

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

IERS Annual Report 2016

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IERS Annual Report 2016

Edited by Wolfgang R. Dick and Daniela Thaller

Technical support: Sonja Geist and Sandra Schneider-Leck

International Earth Rotation and Reference Systems Service
Central Bureau
Bundesamt für Kartographie und Geodäsie
Richard-Strauss-Allee 11
60598 Frankfurt am Main
Germany
phone: ++49-69-6333-273/261/250
fax: ++49-69-6333-425
e-mail: central_bureau@iers.org
URL: www.iers.org

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1 Foreword

Analysis of the International Terrestrial Reference Frame 2014 (ITRF2014) continued through 2016 culminating in the adoption of the of the new reference frame in early 2017. Ongoing documentation of the ITRF2014 resulted in the release of the Journal of Geophysical Research: Solid Earth paper in 2016 and the first of the IERS Technical Notes being released in early 2017. The last major piece of ITRF2014 documentation will be an additional IERS Technical Note providing further analysis of and comparison with the new terrestrial reference frame. It is expected that this Technical Note will be published later in 2017.

For the second year in a row, the IERS announced and implemented a leap second. This time the leap second was the last second of the year on 31 December 2016. Software in the IERS Conventions was changed to account for this additional leap second.

The symposium “Geodesy, Astronomy, and Geophysics in Earth Rotation (GAGER2016)”, cosponsored by the International Astronomical Union (IAU), International Association of Geodesy (IAG), and the IERS, was held 18–23 July 2016 in Wuhan, China. It is expected that the contributions to the symposium will be submitted to a special issue of the Journal of Geodynamics.

The first data release (DR1) from the European Space Agency’s Gaia mission was released in September 2016. This new source of celestial reference frame information will prove revolutionary to the scientific community and we commend the Gaia team for their excellent work.

The Working Group (WG) on Combination at the Observation Level, which began its work in 2009, concluded its efforts in 2016. We thank the WG Chair Richard Biancale and all of the WG members for their efforts in support of this important area of research.

The Bureau des Poids et Mesures (BIPM) phased out their support of the IERS Conventions Center in 2016. In response, the Observatoire de Paris joined with the U.S. Naval Observatory in co-directing the IERS Conventions Center. As a result, Christian Bizouard will now be co-director of the Conventions Center with Nick Stamatakos. In addition, Jean Souchay replaced Bryan Dorland as the IERS Directing Board (DB) member from the ICRS Center as part of the rotating co-directorship.

The IERS DB named Detlef Angermann as the IERS representative to the IAG Commission 1 Steering Committee and Richard Gross as the IERS representative to the IGS Governing Board.

Brian Luzum

2 The IERS

2.1 Structure

From 2016 to 2017, 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 2016 and 2017. For reports of components see [Chapter 3](#).

Analysis Coordinator Thomas Herring

Central Bureau *Director:* Daniela Thaller

Technique Centres **International GNSS Service (IGS)**

IGS Representatives to the IERS Directing Board:

Steven Fisher (until Feb. 2016), Tim Springer (until Feb. 2016),
Rolf Dach (since Feb. 2016), Chuck Meertens (since Feb. 2016)

IERS Representative to the IGS Governing Board:

Claude Boucher (until 19 Feb. 2016),
Richard Gross (since 20 Feb. 2016)

International Laser Ranging Service (ILRS)

ILRS Representatives to the IERS Directing Board:

Jürgen Müller (until 30 March 2016), Erricos C. Pavlis
Ludwig Combrinck (since 1 Apr. 2016)

IERS Representative to the ILRS Directing Board: Daniela Thaller

International VLBI Service for Geodesy and Astrometry (IVS)

IVS Representatives to the IERS Directing Board:

Chopo Ma (until 30 Sep. 2017), Rüdiger Haas,
Guanli Wang (since 12 Oct. 2017)

IERS Representative to the IVS Directing Board:

Chopo Ma (until 30 Sep. 2017), Rüdiger Haas (since 16 Oct. 2017)

International DORIS Service (IDS)

IDS representatives to the IERS:

Jérôme Saunier, Hugues Capdeville

IERS Representative to the IDS Governing Board:

Brian Luzum

Product Centres **Earth Orientation Centre**

Primary scientist and representative to the IERS Directing Board:

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:* Brian Luzum (until 31 Dec. 2015),

Gérard Petit (until 31 Aug. 2016),

Nick Stamatakos (since 1 Jan. 2016),

Christian Bizouard (since 1 Sep. 2016)

Current representative to the IERS Directing Board:

