast, atmospheric reanalysis systems use a constant analysis system to reprocess the historical atmospheric observational data. Thus the earlier periods are analyzed with a more advanced system than existed during their era, and the whole record of reanalysis is more suitable for long-term studies. The reanalyses were developed for consistent climate studies, and we use them here for long-term geodetic studies.

The AAM and related data are from the following large meteorological centers: US National Centers for Environmental Prediction, NCEP (formerly known as the National Meteorological Center); the Japan Meteorological Agency, JMA; the United Kingdom Meteorological Office, UKMO; and the European Center for Medium-Range Weather Forecasts (ECMWF). The ECMWF AAM is not updated daily in the on-line service but rather by links by our contributors, as noted below.

The SBA has on-line links from a number of contributors listed on the website; these include a number of atmospheric data related to surface loading, path delays, and gravity. The specialized ECMWF fields are accessed this way. Cooperating institutions are: the GeoForschungsZentrum, Potsdam, Germany; Vienna University of Technology, Austria; University of Luxembourg, Goddard Space Flight Center, University of Strasbourg, France, and the University of New Brunswick, Canada.

During 2017, the SBA updated fields from AAM; the updates were performed by Dr. Y. Zhou of the Shanghai Astronomical Observatory, China. Additional updates for the full 2017 datasets and on into 2018 are planned.

Special Bureau for the Ocean

The oceans have a major impact on global geophysical processes of the Earth. Nontidal changes in oceanic currents and ocean-bottom pressure are a major source of polar motion excitation and also measurably change the length of the day. The changing mass distribution of the oceans causes the Earth's gravitational field to change and causes the center-of-mass of the oceans to change which in turn causes the center-of-mass of the solid Earth to change. The changing mass distribution of the oceans also changes the load on the oceanic crust, thereby affecting both the vertical and horizontal position of observing stations located near the oceans. As part of the IERS Global Geophysical Fluids Center, the Special Bureau for the Oceans (SBO) is responsible for collecting, calculating, analyzing, archiving, and distributing data relating to nontidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocenter. The oceanic products available through the SBO website at <https://euler.jpl.nasa.gov/sbo> are produced primarily by general circulation models of the oceans that are operated by participating modeling groups and include oceanic angular momentum, center-of-mass, and bottom pressure. Through the

SBO website, oceanic data can be downloaded and a bibliography of publications pertaining to the effect of the oceans on the solid Earth can be obtained. Additional information about the SBO can be found in an unpublished manuscript available through the SBO Publications website at https://euler.jpl.nasa.gov/sbo/sbo_publications.html and in the SBO chapter of IERS Technical Note 30, Proceedings of the IERS Workshop on Combination Research and Global Geophysical Fluids.

During 2017, the SBO website was maintained and products from the ECCO/JPL ocean model were updated. Daily values of oceanic angular momentum, oceanic excitation functions, and oceanic center-of-mass from the kf079 (simulation) and kf080h (data assimilating) runs of the ECCO/JPL ocean model are now available from 02 January 1993 through 30 January 2018. These values can be extended back to 06 January 1949 using the corresponding values from a 50-year-long simulation run of the ECCO/JPL ocean model whose results are also available through the SBO website.

In addition, a link is provided to the ECCO/JPL website at <https://ecco.jpl.nasa.gov> from which grids of modeled ocean-bottom pressure can be obtained, a link is provided to the GGFC website at <http://geophy.uni.lu/ggfc-oceans/ECMWF-loading.html> from which grids of ocean loading determined from the ECCO/JPL modeled ocean-bottom pressure can be obtained, and a link is provided to the GLObal Undersea Pressure (GLOUP) data bank of ocean-bottom pressure observations at <http://www.ntsif.org/files/acclaimdata/gloup/gloup.html>. Finally, a link is provided to the GFZ Helmholtz Centre Potsdam's Effective Angular Momentum Functions (EAM) website at <https://isdc.gfz-potsdam.de/esmdata/eam> from which consistent estimates of atmospheric, oceanic, and hydrologic angular momentum can be obtained.

In addition to these data sets, a subroutine to compute oceanic angular momentum, center-of-mass, and bottom pressure from the output of general circulation models can be downloaded from the SBO website along with a bibliography of related articles.

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

Special Bureau for Hydrology

The Special Bureau for Hydrology (<http://www.csr.utexas.edu/research/ggfc/>) provides access to data sets of terrestrial water storage (TWS) variations from major climate and land surface models and GRACE (Gravity Recovery and Climate Experiment) satellite gravity measurements. The web site contains TWS estimates from five numerical models, the NCEP (National Center for Environmental Prediction) reanalysis, the ECMWF (European Center for Medium Range Weather Forecasting) reanalysis, the CPC (Climate Prediction Center) Land Data Assimilation System (LDAS), the NASA's Global Land Data Assimilation System (GLDAS), and the NOAA LandWorld land dynamics model. Global gridded TWS changes estimated from GRACE time-variable gravity observations are also provided in our online data archive (at <http://www2.csr.utexas.edu/research/ggfc/dataresources.html>). The NASA GLDAS and GRACE data products are updated on a regular basis.

SBH also provides fully normalized gravity spherical harmonic coefficients (in the same definition as the GRACE products) up to degree and order 100, computed from the GLDAS-estimated TWS changes. This product offers the convenience for hydrologists who want to compare GRACE estimates and model predictions in a more consistent way by applying similar truncation and spatial filterings to both GRACE and model estimates. This data set is highly welcomed by the hydrological community.

In addition, TWS change estimates from historical GRACE release-01 and release-04 products are also provided in our online data archive (at <http://www2.csr.utexas.edu/research/ggfc/dataresources.html>). Some other data sets available in the SBH online data archive include daily hydrological excitations of polar motion and length-of-day computed from the NCEP/NCAR Reanalysis and the list of global major artificial reservoirs and their capacities. We have updated the monthly GLDAS TWS estimates to extend the coverage from January 2002 to December 2016. GLDAS gravity spherical harmonic coefficients have also been updated to cover the period January 2002 to December 2016. GRACE release-05 monthly TWS estimates with decorrelation and 300 km and 500 km Gaussian smoothing applied have been updated to extend the coverage to June 2017.

Combinational Products

A complete list of the available combination products is provided below:

- UNB Vienna Mapping Function Service (<http://unb-vmf1.gge.unb.ca/Products.html>), M. Santos, University of New Brunswick, Canada.

- AAM analysis (and forecast) series from various atmospheric models (<http://files.aer.com/aerweb/AAM/>), D. Salstein, Atmospheric and Environmental Research, USA.
- Vienna Mapping Function Service, AAM analysis, Atmospheric loading and time-variable gravity (<http://ggosatm.hg.tuwien.ac.at/index.html>), J. Boehm & M. Schindelegger, Technical University of Vienna, Austria.
- Time-variable gravity field and AM from various hydrology models and from GRACE (<http://www.csr.utexas.edu/research/ggfc/>), J.-L. Chen, University of Texas at Austin, USA.
- Atmospheric (<http://vlbi.gsfc.nasa.gov/services/aplo/>), non-tidal oceanic (http://vlbi.gsfc.nasa.gov/services/ocean_load/) and hydrological (http://vlbi.gsfc.nasa.gov/services/hydro_load/) loading, D. MacMillan, NASA Goddard Space Flight Center, USA.
- Atmospheric, oceanic and hydrological loading, AM and time-variable gravity (<http://isdg.gfz-potsdam.de/esmdata/>), H. Dobslaw & R. Dill, GFZ, Potsdam, Germany.
- Atmospheric, oceanic and hydrological loading (<http://geophy.uni.lu/>), T. van Dam, University of Luxembourg, Luxembourg.
- Atmospheric, oceanic and hydrological loading and time-variable loading (<http://loading.u-strasbg.fr>), J.-P. Boy, EOST/IPGS, University of Strasbourg, France.

*Jean-Paul Boy, Tonie van Dam, David Salstein,
Richard Gross, Jian-Li Chen*

3.6 ITRS Combination Centres

3.6.1 Deutsches Geodätisches Forschungsinstitut der TU München (DGFI-TUM)

In 2017, the ITRS Combination Centre at DGFI-TUM focuses on further comparisons of the three ITRS realizations, the ITRF2014 (IGN, France; Altamimi et al. 2016), the JTRF2014 (JPL, USA; Abbondanza et al. 2017) and the DTRF2014 (DGFI-TUM, Germany; Seitz et al. 2016). This report comprises the three following topics: (1) SLR and VLBI scale investigations, (2) comparison of the three ITRS realizations by Precise Orbit Determination (POD) of SLR satellites, and (3) consistent realization of the terrestrial and celestial reference systems.

SLR and VLBI scale investigations

At DGFI-TUM, detailed investigations on the scale of the terrestrial reference frame which is realized by a weighted mean of SLR and VLBI observations have been performed. This was largely motivated by the fact that a scale bias of 1.37 ppb between SLR and VLBI has been found in the ITRF2014 solution (Altamimi et al., 2016) which is not visible in the DTRF2014 solution (Seitz et al., 2016). The results of the scale investigations were presented at the IAG-IASPEI 2017 Scientific Assembly in Kobe, Japan, and are published in the corresponding IAG-IASPEI Symposia Proceedings (Bloßfeld et al., 2018). A summary of the outcome of these investigations is given below.

As recommended by the IERS Directing Board, in a first step, the long-term single-technique SLR and VLBI solutions provided by DGFI-TUM and IGN were compared directly. It was found that no scale bias is visible in the SLR and VLBI intra-technique solutions of IGN and DGFI-TUM. The results of 14-parameter Helmert transformations between the IGN and DGFI solutions show a scale agreement within 0.2–0.3 ppb for the single-technique VLBI and SLR solutions. This indicates that the effects might be caused by the inter-technique combination. Furthermore, two different test scenarios were applied to compare the individual SLR and VLBI solutions of DGFI-TUM: (i) direct comparison by using the available co-location sites between both techniques, and (ii) an indirect comparison of VLBI and SLR via GNSS co-locations. The results of these tests confirmed that the DTRF2014 does not show a significant bias between the SLR and VLBI scale (see Bloßfeld et al. 2018 for more details).

To further investigate the scale bias between VLBI and SLR, the three ITRS realizations were compared with the combined VLBI and SLR solutions obtained by the Combination Centres (CC) of the IVS and ILRS, respectively. Fig. 1 shows epoch-wise estimated scale parameters

of the IVS combined solutions (VLBI-only) w.r.t. several TRF realizations. It is clearly visible that the DTRF2008, the DTRF2014, the JTRF2014, and the quarterly VLBI-only TRF solution VTRF2015q2 agree quite well with the IVS combined solutions showing a mean value close to 0. The ITRF2008 as well as the ITRF2014 show a mean bias of about -0.5 ppb. Similar investigations have been performed for SLR by the primary ILRS CC located at ASI (Italy). Fig. 2 displays the epoch-wise estimated scale parameters of the combined ILRSA solutions w.r.t. the most recent ITRS realizations. Again, the DTRF2014 as well as the JTRF2014 do not show a long-term mean offset w.r.t. the SLR-only solutions, whereas the ITRF2014 shows a mean offset of about 0.7 ppb. Thus, the DTRF2014 and the JTRF2014 do not distort the scale of the VLBI and SLR subnets.

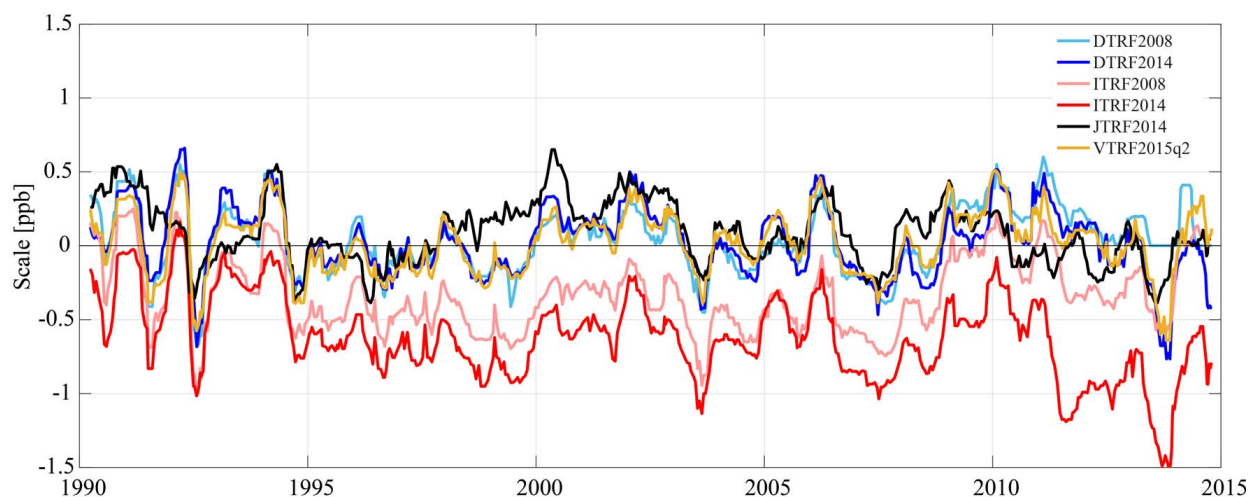


Fig. 1: Scale of the combined IVS solutions w.r.t. different TRF realizations. This plot has been kindly provided by S. Bachmann in July 2017 (IVS CC at BKG, Germany).

Comparison of ITRF2014, JTRF2014, DTRF2014, and SLRF2008 by POD of SLR satellites

The three ITRS realizations ITRF2014, DTRF2014 and JTRF2014 have been evaluated by using their station positions as apriori values within Precise Orbit Determination (POD) for SLR satellites. This study was based on POD of ten geodetic satellites at high (with an altitude more than 2000 km) and low (with an altitude below this value) Earth orbiting geodetic satellites in total over 24 years from 1993.0 to 2017.0 using SLR-only orbit determination (see Rudenko et al., 2018). In this report, we present as an example of this POD study some results for the SLR satellites Lageos-1 and Starlette (see Fig. 3). The results revealed almost the same accuracy level for the ITRF2014, JTRF2014 and DTRF2014, and all of them performed better than the previous realization for SLR, the SLRF2008. It was found from this analysis that the JTRF2014 (after an editing done for SLR stations Conception and Zimmerwald) and DTRF2014+NTL (with non-tidal loading corrections

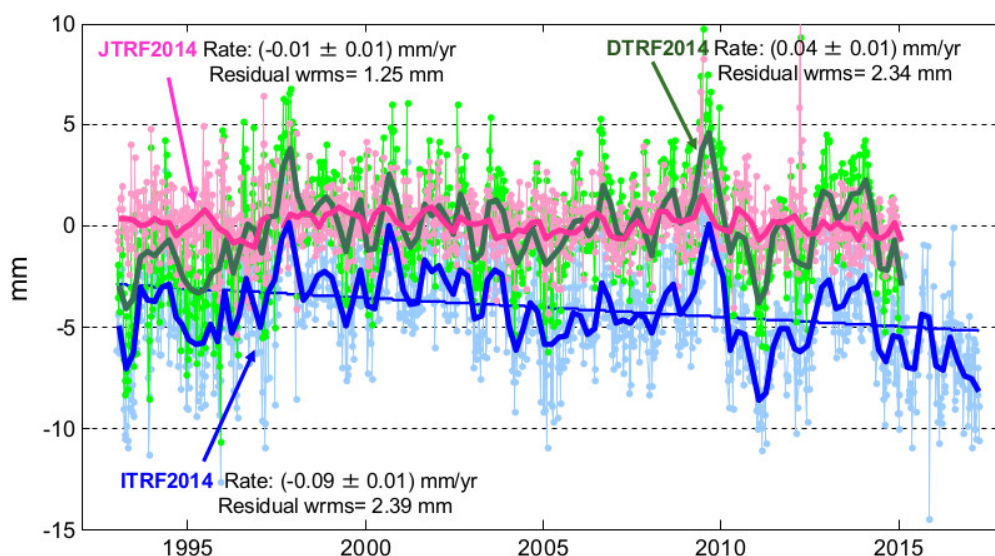


Fig. 2: Scale of the combined ILRSA solutions w.r.t. different TRF realizations. This plot has been kindly provided by C. Luceri in July 2017 (ILRS CC at ASI, Italy).

applied) showed the best performance, however, the differences between the ITRS realizations obtained from the POD studies are only at (or below) the mm-level. The SLRF2008 and ITRF2008 cause a 0.2 – 0.3 mm/y trend in the mean of SLR fits in the time span 2001.0 – 2017.0. Further details on these studies can be found in Rudenko et al. (2018).

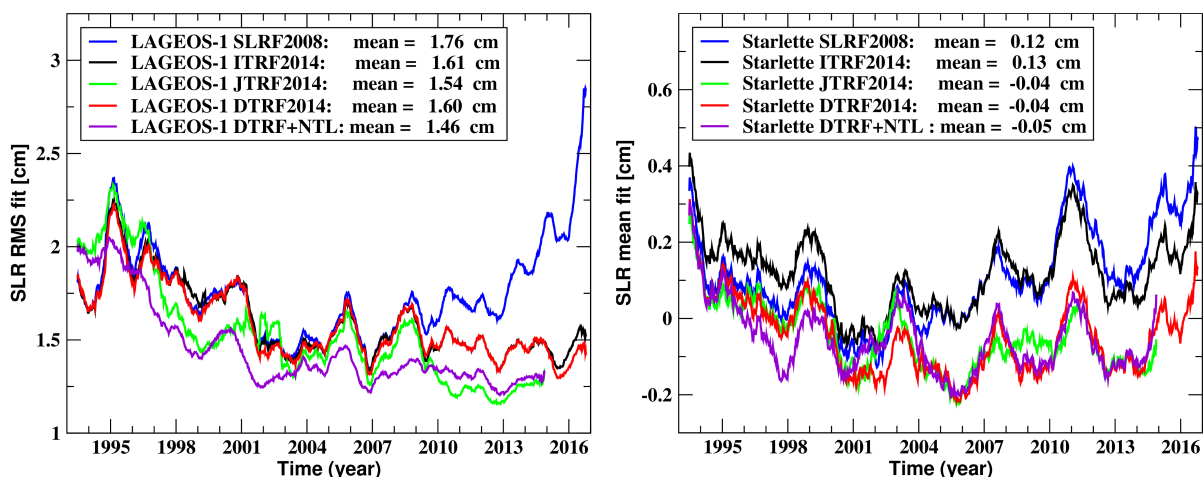


Fig. 3: (Left) 50-week running averages of the RMS fits of SLR observations (in cm) for LAGEOS-1 orbits derived using SLRF2008, ITRF2014, JTRF2014, DTRF2014 linear, and DTRF2014+NLT. (Right) 50-week running averages of the mean fits of SLR observations (in cm) for Starlette orbits derived using SLRF2008, ITRF2014, JTRF2014

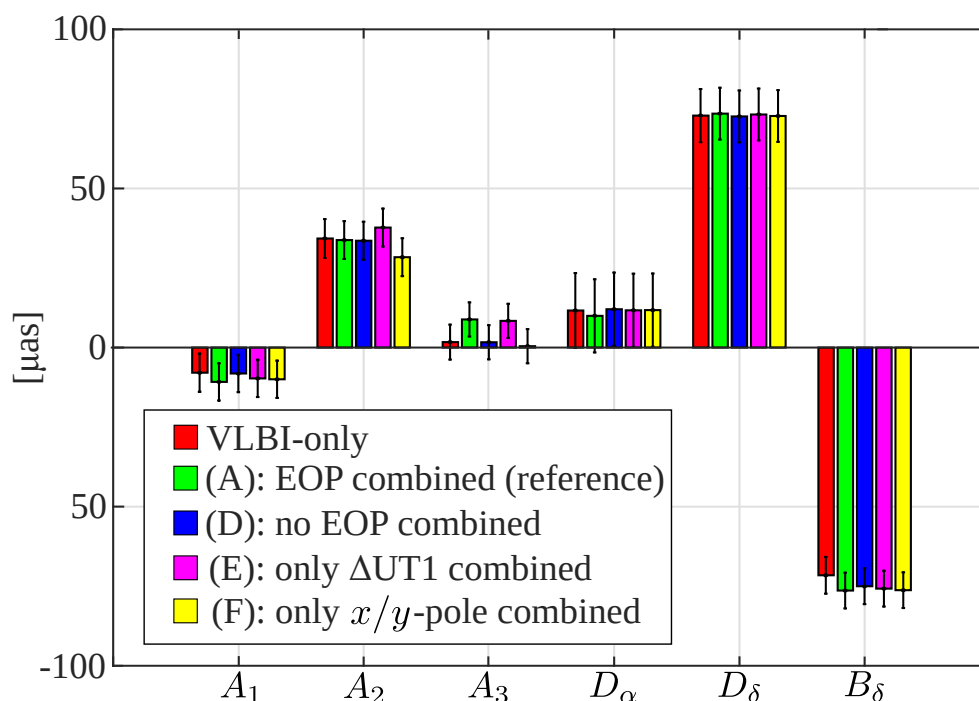


Fig. 4: CRF transformation parameters and their standard deviations (error bars) of VLBI-only and different EOP combination setups w.r.t. ICRF2. A_1 , A_2 and A_3 denote the rotations between two CRFs w.r.t. the three axes, D_α , D_δ represent the drifts of right ascension and declination, and B_δ means a bias in declination.

Consistent realization of the terrestrial and celestial reference systems

With the Resolution No. 3 of the International Union of Geodesy and Geophysics (IUGG) adopted by the General Assembly in 2011, the IUGG urged “that highest consistency between the ICRF, the ITRF, and the EOP as observed and realized by the IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS”. So far, the highest consistency could not be achieved, as three independent IERS product centers are in charge of computing the terrestrial and celestial reference frame as well as the EOP. At DGFI-TUM, various studies and test combinations have been performed to estimate all three components (CRF, TRF and EOP) in a common adjustment. In 2017, within the project “Consistent celestial and terrestrial reference frames by improved modelling and combination” as part of the DFG Research Unit FOR1503 “Space-time reference systems for monitoring global change and for precise navigation in space”, a simultaneous and consistent realization of TRF, CRF and EOP (Kwak et al., 2018) in accordance with the IUGG Resolution was obtained. The joint parameter estimation was based on homogeneously processed VLBI, GNSS, and SLR single-technique solutions for 11 years (2005.0–2016.0). Several types of combined solutions were computed following the selections of different local ties, EOP combination setups, and different weights of the techniques. The impacts of the different combination setups on

CRF, TRF, and EOP were investigated. The following conclusions were derived (more details are reported in Kwak et al., 2018):

- The combination of different space geodetic techniques improves the precision of the estimated parameters due to the larger number of observations.
- The CRF benefits from the precise terrestrial x/y-pole coordinates estimated by GNSS (Fig. 4).
- The combination of ΔUT1 from VLBI and the satellite techniques affects the right ascension and therefore the CRF z-rotation (Fig. 4).
- It became evident that the common determination of TRF, CRF and EOP systematically influences future CRF computations at the level of several μas .