Brian Luzum (until 31 Dec. 2015),

Gérard Petit (until 31 Aug. 2016),

Christian Bizouard (since 1 Sep. 2016)

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

Bryan Dorland (until 31 Dec. 2016),

Jean Souchay (since 1 Jan. 2017)

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:*

Tonie van Dam (until Feb. 2016),

Jean-Paul Boy (since Feb. 2016)

Co-Chair: Jean-Paul Boy (until Feb. 2016),

Tonie van Dam (since Feb. 2016)

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 Combination at the Observation Level
(ceased operation in Apr. 2016)**

Chair: Richard Biancale

Co-Chair: Manuela Seitz

Working Group on SINEX Format

Chair: Daniela Thaller

Working Group on Site Coordinate Time Series Format

Chair: Laurent Soudarin

(Status as of December 2017)

2.2 Directing Board

In 2016 to 2017, the IERS Directing Board had the following members (for addresses see [Appendix 2](#)):

Chair	Brian Luzum
Analysis Coordinator	Thomas Herring
<i>Product Centres Representatives</i>	
Earth Orientation Centre	Christian Bizouard
Rapid Service/Prediction Centre	Christine Hackman
Conventions Centre	Brian Luzum (until 31 Dec. 2015), Gérard Petit (until 31 Aug. 2016), Christian Bizouard (since 1 Sep. 2016)
ICRS Centre	Bryan Dorland (until 31 Dec. 2016), Jean Souchay (since 1 Jan. 2017)
ITRS Centre	Zuheir Altamimi
Global Geophysical Fluids Centre	Tonie van Dam (until Feb. 2016), Jean-Paul Boy (since Feb. 2016)
Central Bureau	Daniela Thaller
<i>Technique Centers Representatives</i>	
IGS	Steven Fisher (until Feb. 2016), Tim Springer (until Feb. 2016), Rolf Dach (since Feb. 2016), Chuck Meertens (since Feb. 2016)
ILRS	Jürgen Müller (until 30 March 2016), Erricos C. Pavlis, Ludwig Combrinck (since 1 Apr. 2016)
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	Lestrade, Jean-François
Angermann, Detlef	Luceri, Vincenza
Arias, Elisa Felicitas	Ma, Chopo
Behrend, Dirk	McCarthy, Dennis D.
Bergstrand, Sten	Métivier, Laurent
Bianco, Giuseppe	Moore, Angelyn W.
Bloßfeld, Mathis	Müller, Jürgen
Boucher, Claude	Neilan, Ruth E.
Bruyninx, Carine	Noomen, Ron
Capitaine, Nicole	Pearlman, Michael R.
Chen, Jianli	Petit, Gérard
Chin, Mike	Ray, Jim
Collilieux, Xavier	Rebischung, Paul
Dawson, John	Reigber, Christoph
Dorland, Bryan	Rothacher, Markus
Fisher, Steven	Salstein, David
Gambis, Daniel	Seitz, Manuela
Garayt, Bruno	Shelus, Peter J.
Gaume, Ralph A.	Soudarin, Laurent
Gipson, John	Springer, Tim
Heflin, Mike	Stamatakis, Nick
Hugentobler, Urs	van Dam, Tonie
Johnston, Gary	Vondrák, Jan
Lambert, Sébastien	Weber, Robert
Lemoine, Frank	Willis, Pascal
Lemoine, Jean-Michel	Yatskiv, Yaroslav S.

Ex officio Associate Members:

IAG Secretary General: Drewes, Hermann
 IAU General Secretary: Benvenuti, Piero
 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 Subcommission 3.2: Shen, Zheng-Kang
 Chair of IAG Subcommission 3.3: Chen, Jianli
 President of IAU Division A: Lemaître, Anne

President of IAU Commission A1: Brown, Anthony G.A.
President of IAU Commission A2: Gross, Richard S.
President of IAU Commission A3: Hohenkerk, Catherine Y.

(Status as of December 2017)

3 Reports of IERS components

3.1 Directing Board

The IERS Directing Board (DB) met twice in the course of the year 2016. Summaries of these meetings are given below.

Meeting No. 62 April 17, 2016, Technical University of Vienna, Gusshausstr. 27, Vienna, Austria

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

Formalities The minutes of IERS DB Meeting #61 were distributed together with the agenda of DB Meeting #62.