References

- Abbondanza C., Chin T., Gross R., Heflin M., Parker J., Soja B., van Dam T., Wu X.: JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, *J. Geophys. Res. Solid Earth*, doi:10.1002/2017JB014360, 2017
- Altamimi, Z., P. Rebischung, L. Metivier, and C. Xavier: ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, *J. Geophys. Res. Solid Earth*, 121, doi:10.1002/2016JB013098, 2016
- Bloßfeld M., Angermann D., Seitz M.: DGFI-TUM analysis and scale investigations of the latest terrestrial reference frame realizations, *IAG-IASPEI Symposia Proceedings*, Springer, 2018
- Kwak Y., Bloßfeld M., Schmid R., Angermann D., Gerstl M., Seitz M.: Consistent realization of celestial and terrestrial reference frames. *J. Geod.*, doi:10.1007/s00190-018-1130-6, 2018
- Rudenko S., Bloßfeld M., Müller H., Dettmering D., Angermann D., Seitz M.: Evaluation of DTRF2014, ITRF2014 and JTRF2014 by Precise Orbit Determination of SLR Satellites. *IEEE T. Geosci. Remote*, 56(6), 3148–3158, doi:10.1109/TGRS.2018.2793358, 2018
- Seitz M., Bloßfeld M., Angermann D., Schmid R., Gerstl M., Seitz F.: The new DGFI-TUM realization of the ITRS: DTRF2014 (data). *Deutsches Geodätisches Forschungsinstitut, Munich*, doi:10.1594/PANGAEA.864046, 2016

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3.6.2 Institut National de l'Information Géographique et Forestière (IGN)

This report summarizes the activities of the ITRS Combination Centre at IGN during the year 2017.

Research and development activities

The members of the IGN CC, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF software. Scientific results of specific data analysis and combination are published in peer-reviewed journals, as listed in the references' section, but also presented at international scientific meetings.

IERS Technical Note 38 on ITRF2014

A dedicated IERS Technical Note (No. 38) on ITRF2014 analysis and results was published in 2017. It summarizes the analysis strategy, the combination model used, and all the products related to the ITRF2014. The technical note describes the main ITRF2014 products: station positions and velocities, the post fit residuals of the least squares adjustment as well as the transformation parameters between ITRF2014 and ITRF2008. The main technical procedure used to generate the ITRF2014, a thorough discussion of its quality as well as most important geodetic and geophysical results were published in this Technical Note.

Analysis and Publication of ITRF2014 Plate Motion Model

Using the horizontal velocity field of a subset of the ITRF2014 sites away from plate boundaries, Glacial Isostatic Adjustment regions and other deforming zones, an ITRF2014 Plate Motion Model was derived and published in *Geophysical Journal International* (Altamimi et al., 2017). Based on several geophysical and statistical criteria, the ITRF2014-PMM was adjusted to the velocity field of a network of 297 ITRF2014 sites and comprises rotation poles for eleven plates intended for geophysical and operational geodetic applications. Following strict criteria of site selection, satisfying the notion of rigid-plate motion hypothesis, at the level of (or better than) 0.3 mm yr^{-1} WRMS in average, the estimated PMM is fully consistent with the ITRF2014.

Publications

Altamimi, Z., L. Métivier, P. Rebischung, Hélène Rouby and X. Collilieux (2017), ITRF2014 plate motion model, *Geophys. J. Int.* 209, 1906–1912, doi: 10.1093/gji/ggx136.

Altamimi Z., P. Rebischung, and X. Collilieux (2017), The International Terrestrial Reference Frame: Lessons from ITRF2014, *Rend. Fis. Acc. Lincei*, doi:10.1007/s12210-017-0660-9

Bruni, S., P. Rebischung, S. Zerbini, Z. Altamimi, M. Errico, E. Santi (2017), Assessment of the possible contribution of space ties on-board GNSS satellites to the Terrestrial Reference Frame, Journal of Geodesy, doi:10.1007/s00190-017-1069-z

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3.6.3 Jet Propulsion Laboratory (JPL)

Introduction The Jet Propulsion Laboratory is continuing to develop an approach to determining ITRF-like terrestrial reference frames based upon the use of a Kalman filter/smoothers (Wu et al., 2015). Kalman filters are commonly used to estimate the parameters of some system when a stochastic model of the system is available and when the data contain noise. For the purpose of determining a terrestrial reference frame, the system consists of the positions and velocities of geodetic observing stations and associated EOPs along with their full covariance matrices. The data consist of time series of observed VLBI, SLR, GNSS, and DORIS station positions and EOPs along with the data measurement covariance matrices. In addition, measurements from ground surveys of the positions of reference marks of co-located stations are used to tie the technique-specific station networks to each other. The Kalman filter and smoother for reference frame determination software (KALREF) being developed at JPL combines these measurements to determine ITRF-like reference frames subject to constraints imposed on the allowed evolution of the station positions. KALREF includes options for constraining the stations to move linearly or to move linearly and seasonally. Through the use of stochastic models for the process noise, the station positions can be constrained to exactly follow this linear or linear and seasonal motion (by setting the process noise to zero), to exactly recover the observed station positions (by setting the process noise to a large value), or to follow a smoothed path (by setting the process noise to some intermediate value). The sequential estimation approach to determining terrestrial reference frames that is being developed at JPL has been used to determine JTRF2014, JPL's realization of a terrestrial reference frame using the ITRF2014 input data sets (Abbondanza et al., 2017).

During 2017, besides continuing to analyze the JTRF2014 solution, JPL also continued to both explore the possibility of accounting for regional deformation of the crust and mantle when determining TRFs and to develop a sequential estimation approach to jointly determine terrestrial and celestial reference frames (CRFs).

JTRF2014 The JTRF2014 reference frame is represented by time series of the smoothed positions of the 972 GNSS, VLBI, SLR, and DORIS stations that comprise the frame. JTRF2014's origin is located at the quasi-instantaneous center-of-mass of the Earth as determined from SLR observations and its scale is a weighted average of the quasi-instantaneous VLBI and SLR scales. In order to investigate the difference between the VLBI and SLR scales, a number of special solutions were determined using only VLBI and SLR data and in which the scale

was fixed to the VLBI scale. In these solutions, because of the sequential estimation approach taken at JPL, a time series of the Helmert parameters mapping the VLBI scale to SLR is obtained, allowing the time-variable structure of the scale difference between VLBI and SLR to be studied. In all, six special solutions were determined in which different models for the station motion were used (linear only; linear and annual; linear, annual and semiannual) and in which the process noise was either turned on or kept off. All six solutions showed a bias between the VLBI and SLR scales, ranging between 5.6 mm and 9.0 mm at 2010, and a rate difference ranging between 0.08 mm/yr and 0.25 mm/yr. The VLBI baselines were found to be larger (on average) than SLR's.

The process noise used to determine JTRF2014 was estimated from atmospheric, oceanic, and hydrologic loading models. While the process noise used in JTRF2014 varied spatially, being different at different observing stations, it did not vary with time. The effect on the TRF of time variations in the process noise was studied using just VLBI data (Soja et al., 2018a). Time-independent process noise was estimated from the entire history of the modeled load at each station; time-dependent process noise was estimated from monthly values of the modeled load. The coordinates of individual stations were found to differ by as much as 1 cm between the solutions with time-dependent and time-independent process noise; nearly 1/3 of the stations had vertical coordinates that differed by more than 1 mm. However, when averaged over the entire history of the observations, the cyclic effect of the time-dependent process noise on the station coordinates averaged out, resulting in wrms differences at just the 0.01 mm level between the time-dependent and time-independent solutions.

Besides studying the effect on the TRF of time-dependent process noise, the effect of the level of process noise was also studied during 2017, again using just VLBI data and focusing on the predictions (Soja et al., 2018b). Predictions were computed from the TRF solutions by extrapolating the deterministic part of the station motion model. VLBI data spanning 1980 to 2016.5 were used with the TRFs being determined from the data spanning 1980 to the end of 2013. Predictions from these solutions for 2014–2016.5 were then compared to the 2014–2016.5 observations in order to evaluate the accuracy of the predictions. Not surprisingly, it was found that the accuracy of the predictions significantly depended on the level of the process noise. While larger values of the process noise allowed the smoothed station coordinates to better fit the observed positions, the predictions were found to be worse. On the other hand, lower levels of process noise improved the accuracy of the predictions, making them more similar to the predictions from a solution determined without any process noise.

Regional Deformation

Current generation terrestrial reference frames, like JTRF2014, suffer from biases introduced by the space-time sampling pattern of the input space-geodetic measurements, particularly by the gaps in the spatial distribution and temporal history of the space-geodetic observing stations. During 2017, JPL continued its efforts to improve terrestrial reference frames by developing procedures to account for gaps in the spatial distribution and temporal history of observing stations by: (1) reconstructing the history of the deformation of the Earth's global surface from GRACE measurements and geophysical fluid models of the processes that are causing the Earth's surface to be deformed and observing stations to be displaced, (2) using the reconstructed deformation field to construct spatial and temporal correlations of the expected station displacements, and (3) including the spatial and temporal correlations in a Kalman filter solution for an ITRF-like reference frame. By accounting for gaps in the spatial distribution and temporal history of observing stations when determining the frame, biases caused by those gaps are expected to be reduced, particularly in the geocenter and scale parameters of the frame because those parameters are determined solely from observations taken by the non-uniformly distributed SLR and VLBI stations.

During 2017, GRACE gravity data and atmospheric, oceanic, and hydrologic loading models were used to compute the correlation between the GRACE-observed or modeled load at some test point on the Earth's surface (e.g., a space-geodetic observing station) and all other grid points of the data or model. After removing linear trends as well as annual and semiannual periodic terms from each data set, the spatial correlation patterns from these data sets generally agreed with each other on regional (sub-continental) scales, but major disagreements were seen on larger (inter-continental) scales. A regional filter on the correlation maps was therefore applied in order to extract only the continental-scale spatial patterns common in all the data sets. Trial reference frame solutions using the continental-scale correlations were determined with the geocenter and scale parameters of the solutions being found to exhibit improved stability.

Joint Determination of Terrestrial and Celestial Reference Frames

Currently, terrestrial and celestial reference frames are determined separately from each other. This leads to inconsistencies between the frames and the Earth Orientation Parameters (EOPs) that link them together, consequently degrading their quality. During 2017, JPL continued its efforts to improve terrestrial reference frames by continuing to develop the capability to jointly and consistently determine the TRF with the CRF and EOPs. To do this, KALREF is being extended to include the processing of celestial pole offsets and source coordinates. This

will allow the proper motions of radio sources, which are not accounted for in current CRF solutions, to be taken into account.

But before attempting a joint TRF/EOP/CRF solution, procedures must be developed to determine just the CRF using a Kalman filter/smoothing. A Kalman filter and smoother to determine CRFs from VLBI-only observations has been developed. In previous CRF determinations, the coordinates of radio sources have always been considered to be constant. However, a number of radio sources show clear apparent proper motions. The use of a Kalman filter/smoothing allows the time variability of the radio source coordinates to be taken into account via a stochastic model. In an initial test, observations of 334 radio sources spanning 1994 to 2016.5 were used to determine a CRF wherein the positions of 66 of the sources were modeled as a random walk whose strength was derived from the Allan standard deviations of the observed positions of the radio sources. The ability of the Kalman filter to track changes in the apparent positions of those sources that were modeled as a random walk was demonstrated (Soja et al., 2017).

However, because determining a CRF with a Kalman filter is computationally intensive, and since many radio sources exhibit no variability, a two-step approach to determining CRFs was explored. In the first step, a conventional CRF is determined by least-squares in which the source positions are assumed to be constant in time. In the second step, the observed residuals are Kalman filtered to determine time-variable corrections to the constant source CRF. The two-step approach was found to take less computer time and to yield CRFs comparable to those determined by using just the Kalman filter to determine the CRFs.

References

- Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, T. van Dam, and X. Wu (2017), JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, *J. Geophys. Res.*, 122, 8474-8510, doi:10.1002/2017/JB014360.
- Soja, B., R. S. Gross, C. Jacobs, T. Chin, C. Abbondanza, M. Heflin, J. Parker, X. Wu, M. Karbon, T. Nilsson, R. Heinkelmann, and H. Schuh (2017), A celestial reference frame based on Kalman filtering, in *Proceedings of the 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA)*, Gothenburg, Sweden, May 15–19, 2017.
- Soja, B., R. S. Gross, C. Abbondanza, T. M. Chin, M. B. Heflin, J. W. Parker, X. Wu, K. Balidakis, T. Nilsson, S. Glaser, M. Karbon, R. Heinkelmann, and H. Schuh (2018a), Application of time-variable pro-

- cess noise in terrestrial reference frames determined from VLBI data, *Adv. Space Res.*, 61, 2418–2425, doi:10.1016/j.asr.2018.02.023.
- Soja, B., R. S. Gross, C. Abbondanza, T. M. Chin, M. B. Heflin, J. W. Parker, X. Wu, T. Nilsson, S. Glaser, K. Balidakis, R. Heinkelmann, and H. Schuh (2018b), On the long-term stability of terrestrial reference frame solutions based on Kalman filtering, *J. Geodesy*, 92(9), 1063–1077, doi:10.1007/s00190-018-1160-0.
- Wu, X., C. Abbondanza, Z. Altamimi, T. M. Chin, X. Collilieux, R. S. Gross, M. B. Heflin, Y. Jiang, and J. W. Parker (2015), KALREF—A Kalman filter and time series approach to the International Terrestrial Reference Frame realization, *J. Geophys. Res. Solid Earth*, 120(5), 3775–3802, doi:10.1002/2014JB011622.

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Jay Parker, Benedikt Soja, Xiaoping Wu*

3.7 IERS Working Groups

3.7.1 Working Group on Site Survey and Co-location

The working group is concerned with local tie surveying, i.e. determining the vectors between stations' geometric reference points (GRP), their relations to geodetic site markers and temporal and spatial correlation and evolution. The working group also utilizes geometric measurement techniques to isolate station-specific geometric variations in order to quantify and improve the knowledge of such variations with the objective to remove systematic technique biases and create a coherent geodetic system on the observational level. The working group covers practical (i.e. surveying and data exchange) as well as theoretical issues.

At the Unified Analysis Workshop in Paris, the guidelines for the coming years stated that it is more beneficial for the coming ITRFs to survey the GRP vectors at sites that have not been measured, rather than to reiterate measurements at those sites with existing ties. Other desired focus areas were also explicitly stated (see Section 4).

Complementary to the GRP relationships, the structural deformations of the Onsala 20m VLBI telescope were quantified and reveal internal properties that traditional local tie surveying techniques are unable to identify. Similar measurements should be performed also at other sites to capture local characteristics of the different stations.

The IERS Technical Note No. 39, "IGN best practice for surveying instrument reference points at ITRF co-location sites", was published, reflecting IGN's comprehensive experience from surveying at different sites. Also, the St. Croix site has been surveyed by the NGA and the local tie data been made publicly available.

Publications

Gross R., T. Herring. Unified Analysis Workshop July 2017 Paris, France. http://ggosdays.com/media/filer_public/71/81/718149fdb295-43dd-b82e-d01cacc8363e/uaw2017_report_v4.pdf

Haas R., G. Elgered (eds.). Proceedings of the 23rd European VLBI Group for Geodesy and Astrometry Working Meeting, May 2017 Gothenburg, Sweden. http://www.oso.chalmers.se/evga/23_EVGA_2017_Gothenburg.pdf

- Bergstrand S., R. Haas, M. Herbertsson, C. Rieck, J. Spetz, C.-G. Svantesson. Geometric Variations of a Geodetic Radio Telescope
- Lösler M., C. Eschelbach, R. Haas. Unified Model for Surface Fitting of Radio Telescope Reflectors
- Nickola M., A. de Witt, H. Krásná, C. Jacobs, L. Combrinck, J. Böhm. HartRAO Antenna Axis Offset and its Effect on Troposphere Modelling and Antenna Coordinates

Holst C., D. Schunck, A. Nothnagel, R. Haas, L. Wennerbäck, H. Olofsson, R. Hammargren and H. Kuhlmann. Terrestrial Laser Scanner Two-Face Measurements for Analyzing the Elevation-Dependent Deformation of the Onsala Space Observatory 20-m Radio Telescope's Main Reflector in a Bundle Adjustment. *Sensors*, 17(8), <https://doi.org/10.3390/s17081833>

Poyard J.-C., X. Collilieux, J.-M. Muller, B. Garayt and J. Saunier. IGN best practice for surveying instrument reference points at ITRF co-location sites. IERS Technical Note 39, <https://www.iers.org/iers/EN/Publications/TechnicalNotes/tn39.html?nm=94912>

Co-location survey: online reports http://itrf.ign.fr/local_surveys.php

- Fancher K.L., B. Erickson. St. Croix co-location survey, May 2017

Sten Bergstrand

3.7.2 Working Group on SINEX Format

General aspects

The IERS Working Group (WG) on SINEX Format was established in early 2011. The Charter of this WG is available on its website maintained at the IERS Central Bureau: <https://www.iers.org/WGSINEX>

Information related to the working group's activities are available there as well, such as agenda and minutes of the meetings held so far. The latest version of the SINEX format is v 2.02. A full format description is available at: <https://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html>

The SINEX format is used by all four space-geodetic techniques to provide their products. In addition, the combined terrestrial reference frame (ITRF) is also provided in SINEX format. To ensure that all technique-specific needs are covered by the SINEX format, representatives from each Technique Service are members of the SINEX Working Group. Additionally, representatives of the IERS ITRF Combination Centers, the IERS Working Group on Co-location and Site Survey, and the IERS Convention Center are involved in the working group. The IERS Analysis Coordinator is an ex-officio member of the working group in order to cover the needs of the combined IERS products.

During the year 2017 there was no special meeting of the working group. All discussions on possible format revisions and additions have been done mainly in conjunction with the Unified Analysis Workshop, and partly via email or personal communication.

Unified Analysis Workshop

The Unified Analysis Workshop (UAW) 2017 (see Chapter 4) had a dedicated session on Standards, Conventions and Formats. The most important topic related to the SINEX format was the handling of 9-character station names in SINEX files as the IGS switched already to longer names for RINEX files. In the case of the SINEX format, a 1-to-1 adoption of the 9-character station names would exceed the 80-character line actually used in SINEX. The UAW finally recommended to first prepare example descriptions for the two suggested methods before deciding which kind of format change should be done for SINEX:

- Use an extra block in the SINEX file for file-internal referencing (long stations name versus the 4-character abbreviation). But these abbreviations might not be used unambiguously outside SINEX anymore.
- Extend the 4-character station name actually used in the SINEX file to 9 (or even 12) characters. This would mean that the restriction to 80 characters per line in SINEX is abandoned.

A final decision was not taken until the end of 2017.

Daniela Thaller on behalf of the SINEX WG

3.7.3 Working Group on Site Coordinate Time Series Format

The IAG services that distribute GNSS, SLR, VLBI and DORIS data and products proposes plots and/or files of coordinates time series for the stations of the tracking networks, as well as web services to display these time series. The aim of this working group is to define a common exchange format for coordinates time series for the geodetic techniques. For details on the goals and on previous work see the reports for 2012 to 2015 and the web site <http://iers.org/WGSCTSF>.

There has been no progress during 2016 and 2017. Efforts to find a new Chair of the WG have not been successful so far. 75% of the work is done, the requirements are defined, and two different format have been proposed. The next step is to share the formats within the WG and to evaluate them.

Laurent Soudarin

4 IAG/GGOS/IERS Unified Analysis Workshop (UAW)

Introduction Unified Analysis Workshops are co-organized by the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS) and International Earth Rotation and Reference Systems Service (IERS). This was the 5th in a series of workshops that are held every two to three years for the purpose of discussing issues that are common to all the space-geodetic measurement techniques. Attendance at the Workshops are by invitation only with each IAG Service nominating 5–6 experts to attend and participate in the discussions. At this Workshop, held on July 10–12, 2017 at Paris, France, the discussions focused on:

- GNSS Systematic Errors and Biases
- VLBI Systematic Errors and Biases
- SLR Systematic Errors and Biases
- DORIS Systematic Errors and Biases
- Site Survey and Co-location
- Reference Systems and Frames
- Conventional Mean Pole
- Standards, Conventions, and Formats
- Interoperability of Portals and Metadata

This report summarizes the Workshop discussions and resulting recommendations.

GNSS Systematic Errors and Biases

Chairs:

Tom Herring (MIT, USA)

Michael Moore (Geoscience Australia)

Four primary areas of sources of errors and biases were considered and the following recommendations reached:

1. The gravity fields used in the GNSS orbit integrations should be updated to match modern fields to make them consistent with the fields being used by the other IAG Services. The update would include the static part of the field and a time variable component. For the GNSS satellite altitudes, temporal variations in only the lowest degree terms would be needed with just the 2nd degree terms possibly being the only ones needed. Projection of the temporal variations past the time when observed changes are available could use a simple annual sine and cosine fit. Planetary

bodies in addition to the Sun and Moon should also be included in gravitational force modeling.

2. Other components of the force models for GNSS should also be updated and validated. The force models associated with radiation forces are the most uncertain and modeling of these forces can be made more consistent with the exchange of attitude information. The IGS plans to develop an attitude format and make attitude information available so that analysis centers can validate their models. The IGS has noted the appearance of the GPS draconitic period and harmonics of this period in time series of various geodetic products (e.g., positions and Earth orientation parameters). Long orbital arc analyses (longer than the 24-hrs used by most IGS analysis centers) should be investigated to assess the levels of spurious signals in these analyses and to better understand the origin of the draconitic signals.
3. An updated short-period (diurnal and semidiurnal) model is needed and a method to determine whether this is an ocean-tide only with libration terms added or an empirical model based on VLBI data needs to be established. (GNSS estimates of short period EOP terms might be affected by orbital modeling errors). The number of tidal waves to be included and the representation of the tidal signals also need to be decided.
4. Site dependent calibration of GNSS antennas are needed since these have a direct effect on the ITRF realization and position offsets when antennas are changed. Tests of the use of antenna specific phase center models are encouraged when these values are available without disturbing an existing antenna installation. Investigation and potential development of an in situ antenna calibration system are strongly encouraged. In situ calibration would be deployed at core sites where GNSS stations are tied to other geodetic systems.

VLBI Systematic Errors and Biases

Chairs:

John Gipson (NASA/GSFC, USA)

Axel Nothnagel (U Bonn, Germany)

The IVS network consists of around 40–50 VLBI stations distributed across the world. VLBI is unique in its ability to measure UT1 and nutation. Together with SLR, VLBI determines the scale of the ITRF. In this session, we focus on error/modeling sources that might have an impact on either scale or EOP parameters determined from VLBI. A long-standing issue is that the scale difference between VLBI and SLR is about 1.4 ppb. In ITRF2014 this problem is handled by “splitting-the-difference” between VLBI and SLR, with the intrinsic scale of each

differing by about 0.7ppb from ITRF2014. In this session, we review various error sources that might have an impact on the scale difference between VLBI and SLR.

The IERS Conventions contain a model of diurnal and semi-diurnal variation of EOP (“HF-EOP”). The current IERS HF-EOP model is over 20 years old. The quantity and precision of space geodetic data has improved substantially over this time. Any errors in the HF-EOP model used will result in either changing the values of estimated quantities, or increasing the residuals, or both. We present a HF-EOP model based only on VLBI data and demonstrate that it improves the processing of GNSS satellites. This suggest that in some real sense, the VLBI-derived model is better than the IERS model.

The VLBI action items resulting from the UAW discussions are:

1. HF-EOP tide models. It is recommended that a task force with members from each of the measurement techniques be established in order to test the different geophysical and empirical HF-EOP tide models that have become available recently. The models should be assessed by each technique and the task force should consider different metrics to assess the models. The objective of the task force is to recommend a new HF-EOP tide model for adoption by the IERS Conventions. Results of the task force should be presented at the EGU conference in 2018.
2. Gravitational deformation of VLBI antennae. It is recommended that as many VLBI antennae as possible be measured to determine their gravitational deformation. A. Nothnagel has agreed to provide recommendations for making these measurements; antennae that are being decommissioned or that are used frequently should be measured first. It is further recommended that gravitational deformation of VLBI antennae be taken into account when reducing VLBI observations. This means that the ability to account for gravitational deformation should be implemented in all VLBI data reduction software packages. It is anticipated that measuring all radio telescopes of the IVS will take a long time and will most probably stay incomplete for some time to come. In order to maintain consistency between the products of different IVS ACs, the IVS Analysis Coordinator in conjunction with the IVS board will determine when the modeling of gravitational deformation for different antennas will be turned on. It is expected that the coordinates for each of these telescopes will change and a gradual impact on the scale of the TRF can be expected. The effect of changes in other parameters of interest, such as EOP or station coordinates, is expected to be small but will be studied by comparing solutions with and without gravitational deformation.