Changes in IERS personnel Brian Luzum reported on changes in IERS personnel:

- New Conventions Centre representative: Gérard Petit
- New GGFC representative: Jean-Paul Boy (co-chair Tonie van Dam)
- New IGS representatives: Rolf Dach and Chuck Meertens
- New ILRS (LLR) representative: Ludwig Combrinck
- New primary scientist at USNO for Conventions Centre: Nick Stamatakis
- IERS representative to the IGS Governing Board: Richard Gross

Still open: IERS representative to IAG Commission 1 Steering Committee. (Remark: In the meantime, Detlef Angermann was nominated as the IERS representative.)

IERS Associate Members The current list was sent to the DB members in preparation of the DB meeting and presented during the meeting. The IERS DB members should send missing names to IERS Central Bureau until the end of the week. The list will be closed then.

New Action Item #62.01 Send missing names to IERS Central Bureau

IERS Convention Centre Gérard Petit reported on IERS Conventions updates:

- BIPM discontinues promotion of the IERS Conventions Centre co-chair (G rard Petit will continue to support the activities); the idea is that people presently involved in the Editorial Board (see presentation) take a more prominent role.
- Recent technical work in Chapter 7 (Conventional mean pole) and Chapter 9 (Model for atmospheric propagation delays)
- Open topics (e.g.): Chapter 11 (general relativistic models for propagation)

Discussion:

S bastien Lambert: OPA is in principle willing to coordinate the IERS Conventions Centre's activities, but this has to be clarified first with Paris Observatory.

New Action Item #62.02 Send official letter to resign from IERS Conventions Centre

ITRF2014 Zuheir Altamimi reported on the latest activities: The ITRF2014 was
Report from ITRS Centre published in January 2016, including

- 1499 stations located at 975 sites
- 91 co-located sites
- 36 new surveys
- 212 local tie vectors GNSS → other techniques (14 DORIS/DORIS)
- A dedicated website has been established: http://itrf.ign.fr/ITRF_solutions/2014/
- PSD models
- Seasonal signals available on request only

A web-based tool is in preparation for calculating the "observed coordinate".

Differences between VLBI- and SLR-derived scales found: possible alternative to the link via GNSS network?

One reason can be the small VLBI networks (85 percent of the sessions with only 3–9 stations).

Updating Chapter 4 of the conventions with models for non-linear station motion (PSD modelling).

ITRF2008 and ITRF2014 agree at the level of 5 mm.

DGFI and JPL solutions are ready and a Technical Note (TN) will be issued soon. A second TN on evaluations of the three solutions will be prepared, and all Technique Centres are invited to contribute.

An article on ITRF2014 was submitted to Journal of Geophysical Research.

Request by Rolf Dach: Provide seasonal signals for stations; put a related info on the ITRF2014 website that the seasonal signals are available.

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

Detlef Angermann reported on the latest activities: DTRF2014 is available at <ftp.dgfi.tum.de> (anonymous ftp): conventional solution (without non-tidal loading corrections).

Differences in the scale found between VLBI and SLR (see Test 3, DTRF2014 with VLBI defining the scale vs. 3 (11) SLR defining the scale). This raises the question to what extent the epoch of the calculation of the transformation parameters is significant.

Offset differences: ± 0.4 to 0.7 mm; rate differences ± 0.4 to 0.8 mm/yr (still small at 2000.0, but propagates in 2010.0: offset between 4 and 7 mm). Investigations via GNSS provide larger values for rates. Two major questions to be answered: How well is the datum transferred to the GNSS network? What is the reason for the rate differences between SLR- and VLBI-derived scale?

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

Richard Gross reported: The JTRF2014 is realized as a sub-secular frame at weekly intervals, containing in total 952 stations in the final solution, using a Kalman filter with linear, annual and semi-annual models. All local ties (old and new) are used with weighting.

- Comparison to ITRF2014: 1.6 mm/yr in scale at 2005.0
- Consistency with ITRF2014: WRMS below 5 mm
- No adjustment of VLBI and SLR scale: using the intrinsic scale coming from the network
- Solution format: 1838 SINEX files
- Website under development: with time series available
- Including post-seismic displacement

Large difference of 0.5 mm/yr between VLBI- and SLR-derived scales found (consistent to the values shown by Detlef Angermann).

Thomas Herring: use the 9 co-located stations to recalculate the scale differences.

Discussion

Thomas Herring: Take alternative approach “no difference in the VLBI and SLR scales” and find local ties, which support this approach.

All 3 ITRS Combination Centres should compare the coordinates and the scale for 9 co-located sites from the single technique solutions and the combined solution. Including the (new) ties. Epochs: 2000.0 and 2010.0.

Decisions All 3 ITRS Combination Centres compare for 9 co-located sites the single technique solutions and the combined solution.