3. Relativistic effects on VLBI observations. It is recommended that experts be consulted to understand the differences evident in the different formulations available for this effect. The impact of these differences should be assessed by using the different formulations in test solutions.
4. Source structure variability. It is recommended that this be studied by using the CONT14 observations to show the impact of accounting for source structure when reducing VLBI observations. It is further recommended that simulations be used to assess the impact of source structure on VGOS observations and that a strategy for broadband observations be developed.
5. Mean pole tide model. It is recommended that the new mean pole tide model (see section below on Conventional Mean Pole) be implemented in all VLBI data reduction software packages. But the date to start using the new mean pole tide model in routine operations must be coordinated with the other measurement techniques.
6. Atmospheric pressure loading. It is recommended that the impact on the station coordinates of removing atmospheric pressure loading be included in the SINEX files so that the effect can be restored if needed. If other loading effects are used when reducing VLBI observations, such as hydrologic or non-tidal oceanic, then their effects should also be reported and they should be reported separately, not as an aggregate.

SLR Systematic Errors and Biases

Chairs:

Cinzia Luceri (e-Geos/ASI, Italy)

Erricos Pavlis (JCET/UMBC, USA)

The International Laser Ranging Service (ILRS) contributes to ITRF development unique information that only Satellite Laser Ranging (SLR) is sensitive to: the definition of the origin, and in equal parts with VLBI, the scale of the frame. For the development of ITRF2014, the ILRS analysts adopted a revision of the internal standards and procedures in generating our contribution from the eight ILRS Analysis Centers. The improved results for the ILRS components were reflected in the resulting new time series of the ITRF origin and scale, showing insignificant trends and tighter scatter. This effort was further extended after the release of ITRF2014, with the execution of a Pilot Project (PP) in the 2016–2017 timeframe that demonstrated the robust estimation of persistent systematic errors at the millimeter level. ILRS ACs will now turn this into an operational tool to monitor station performance and to generate a history of systematics at each station, to be used with each re-analysis for future ITRF model developments. This is part of a

broader ILRS effort to improve the quality control of the data collection process as well as that of our products. To this end, the ILRS has established a “Quality Control Board–QCB” that consists of members from the analysis and engineering groups, the Central Bureau, and even user groups with special interests. The QCB meets by telecon monthly and oversees the various ongoing projects, develops ideas for new tools and future products. This session focused on the main topic with an update on the results so far, the schedule for the near future and the plans for its operational implementation, along with a brief description of upcoming new ILRS products.

The recommendations resulting from the SLR discussions are:

1. Quality control. It is recommended that the ILRS Central Bureau help the SLR network improve communication and response to errors that are identified through the quality control process.
2. Metadata. It is recommended that complete and accurate meta-data to improve the discoverability of ILRS data and products continue to be developed.
3. Time biases. The time biases estimated from the quality control pass-by-pass analyses should be compared with the results of J. Ries. The time bias table from T2L2 should be obtained and the time biases from the pass-by-pass analyses should also be compared to it. The data handling file for the time biases in the ILRS should be refined.
4. Network-fixed products. The ILRS should release EOPs and station coordinates in a defined TRF (i.e., the current ITRF) in addition to providing loosely constrained SINEX files.
5. Atmospheric loading. The ILRS should establish a pilot project to study the impact of applying non-tidal atmospheric loading when reducing SLR observations. If successful, the ILRS should provide products based upon removing atmospheric loading effects.
6. Range and time biases. The ILRS should include in the SINEX file the range and time biases that are applied when reducing SLR observations. This should be done to facilitate research into the effect of estimating range and time biases.

DORIS Systematic Errors and Biases

Chairs:

Hugues Capdeville (CLS, France)

Frank Lemoine (NASA/GSFC, USA)

The DORIS technique is composed of a ground network of 55–60 stations, and a satellite constellation. The satellites presently orbit at altitudes of ~800 to 1335 km at a variety of inclinations. For ITRF2014,

the DORIS analysis centers implemented a number of improvements to the processing that eliminated errors present in ITRF2008. Nonetheless, the analysis for ITRF2014 as well as the ex post facto studies showed that systematic errors still affect the DORIS Doppler observation, the reference frame parameters, or the derived products. These errors are derived from incomplete modeling of the behavior of the DORIS oscillators on the orbiting spacecraft, or from errors in the force models required to accurately model satellite motion for these satellites that orbit at LEO altitudes. This session provided new information and made recommendations for standards of DORIS data processing:

1. Geocenter. Forward modeling of the geocenter is essential to altimeter satellite POD and helps produce consistency between GPS and SLR/DORIS orbits. Can we consider adoption of forward geocenter modeling as part of the processing for the next ITRF? A lack of such a model means that the orbits are mis-centered (pro). But is the same model applicable for SLR, DORIS, and GNSS (con)? It is noted that a geocenter model can be derived from DORIS data that is consistent with a Lageos-1 and Lageos-2 geocenter model that considers corrections for loading and biases.
2. Time variable gravity (TVG). The use of an accurate, highest fidelity possible TVG model is a requirement for LEO satellite modeling in general and for the DORIS constellation in particular. It has been observed that increased radial orbit error and radial orbit drifts with geographic correlations occur if the highest fidelity models are not used. It is recommended that all satellite techniques adopt the highest fidelity TVG modeling that is consistent with the sensitivity of their satellites. In particular, satellite techniques should at least embrace a modern static GRACE+GOCE model and include time variations of the degree-2 coefficients.
3. Diurnal and semi-diurnal tide models. Different authors analyzing IDS and ITRF2014 products have noticed the presence of a signal near 14 days (Blossfeld et al., 2016; Moreaux et al., 2016; Tornatore et al., 2016). It should be clarified whether this signal is real or is an alias of a subdaily tidal signal. The newly available diurnal and semi-diurnal tide models should be tested in trial solutions. It is requested that self-contained subroutines that implement these models be provided to ease their integration into processing software since their use must be done at the observation level.
4. Tidal geocenter. This topic was not raised during the Workshop. Do the other techniques apply tidal geocenter models and is there a recommended model to use? Should the same model for tidal geocenter be used as that adopted for diurnal and semi-diurnal EOP variations?

5. Solar radiation pressure (SRP) modeling. Because of the ubiquity of draconitic signals (at 117 days and its subharmonics) in DORIS products, SRP modeling should continue to be improved, particularly on the Jason satellites. The improvements could include detailed modeling of the solar array motion (quaternions) or other approaches could be pursued such as the use of the UCL model. As a word of caution, the draconitic signals in DORIS products are likely to have other components that are intrinsic to DORIS data and that must also be accommodated.
6. Ultra-stable oscillator (USO). The Jason-2 T2L2 data have revealed new information about the behavior of the DORIS USO. Using this data, improved models can be derived to accommodate different processes that affect the behavior of the DORIS USO including the South Atlantic Anomaly (SAA), temperature, aging, and 60-day attitude-related SAA effects. Also, the T2L2 data and experience on Sentinel-3 have revealed the presence of a generic problem for the DORIS USO on LEO satellites. While waiting for a precise corrective model for Jason-3, a multi-satellite solution will be provided by applying a strategy to minimize the SAA effect for stations in this area. Models derived from the T2L2 data will also be tested for Jason-2 and Jason-3. Discussions with CNES and other satellite providers about standards for USO (pre-treatment, shielding, provision of telemetry about, e.g., the temperature of the USO box, linking of USO to GNSS as done on Sentinel-3) need to continue. As a result of recent discussions, the DORIS USO will be connected with GPS when possible in order to aid the monitoring of the USO behavior. CNES will also try to pre-irradiate on the ground a series of USOs more strongly than recent flight versions in order to facilitate testing and analysis.
7. Scale. For the scale, the IDS should continue to investigate this, including looking at the IGS experience regarding modeling and weighting of low-elevation data to see if there is a systematic effect at low-elevation that is presently not being modeled.

Site Survey and Co-location

Chair:

Sten Bergstrand (RISE, Sweden)

The connections between geodetic stations on a geodetic site are key components to a reliable combination of different techniques and a crucial component of a Global Geodetic Observing System on an observational level. Local ties are geometric vectors measured between reference points of different instruments, including the full covariance information in both temporal and spatial domain. These ties are obtained with surveying and monitoring instruments such as theodolites, total

stations, laser trackers, invar rods and communicated through a coordinate system realized through GNSS antennas. Where available, the discrepancies between the analytic results and the corresponding ties exceed the expected uncertainty of the surveys. These discrepancies indicate the presence of unknown or underestimated uncertainties or unresolved systematic errors of the different techniques. This session was intended to identify the needs that can elevate the contribution of site surveying in the next ITRF. The following is a summary of the discussions and recommendations from this session:

Local ties are vectors between geometric reference points in the ITRF with full covariance information in temporal and spatial domain.

Local tie survey methods are available to determine station's geometric reference points to the desired accuracy. Other perturbations may be of geometric nature and quantified by surveying methods, but are not part of the local ties *per se*. To resolve such perturbations is the responsibility of the services.

Systematic technique errors rather than local tie surveys are dominant error sources in discrepancies between ties and solutions. Differences between analytic solutions and local ties are thus primarily indicators of systematic errors of the techniques on the site, not of the local ties.

Annual site surveys are not necessary unless there are indications of instabilities or survey problems.

- References**
- Documentation of IERS 2013 Workshop on Local Surveys and Co-locations is available at: <http://iersworkshop2013.ign.fr/>
 - Resolution on the nomenclature of space geodetic reference points and local tie measurements is available at: <https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/documents.html>
 - The ITRS Center is just about to release "IGN best practice for surveying instrument reference points at co-location sites" as IERS Technical Note 39.

- Recommendations**
1. Optimize a local network setup combination for a bundle adjustment based on instrument specification, e.g. laser tracker (very high accuracy, short distances), theodolites (high accuracy, intermediate distances) and GNSS (low accuracy, long distances).
 2. Development of an *in situ* GNSS antenna calibration method is a high priority and especially important to commission at GNSS sites with long history.
 3. In a choice between surveying on the one hand sites with and on the other hand without existing local ties, sites without local ties should be prioritized.

4. For IDS, IGS, ILRS, and IVS specifically:

- (a) Examine ITRF2014 tie and space geodesy discrepancies available at http://itrf.ensg.ign.fr/ITRF_solutions/2014/ to look for indications of systematic errors.
- (b) Choose sites with poor consistency between local ties and space geodetic solutions to identify and address problems.

Reference Systems and Frames

Chairs:

Zuheir Altamimi (IGN, France)

Richard Gross (JPL, USA)

The terrestrial reference frame (TRF) is the foundation for virtually all space-based, airborne and ground-based Earth observations. Through its tie to the celestial reference frame (CRF) by time-dependent Earth orientation parameters, it is also fundamentally important for interplanetary spacecraft tracking and navigation. The TRF determined by geodetic measurements is the indispensable foundation for all geo-referenced data used by science and society. It plays a key role in modeling and estimating the motion of the Earth in space, in measuring change and deformation of all components of the Earth system, and in providing the ability to connect measurements made at the same place at different times, a critical requirement for understanding global, regional and local change. Providing an accurate, stable, homogeneous, and maintainable terrestrial reference frame to support numerous scientific and societal applications is one of the essential goals of the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS). This session was a forum for discussing the ways and means of improving the TRF, including understanding the deficiencies of the current frames, the possibility of updating them between determinations, and jointly determining them with the CRF. The recommendations resulting from the discussions held during this session are to encourage:

1. The IERS ITRS Combination Centers (CCs) to consider the possibility of updating their frames between determinations.
2. The IAG Services to provide the information needed for the CCs to update their frames.
3. The IERS to identify reference frame users who will benefit from time series reference frames and how these reference frames will satisfy their needs.
4. The IERS to clarify the locations of up-to-date discontinuities in the coordinate time series of the four techniques.

Conventional Mean Pole

Chairs:

Erricos Pavlis (JCET/UMBC, USA)

Nick Stamatakis (USNO, USA)

The Conventional Mean Pole (CMP) model has been provided by the IERS Conventions in a linear form since the 2003 edition. In the 2010 release, the model was initially modified to a cubic one with a linear extrapolation after 2010.0. In 2015, publications of present-day ice sheet mass losses led to a further modification that directed the users to use either a tabular form stored in an online file and maintained by the IERS Earth Orientation Center, or a yearly updated subroutine that essentially reproduced the tabular data. The routine that was available from the IERS Conventions portal, allowed the users to select between any of the above options; a useful feature only for comparison purposes, but one that can potentially generate many inconsistent results amongst the IAG Services. In addition to that, the routine was never updated for the current year, and so the Services had no way to use it and were left with the tabular data as the only option. Furthermore, several users had noticed that the online tabular data files were being changed without any notification to the users, which led to a study of some of the versions that were captured at various times, presented at the last Fall AGU [McCarthy and Stamatakis, 2016]. In early 2017, the ILRS adopted a modified version of the online routine, extending its validity with the introduction of a few additional points, so that ILRS operational products could continue to use the same CMP definition and create the least amount of changes in the processing chain. This session was intended to resolve the issue of the definition of the CMP and its proper implementation in a universally acceptable way. The recommendations resulting from the discussions held during this session are:

1. The IERS Conventions section on the pole tide should be updated to replace the use of the “filtered” mean pole* with the “linear mean pole” model and a clear recommendation should be made to all analysis groups (including the altimetry community) to adopt a common “linear mean pole” model for the pole tide computations. *http://maia.usno.navy.mil/conventions/2010/2010_update/chapter7/icc7.pdf
 - (a) The pole tide model is unchanged; only the “mean pole” subtracted from the IERS polar motion changes (a relatively simple code change that avoids issues associated with the need for regular updates on the “mean pole”).
 - (b) All linear fits to the C01 series shown at the UAW do not differ by much more than the nominal 10 mas goal, even when extended up to 2050; a Special Study Group to evaluate

different options in developing the “linear mean pole” does not seem warranted at this point.

- (c) The specific linear mean pole model recommendation, based on the full extent of the C01 series (1900–2015), is (in milliarcseconds):

$$\overline{Xp} = 55.0 + 1.677 * t$$

$$\overline{Yp} = 320.5 + 3.460 * t$$

where t is in years past 2000.0.

2. The IERS should continue to provide a filtered mean pole table for purposes of modeling/comparing the long-term trend in C21/S21. The filtering procedure should be clearly defined after some discussions, proposals, and tests between now and prior to the next IERS DB meeting. The spectral response of the filter that produces this now-called filtered pole needs to be made clear.
 - (a) This table is especially useful in forward modeling C21/S21 for precision orbit determination.
 - (b) It was noted that C21/S21 are well characterized by the full mean pole and a seasonal variation.
3. The four geometric techniques (and altimetry) should consider how to implement the “linear mean pole”.
4. The IERS Conventions Center should consider renaming the “filtered mean pole” term to avoid confusion with the “linear mean pole”.

Standards, Conventions, and Formats

Chairs:

Daniela Thaller (BKG, Germany)

Detlef Angermann (DGFI-TUM, Germany)

The GGOS Bureau for Products and Standards (BPS) recently compiled a detailed inventory of standards and conventions used within the IAG services for generating their products. The inventory revealed inhomogeneity between individual data sets, and inconsistencies in the analysis chains. The most natural step succeeding the inventory is the identification of present deficiencies, and the provision of recommendations how the inconsistencies can be resolved. All IAG Services need to be involved in this step. For the publication of the products unified, machine-readable and user-friendly formats are required. Modifications, extensions and new definitions need to be coordinated between all producers of geodetic products. This session was a forum for bringing all analysis groups and providers of geodetic products together and to identify the next steps in order to homogenize standards and formats for improved products satisfying the users' needs. The recommendations resulting from the discussions held during this session are:

1. The UAW endorses the recommendations already given in the Inventory compiled by the GGOS Bureau of Products and Standards, namely:
 - (a) The used numerical standards, including time and tide systems, must be clearly documented for all geodetic products.
 - (b) The W0 value given in IAG Resolution No. 1 (2015) should be used as the new reference value for geodetic work.
 - (c) The development of a new Geodetic Reference System GRS20XX based on best estimates of the major parameters is desired.
2. Intermediate updates of the IERS Conventions should be citable (e.g., IERS Conventions 2010 Update 1; IERS2010.1).
3. Work should continue towards ensuring that all techniques use a consistent gravity field model, including time variable gravity (see recommendations from the other UAW 2017 sessions).
4. A process should be developed by which a new model is evaluated, especially *before* it becomes a conventional model. For example,
 - (a) Model developers should provide a dedicated test data set.
 - (b) All techniques should test the model.
 - (c) In order to coordinate the testing, the IERS should issue a call-for-participation.
5. A unique EOP format for all products should be derived that has, for example, clearly defined fixed labels and units and the flexibility to use only relevant columns.
6. The handling of 9-character station names in SINEX files needs to be clarified by the SINEX Working Group. Example descriptions of the following suggested methods should be prepared:
 - (a) Use an extra block in the SINEX file for SINEX-internal referencing (long station name versus the 4-character abbreviation).
 - (b) Extend the 4-character station name in the SINEX file (to 9 or even 12 characters).

Interoperability of Portals and Metadata

Chairs:

Richard Gross (JPL, USA)

Günter Stangl (BEV, Austria)

GGOS is developing a portal through which the data and products produced by the IAG Services can be served to the user community. Seamlessly providing the Service data and products to the user com-

munity through the GGOS portal requires that the GGOS and Service portals be interoperable. In practice, this interoperability is expected to be accomplished through a GGOS-developed interface that serves as an interpreter between the GGOS and Service portals. In this way, the Services can implement their portals as they want without being subject to GGOS-defined specifications. Similarly, if the user is accessing the GGOS portal through an external portal such as the GEO portal at <http://www.geoportal.org> then the GGOS portal must be interoperable with the external portal. This session was a forum for discussing the status and plans for developing the GGOS and Service portals and for fostering a discussion between GGOS and the Services to ensure the interoperability of the portals that they are developing. The recommendation resulting from the discussions held during this session is that:

1. The IAG Services develop web portals that are interoperable with each other and with the GGOS portal.

Richard Gross, Thomas Herring

Appendices

Appendix 1: IERS Terms of Reference

The IERS was established as the International Earth Rotation Service in 1987 by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) and it began operation on 1 January 1988. In 2003 it was renamed to International Earth Rotation and Reference Systems Service. IERS is a member of the ICSU World Data System (WDS). The primary objectives of the IERS are to serve the astronomical, geodetic and geophysical communities by providing the following:

- The International Celestial Reference System (ICRS) and its realization, the International Celestial Reference Frame (ICRF).
- The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).
- Earth orientation parameters required to study earth orientation variations and to transform between the ICRF and the ITRF.
- Geophysical data to interpret time/space variations in the ICRF, ITRF or earth orientation parameters, and model such variations.
- Standards, constants and models (i.e., conventions) encouraging international adherence.

IERS is composed of a broad spectrum of activities performed by governmental or selected commercial organizations. IERS collects, archives and distributes products to satisfy the objectives of a wide range of applications, research and experimentation. These products include the following:

- International Celestial Reference Frame.
- International Terrestrial Reference Frame.
- Monthly earth orientation data.
- Daily rapid service estimates of near real-time earth orientation data and their predictions.
- Announcements of the differences between astronomical and civil time for time distribution by radio stations.
- Leap second announcements.
- Products related to global geophysical fluids such as mass and angular momentum distribution.

- Annual report and technical notes on conventions and other topics.
- Long term earth orientation information.

The accuracies of these products are sufficient to support current scientific and technical objectives including the following:

- Fundamental astronomical and geodetic reference systems.
- Monitoring and modeling earth rotation/orientation.
- Monitoring and modeling deformations of the solid earth.
- Monitoring mass variations in the geophysical fluids, including the atmosphere and the hydrosphere.
- Artificial satellite orbit determination.
- Geophysical and atmospheric research, studies of dynamical interactions between geophysical fluids and the solid earth.
- Space navigation.

The IERS accomplishes its mission through the following components:

- Technique Centers.
- Product Centers.
- ITRS Combination Center(s)
- Research Center(s)
- Analysis Coordinator.
- Central Bureau.
- Directing Board.
- Working Groups.

Some of these components (e.g., Technique Centers) may be autonomous operations, structurally independent from IERS, but which cooperate with the IERS. A participating organization may also function as one or several of these components (except as a Directing Board).

TECHNIQUE CENTERS (TC)

The TCs generally are autonomous independent services, which co-operate with the IERS. The TCs are responsible for developing and organizing the activities in each contributing observational technique to meet the objectives of the service. They are committed to produce operational products, without interruption, and at a specified time lag to meet requirements. The products are delivered to IERS using designated standards. The TCs provide, as a minimum, earth orientation parame-

ters and related reference frame information, as well as other products as required. The TCs exercise overall control of observations from their specific techniques, archiving, quality control and data processing including combination processing of data and/or products received from their participating organizations. TCs are the various international technique specific services: IDS, IGS, ILRS, IVS, and possible future TCs.

PRODUCT CENTERS (PC)

PCs are responsible for the products of the IERS. Such centers are the following:

- Earth Orientation Center, responsible for monitoring earth orientation parameters including long term consistency, publications for time dissemination and leap second announcements.
- Rapid Service/Prediction Center, responsible for publication of semiweekly (possibly daily?) bulletins of preliminary and predicted earth orientation parameters.
- Conventions Center, under the guidance of the IERS Conventions Editorial Board, responsible for the maintenance of the IERS conventional models, constants and standards.
- ICRS Center, responsible for the maintenance of the ICRS/ ICRF.
- ITRS Center, responsible for the maintenance of the ITRS/ ITRF, including network coordination (design collocation, local ties, and site quality). For this purpose the Center is also responsible to provide the ITRS Combination Centers (see below) with specifications, and to evaluate their respective results.
- Global Geophysical Fluids Center, responsible for providing relevant geophysical data sets and related computational results to the scientific community.

ITRS COMBINATION CENTER(S)

ITRS Combination Center(s) are responsible to provide ITRF products by combining ITRF inputs from the TCs and others. Such products are provided to the ITRS Center.

RESEARCH CENTER(S)

Research Center(s) are responsible for carrying out research on a specific subject. They are established by the DB and are related to a corresponding Product Center. Research Center(s) are limited to a term of 4–5 years.

IERS ANALYSIS COORDINATOR (AC)

The AC is responsible for the long-term and internal consistency of the IERS reference frames and other products. He is responsible for ensuring the appropriate combination of the TC products into the single set of official IERS products and the archiving of the products at the

Central Bureau or elsewhere. The AC is elected by the DB for a term of four years with the possibility of re-election for one additional term. The responsibility of the AC is to monitor the TC and PC activities to ensure that the IERS objectives are carried out. This is accomplished through direct contact with the independent TC Analysis Coordinators and PC chairs or equivalent. Specific expectations include quality control, performance evaluation, and continued development of appropriate analysis methods and standards. The AC interacts fully with the Central Bureau, the Product Centers and the Combination Research Center(s).

CENTRAL BUREAU (CB)

The Central Bureau is responsible for the general management of the IERS consistent with the directives and policies set by the Directing Board, i.e., acts as the executive arm of the Directing Board. The CB facilitates communications, coordinates activities, monitors operations, maintains documentation, archives products and relevant information and organizes reports, meetings and workshops. Although the Chairperson of the Directing Board is the official representative of the IERS at external organizations, the CB is responsible for the day-to-day liaison with such organizations. The CB coordinates and publishes all documents required for the satisfactory planning and operation of the Service, including standards/conventions/specifications regarding the performance, functionality and configuration requirements of all elements of the Service including user interface functions. The CB operates the communication center for the IERS. It distributes and/or maintains a hierarchy of documents and reports, both hard copy and electronic, including network information, standards, newsletters, electronic bulletin board, directories, summaries of performance and products, and an Annual Report.

DIRECTING BOARD (DB)

The Directing Board consists of the following members:

- Two representatives from each Technique Center to be selected by the Technique Center's governing board or equivalent. The two representatives will represent that technique regarding
 - a. its network and coordination with other techniques,
 - b. the details of the technical analyses.

It is desired that, as part of reciprocity agreements, IERS representatives are to become members of the Technique Centers directing boards.

- One representative from each Product Center.
- Representative of the Central Bureau.
- IERS Analysis Coordinator.

- Representatives of IAU, IAG/IUGG and GGOS.

The Chairperson is elected by the Board for a term of four years with the possibility of re-election for one additional term. Eligible candidates are members of the DB and IERS Associate Members. The Chairperson does not vote, except in case of a tie. He/she is the official representative of IERS to external organizations.

The DB exercises general control over the activities of the service and modifies the organization as appropriate to maintain efficiency and reliability, while taking full advantage of the advances in technology and theory.

Most DB decisions are to be made by consensus or by a simple majority vote of the members present, provided that there is a quorum consisting of at least one half of the membership. In case of a lack of a quorum, the voting is by correspondence. Changes in the Terms of Reference and Chairperson of the DB can be made by a two third majority of the members of the DB. If a DB member cannot participate in the meeting, he/she can designate a proxy to attend the meeting and vote in the place of the absent DB member. Any appointment of a proxy by a DB member shall be in writing to the CB prior to the meeting, and is valid only for the meeting.

For the DB to effectively assess the value of IERS services to the user communities, and to ensure that the service remains up to date and responsive to changing user needs, the DB will organize reviews of the IERS components at appropriate intervals. The DB will decide, on an annual basis, those components that are to be reviewed and from time to time may select other activities for review, as it deems appropriate. The Central Bureau provides the secretariat of the DB.

The Board shall meet at least annually and at such other times as shall be considered appropriate by the Chairperson or at the request of five members.

WORKING GROUPS

Working Groups may be established by the DB to investigate particular topics related to the IERS components. Working groups are limited to a term of two years with a possible one-time re-appointment. The IERS Analysis Centre Coordinator and the Director of the Central Bureau are ex officio members of each working group, and may send official representatives to meetings which they are unable to attend. Working groups may also collaborate with other scientific organizations like, e.g., IAG, CSTG.

The chair of a working group must prepare, at least annually, a report about the activities of the group to be included in the IERS Annual Report. Working group chairs are invited to participate in DB meetings. Individuals or groups wishing to establish an IERS Working Group must

provide the following at least two weeks prior to the IERS Directing Board Meeting where DB approval is requested.

- Draft charter clearly specifying:
 - Proposed goals (two pages at maximum),
 - Proposed structure of the group or project,
 - Working plan including schedule / deadlines including the anticipated end of work,
- Candidate for a chairperson to be appointed by the DB (optional),
- Initial list of members,
- Proposed plans for an operational phase (if applicable),
- Draft IERS message to inform the IERS community.

IERS ASSOCIATE MEMBERS

Persons representing organizations that participate in any of the IERS components, and who are not members of the Directing Board, are considered IERS Associate Members. Ex officio IERS Associate Members are the following persons:

IAG General Secretary

IAU General Secretary

IUGG General Secretary

President of IAG Commission 1

Chair of IAG Subcommittee 1.1

Chair of IAG Subcommittee 1.2

Chair of IAG Subcommittee 1.4

President of IAG Commission 3

Chair of IAG Subcommittee 3.1

Chair of IAG Subcommittee 3.2

Chair of IAG Subcommittee 3.3

President of IAU Division A

President of IAU Commission A1

President of IAU Commission A2

President of IAU Commission A3

**IERS
CORRESPONDENTS**

IERS Correspondents are persons on a mailing list maintained by the Central Bureau, who do not actively participate in the IERS but express interest in receiving IERS publications, wish to participate in workshops or scientific meetings organized by the IERS, or generally are interested in IERS activities.

October 6, 2015

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(Status as of 1 January 2019)

Appendix 4: Electronic access to IERS products, publications and components

Central IERS web site	http://www.iers.org/ Please note that all other products, publications and centres may be accessed via this web site.
Products	For a complete list of all IERS products see www.iers.org/products .
Earth orientation data	Rapid data and predictions Web access: http://www.usno.navy.mil/USNO/earth-orientation/eo-products ftp access: maia.usno.navy.mil - directory <code>ser7</code> Monthly earth orientation data Web access: http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins ftp access: hpiers.obspm.fr - directory <code>iers/bul/bulb_new</code> Long term earth orientation data Web access: http://hpiers.obspm.fr/eop-pc/index.php?index=eoptable ftp access: hpiers.obspm.fr - directory <code>iers/eop</code> Leap second announcements Web access: http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins ftp access: hpiers.obspm.fr - directory <code>iers/bul/bulc</code> Announcements of DUT1 Web access: http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins ftp access: hpiers.obspm.fr - directory <code>iers/bul/buld</code>
Conventions	Web access: IERS Conventions 2010: http://iers-conventions.obspm.fr/
International Celestial Reference Frame	Web access: http://hpiers.obspm.fr/icrs-pc/newwww/index.php
International Terrestrial Reference Frame	Web access: http://itrf.ensg.ign.fr/ ftp access: itrf.ensg.ign.fr - directory <code>pub/itrf</code>
Geophysical fluids data	Web access: http://loading.u-strasbg.fr/GGFC/

Publications**IERS Messages**

<http://www.iers.org/Messages>

IERS Bulletins

<http://www.usno.navy.mil/USNO/earth-orientation/eo-products/weekly/bulla> (Bulletin A)

<http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins>
(Bulletins B, C, D)

<http://www.iers.org/Bulletins>

IERS Technical Notes

<http://www.iers.org/TechnicalNotes>

IERS Annual Reports

<http://www.iers.org/AnnualReports>

ITRF Mail

<http://list.ensg.ign.fr/www/arc/itrfmail>

IERS Components**Directing Board**

Web page: <http://www.iers.org/DB>

Analysis Coordinator

Web page: <http://www.iers.org/AC>

Central Bureau

Web page: <http://www.iers.org/CB>

Product Centres**Earth Orientation Centre**

Web site: <http://hpiers.obspm.fr/eop-pc/>

Rapid Service/Prediction Centre

Web site: <http://www.usno.navy.mil/USNO/earth-orientation>

Conventions Centre

Web site: <http://iers-conventions.obspm.fr/>

ICRS Centre

Web site: <http://hpiers.obspm.fr/icrs-pc/newwww/index.php>

ITRS Centre

Web site: <http://itrf.ensg.ign.fr/>

Global Geophysical Fluids CentreWeb site: <http://loading.u-strasbg.fr/GGFC/>**Special Bureaus:*****Special Bureau for the Oceans***Web site: <http://euler.jpl.nasa.gov/sbo/>***Special Bureau for Hydrology***Web site: <http://www.csr.utexas.edu/research/ggfc/>***Special Bureau for the Atmosphere***Web site: <https://www.aer.com/science-research/earth/earth-mass-and-rotation/special-bureau-atmosphere/>***Special Bureau for Combination***Web site: <http://geophy.uni.lu/>**Technique Centres****International GNSS Service (IGS)**Web site: <http://www.igs.org/>**International Laser Ranging Service (ILRS)**Web site: <http://ilrs.gsfc.nasa.gov/>**International VLBI Service (IVS)**Web site: <http://ivscc.gsfc.nasa.gov/>**International DORIS Service (IDS)**Web site: <http://ids-doris.org/>**ITRS Combination
Centres****Deutsches Geodätisches Forschungsinstitut (DGFI)**Web site: <http://www.dgfi.tum.de/en/international-services/itrs-combination-centre/>**Institut Géographique National (IGN)**Web site: <http://itrf.ensg.ign.fr/>**Jet Propulsion Laboratory (JPL)**Web page: <http://www.iers.org/ITRSCC-JPL>**Working Groups****Working Group on Site Survey and Co-location**Web site: <http://www.iers.org/WGSiteSurvey>**Working Group on SINEX Format**Web site: <http://www.iers.org/WGSINEX>**Working Group on Site Coordinate Time Series Format**Web page: <http://www.iers.org/WGSCTSF>

Appendix 5: Acronyms

The following acronyms and other abbreviations are used in this report. For more acronyms related to IERS see <http://www.iers.org/Acronyms>.

AAM	Atmospheric Angular Momentum	C/P	Combination and Prediction
AC	Analysis Centre	CA	California, USA
AC	Analysis Coordinator	Caltech	California Institute of Technology
ACC	[IGS] Analysis Center Coordinator	CATREF	Combination and Analysis of Terrestrial Reference Frames
ACES	Atomic Clock Ensemble in Space	CB	Central Bureau
AGN	Active Galactic Nuclei	CB	Coordinating Board
AGU	American Geophysical Union	CC	Combination Centre
AJ	Astronomical Journal	CCD	Charge-Coupled Device
AM	angular momentum	CDDIS	NASA Crustal Dynamics Data Information System
AOV	Asia-Oceania VLBI Group for Geodesy and Astrometry	CDS	Centre de Données astronomiques de Strasbourg (formerly: Centre de Données Stellaire)
APOLLO	Apache Point Observatory Lunar Laser-ranging Operation	CERGA	Centre d'Etudes et de Recherches Géodynamiques et Astronomiques
APSG	Asia-Pacific Space Geodynamics	CfA	Harvard-Smithsonian Center for Astrophysics
AR	Annual Report	CfP	Call for Participation/Proposals
AR	autoregressive	CIO	Conventional International Origin
AR	Argentina	CIP	Celestial Intermediate Pole
ASC	Analysis Standing Committee	CLS	Collecte, Localisation, Satellites
ASI	Agenzia Spaziale Italiana	CM	instantaneous centre of mass of the whole Earth
AUS	Geoscience Australia	CMP	Conventional Mean Pole
AWG	Analysis Working Group	CN	centre of [observation] network
BEV	Bundesamt für Eich- und Vermessungswesen	CN	China
BIPM	Bureau International des Poids et Mesures	CNES	Centre National d'Etudes Spatiales
BKG	Bundesamt für Kartographie und Geodäsie	CNSA	China National Space Administration
BPS	GGOS Bureau for Products and Standards		

CoM	centre of mass	doi	Digital Object Identifier
CONT	continuous VLBI session/campaign	DOMES	Directory Of MERIT Sites (originally; now of more general use)
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate	DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)
COSPAR	Committee on Space Research	DOR-O-T	DORIS Online Tools
CPC	Climate Prediction Center	DPAC	Data Processing and Analysis Consortium
CPO	celestial pole offset	DPOD	DORIS extension of the ITRF for Precise Orbit Determination
CRF	Celestial Reference Frame	DR	Data Release
CRS	Celestial Reference System	DSS	Digitized Sky Survey
CSR	Center for Space Research, University of Texas	DTRF	ITRS realization by DGFI
CSTG	Commission on International Coordination of Space Techniques for Geodesy and Geodynamics	DUT	Delft University of Technology
CTIO	Cerro Tololo Inter-American Observatory	DUT1	= UT1-UTC
d	day	EAM	Effective Angular Momentum
DB	Directing Board	EC	Executive Committee
DC	District of Columbia, USA	ECCO	Estimating the Circulation and Climate of the Ocean
Dec	declination	ECMWF	European Centre for Medium-Range Weather Forecasts
deg	degree	EEMA	error ellipse major axis
Dep.	Department	EGU	European Geosciences Union
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)	EMB	Earth-Moon Barycentre
DGFI	= DGFI-TUM	ENVISAT	Environmental Satellite
DGFI-TUM	Deutsches Geodätisches Forschungsinstitut at Technische Universität München	EO	Earth orientation
DiFX	Distributed FX	EOC	Earth Orientation Centre
DIODE	Détermination Immédiate d'Orbite par Doris Embarqué	EOP	Earth Orientation Parameters
DIS	IERS Data and Information System	EOST	École et Observatoire des Science de la Terre
		ERP	Earth Rotation Parameters
		ESA	European Space Agency

ESOC	European Space Operations Center, ESA	GNSS	Global Navigation Satellite System
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites	GOCE	Gravity field and Ocean Circulation Explorer
EVGA	European VLBI [Group] for Geodesy and Astrometry	GPS	Global Positioning System
e-VLBI	Electronic transfer VLBI	GRACE	Gravity Recovery and Climate Experiment
FR	full rate	GSFC	Goddard Space Flight Center
FTP, ftp	File Transfer Protocol	GSI	Geospatial Information Authority of Japan (formerly: Geographical Survey Institute)
GA	General Assembly	HartRAO	Hartebeesthoek Radio Astronomy Observatory
GA	Geoscience Australia	HEO	High Earth Orbiter
GB	Governing Board	HF-EOP	High Frequency EOP
Gb	gigabit	hr, hrs	hour, hours
GDR	Gaia Data Release	HTTPS	Hypertext Transfer Protocol Secure
GDR	Geophysical Data Record	HY	HaiYan / Haiyang / Hai Yang [satellite]
GEO	Group on Earth Observations	IAA	Institute of Applied Astronomy, St. Petersburg
GFZ	GeoForschungsZentrum Potsdam	IAG	International Association of Geodesy
GGAO	Goddard Geophysical and Astronomical Observatory	IASPEI	International Association of Seismology and Physics of the Earth's Interior
GGFC	Global Geophysical Fluids Centre	IAU	International Astronomical Union
GGIM	= UN GGIM	ICESat	Ice, Cloud, and land Elevation Satellite
GGOS	Global Geodetic Observing System	ICG	International Committee on Global Navigation Satellite Systems
GIA	glacial isostatic adjustment	ICRF	International Celestial Reference Frame
GIOVE	Galileo In-Orbit Validation Element	ICRS	International Celestial Reference System
GIQC	Gaia Initial Quasar Catalog[ue]	ICSU	International Council for Science
GLDAS	NASA's Global Land Data Assimilation System	ID	Identification/Identifier
GLONASS	GLObal'naya NAvigatsionnay Sputnikovaya Sistema [Global Orbiting Navigation Satellite System, Russia]		
GLOUP	GLObal Undersea Pressure		

IDS	International DORIS Service	IRNSS	Indian Regional Navigation Satellite System
IERS	International Earth Rotation and Reference Systems Service (formerly: International Earth Rotation Service)	ISBN	International Standard Book Number
IfE	Institut für Erdmessung [Institute of Geodesy], University of Hannover	ISO	International Organization for Standardization
IGFS	International Gravity Field Service	ITRF	International Terrestrial Reference Frame
IGG	Institute of Geodesy and Geoinformation of the University of Bonn	ITRS	International Terrestrial Reference System
IGMA	ICG Monitoring and Assessment Task Force	ITU	International Telecommunication Union
IGN	Institut National de l'Information Géographique et Forestière (formerly: Institut Géographique National)	ITU-R	ITU Radiocommunication Sector
IGS	International GNSS Service (formerly: International GPS Service)	IUGG	International Union of Geodesy and Geophysics
IGS-RTS	IGS Real-Time Service	IVS	International VLBI Service for Geodesy and Astrometry
IHRS	International Height Reference System	Jason-CS	Jason Continuity of Service [mission]
IIUL	integrated IGS Ultra LODs	JCET	Joint Center for Earth Systems Technology, GSFC
ILRS	International Laser Ranging Service	JGR	Journal of Geophysical Research
ILRSA	ILRS official solution	JMA	Japan Meteorological Agency
INFN	Istituto Nazionale di Fisica Nucleare [National Institute for Nuclear Physics]	JPL	Jet Propulsion Laboratory
INT, Int.	Intensive [VLBI session]	JTRF	ITRS realization by JPL
Int.	International	KALREF	Kalman filter for Reference frames
IPGS	Institut de Physique du Globe de Strasbourg	kHz	kilohertz
IR	infrared	LAGEOS	Laser Geodynamics Satellite
IRIS	International Radio Interferometric Surveying	LAREG	Laboratoire de Recherches en Géodésie
		LARES	Laser Relativity Satellite
		LARGE	Laser Ranging to GNSS s/c Experiment
		lat	latitude
		LBA	Australian Long Baseline Array

LBO	Long Baseline Observatory	MX	Mexico
LDAS	Land Data Assimilation System	N	number
LEO	Low Earth Orbit(er)	N, E	north, east
LLR	Lunar Laser Ranging	NASA	U.S. National Aeronautics and Space Administration
LoD	Length of Day	NAVGEN	[U.S.] Navy Global Environmental Model
LOD	Length of Day	NCAR	U.S. National Center for Atmospheric Research
lon	longitude	NCEP	U.S. National Centers for Environmental Prediction
LQAC	Large Quasar Astrometric Catalog[ue]	ND	neutral density
LS	least-squares	NERS	Network Earth Rotation Service
MA	Massachusetts, USA	NEU	North, East, Up [position/coordinates/directions]
mag	magnitude	NGA	National Geospatial-Intelligence Agency
mas	milliarcsecond(s)	NGS	U.S. National Geodetic Survey
masec	milliarcseconds	NIR	near-infrared
Mb	megabit	NISAR	NASA-ISRO Synthetic Aperture Radar [satellite]
MCC	Russian Mission Control Centre	NIST	[U.S.] National Institute of Standards and Technology
MD	Maryland, USA	No., Nos.	Number, Numbers
MeO	Métrologie Optique [Grasse SLR/LLR system]	NOAA	U.S. National Oceanic and Atmospheric Administration
MGEX	Multi-GNSS [Global] Experiment, Multi-GNSS Extension	NP	SLR normal point(s)
MilliQuas	Million Quasars Catalog	NRT	Near Real-Time (products)
MIT	Massachusetts Institute of Technology	ns	nanosecond(s)
MJD	Modified Julian Day	NSF	US National Science Foundation
MLRO	Matera Laser Ranging Observatory	NSOAS	National Satellite Ocean Application Service
MOBLAS	Mobile Laser Ranging System	NTL	non-tidal loading
MPIfR	Max-Planck-Institut für Radioastronomie / Max Planck Institute for Radio Astronomy	NTP	Network Time Protocol
ms	millisecond(s)		
msec	milliseconds		

NTT	Ny-Ålesund Twin [Radio] Telescope	QSO	Quasi-Stellar Object [quasar]
OAM	Oceanic Angular Momentum	QZSS	Quasi-Zenith Satellite System
Obs.	Observatory, Observatoire, Observatório	RA	radio astronomy
OHIG	O'Higgins [station]	RA	right ascension
OP	Observatoire de Paris	RAEGE	Red Atlantica de Estaciones Geodinamicas y Espaciales
ORBEX	orbits exchange in SINEX-like format	REFAG	[Symposium on] Reference Frames for Applications in Geosciences
OTT	Onsala Twin [Radio] Telescope	RF	radio frequency
PANDOR	Pré traitement et ANalyse des mesures DORis	RFI	radio frequency interference
PC	Product Centre	RINEX	Receiver INdependent EXchange format
PDF	Portable Document Format	RMS	Root Mean Square
PLATO	Performance Simulations & Architectural Trade-Offs	RRFID	USNO Radio Reference Frame Image Database
PM	Polar Motion	RS/PC	IERS Rapid Service/Prediction Center
PMM	Plate Motion Model	RT	real-time
POD	Precise [or Precision] Orbit Determination	RT-AC	Real-Time Analysis Center
POLAC	Paris Observatory Lunar Analysis Center	RT-CC	Real-Time Combination Center
PP	Pilot Project	RTCM	Radio Technical Commission for Maritime Services
ppb	parts per billion (10 ⁻⁹)	RTS	IGS Real-Time Service
PPP	Precise Point Positioning	s/c	spacecraft
ps	picosecond(s)	SAA	South Atlantic Anomaly
PSD	post-seismic deformation	SARAL	Satellite with ARGOS and ALTIKA
PSMSL	Permanent Service for Mean Sea Level	Sat.	satellite
PZT	Photographic Zenith Tube [or Telescope]	SB	Special Bureau
QC	quality control	SBA	Special Bureau for the Atmosphere
QCB	Quality Control Board	SBCP	Special Bureau for Combined Products / Special Bureau for the Combination Products
		SBH	Special Bureau for Hydrology
		SBO	Special Bureau for the Oceans

SC	Special Committee	SyRTE	Systèmes de Référence Temps-Espace [department]
SDev	standard deviation	T2L2	Time Transfer by Laser Link
SDSS	Sloan Digital Sky Survey	TAI	Temps Atomique International (International Atomic Time)
SDSS DR	SDSS Data Release	TAROT	Télescopes à Action Rapide pour les Objets Transitoires
sec	second(s) [of time]	Tb	terabit
SGP	Space Geodesy Project	TBD	to be defined
SGSLR	Space Geodesy SLR [system]	TC	Technique Centre
SIC	Satellite Identification Code	TEC	Total Electron Content (Total Electron Count)
SINEX	Solution (Software/technique) INdependent EXchange Format	TECU	TEC Unit
SIRGAS	Sistema de Referencia Geocéntrico para Las Américas	TGAS	Tycho Gaia Astrometric Solution
SLR	Satellite Laser Ranging	TIO	terrestrial intermediate origin
SLRF	ITRS realization by ILRS	TN	IERS Technical Note
SNSPD	Super-Conducting Nanowire Single Photon Detector	ToR	Terms of Reference
SOFA	Standards Of Fundamental Astronomy	TRF	Terrestrial Reference Frame
SOKENDAI	Graduate University for Advanced Studies	TRS	Terrestrial Reference System
SOS-W	Satellite Observing System-Wettzell	TT	Terrestrial Time
SpinSat	Special Purpose Inexpensive Satellite	TTW	Twin [Radio] Telescope at Wettzell
SPOT	Satellite Pour l'Observation de la Terre	TU	Technical University
SRP	solar radiation pressure	TUM	Technische Universität München (Technical University of Munich)
SSALTO	Segment Sol multi-mission d'ALTimétrie, d'Orbitographie et de localisation précise	TWS	terrestrial water storage
SSEM	Station Systematic Error Monitoring	TX	Texas, USA
STD	standard deviation	U	University
SWOT	Surface Water Ocean Topography [mission]	UAW	GGOS Unified Analysis Workshop
		UBAD	USNO Bright-Star Astrometric Database
		UCAC	USNO CCD Astrograph Catalog
		UCL	University College London
		UK	United Kingdom

UKMO	Met Office (formerly: UK Meteorological Office)	UTC	Coordinated Universal Time
UMBC	University of Maryland, Baltimore County	UTGPS	Universal Time-like quantity using Global Position System
UN	United Nations	VCS	VLBA Calibrator Survey
UNAVCO	University Navstar Consortium	VEX	VLBI Experiment Documentation
UNB	University of New Brunswick	VGOS	VLBI Global Observing System
UN-GGIM	Global Geospatial Information Management Initiative of the UN	VLBA	Very Long Baseline Array, NRAO
UPC	URAT Parallax Catalog	VLBI	Very Long Baseline Interferometry
URAT	USNO Robotic Astrometric Telescope	VSH	vector spherical harmonics
URL	Uniform Resource Locator	VTRF	VLBI terrestrial reference frame
US, U.S.	United States	VTs	[Gaia] Validation Test Specification
USNO	United States Naval Observatory	w.r.t.	with respect to
USO	Ultra Stable Oscillator	WDS	ICSU World Data System
UT	University of Texas	WG	working group
UT, UT0, UT1	Universal Time	WISE	Wide-field Infrared Survey Explorer
UT2R	Universal Time	WRMS, wrms	Weighted Root Mean Square
UTAAM	NCEP [or NOAA] AAM analysis and forecast data	WSCS	weighted smoothing cubic spline
		yr	year
		ZPD	zenith path delay