New Action Items

- #62.03 Prepare IERS Technical Notes on ITRF2014 (including techniques' input solutions and validation of all three combined solutions)
- #62.04 Update Chapter 4 of the IERS Conventions
- #62.05 Info on ITRF2014 website that seasonal signals are provided upon request
- #62.06 Compare the 9 co-located sites solutions

**Reports from Technique
Centres
IDS**

Hugues Capdeville reported on the latest activities:

- Current DORIS network and operational status: 6 DORIS missions in flight with DGXX(S) Receiver; 3 future missions planned between 2018 and 2022.
- Analysis update: 6 active analysis centres, extended combined series and implementation of DORIS RINEX for the ACs.
- DORIS scale increase in 2012 understood (changes of tropospheric model).
- Evaluation of the DORIS versions of DTRF-, ITRF- and JTRF2014 solutions.
- Orbit comparisons w.r.t. DPOD2008 solutions.
- Switch to ITRF2014 products for IDS operational products:
 - IDS CC will compute its cumulative positions and velocity solution and DPOD solution using linear motions (without PSD). DPOD will be aligned to ITRF2014.
 - A few DORIS stations benefit from ITRF2014 PSD model.
 - IDS CC will use ITRF2014 (with PSD corrections) for the evaluation of DORIS products – decision to switch to ITRF2014 at next AWG meeting.
- IDS News:
 - Special Issue in Adv. Space Research: Improvements in DORIS analysis and work related to ITRF2014 (available in 2016).

- Next IDS Meetings:
 - IDS AWG May 26–27, 2016 at TU Delft
 - IDS Workshop Oct. 31 – Nov. 01, 2016 in La Rochelle

IGS Rolf Dach reported on the latest activities:

- Orbit combination changed from NGS to a consortium (Geoscience Australia and MIT), combination software now cloud based.
- ITRF2014 and way forward: ACs agreed to be prepared (except for JPL) to use ITRF2014 in the software, but IGS has to solve the orbit discrepancy (in x and y component).
- Review list of antenna calibration (ongoing work by R. Schmid), available in June; switch processing to ITRF2014 in early September.
- Extension from GPS/GLONASS to real multi-GNSS processing. Incorporation of new systems started, to be included in the legacy network. IGS products not to be affected by BeiDou orbit mismodelling.
- ESA took pre-launch calibrations from Block 2A Galileo satellites → GNSS can contribute to scale (2 independent sets of antenna calibrations)
- MGEX-related extension of the SINEX format (no GLONASS, no BeiDou yet): antenna serial number has to be extended from 5 to 20 characters.

ILRS Erricos Pavlis reported on the latest activities:

- Current ILRS network:
 - First station in India
 - Less than 12 stations are responsible for the bulk of the observations of the LAGEOS satellites.
 - Larger tracking capacity for the ILRS network expected with new technology systems
- Recent developments:
 - Working groups now called “Standing Committees” (following IAG rules)
 - Review and update of ILRS ToR underway
 - New “Quality Control Board” (QCB) established
 - Space Debris Study Group formed

- Network status
 - Several sites are now working routinely at kHz rates
- Analysis Activities:
 - Once the evaluation of the ITRF2014 by the ACs is completed, it will be adopted as the ILRS TRF standard for operations, analysis, data QC, etc.
 - Re-analysis of the data as soon as the ACs completely switched to ITRF2014
 - Pilot Project on station systematics in progress
 - New near real-time product
 - ILRS special issue in the Journal of Geodesy in preparation
- General ILRS Issues/Concerns
 - More on-site tools needed for diagnostics and real-time performance assessment
 - Mix of legacy and modern technologies → quality affected until majority of the stations adopt the new technologies.
- Future meetings
 - Next ASC (Analysis Standing Committee) meeting scheduled for April 22 during EGU 2016.
 - 20th Int. Workshop on Laser Ranging hosted by GFZ Potsdam, Germany, October 9–14, 2016.
 - 21st Int. Workshop on Laser Ranging will be hosted by SERC in Canberra, Australia, in 2018.

IVS Rüdiger Haas reported on the latest activities:

- 9th IVS General Meeting March 13–19, 2016 and 2nd IVS VLBI school March 9–12, 2016 in South Africa (all material from the IVS school is available on EVGA website <http://www.evga.org/>)
- IVS strategic plan finalized (will be available on IVS webpage)
 - Frequency range 3–14 (18) GHz
 - Transition and operational phase
 - Different products (ultra-rapid, rapid, intermediate, final)
 - 24/7 mode
 - UT1–UTC every 3 h
- VGOS development
 - 3-station broadband network in North America

- VGOS projects make progress (Ishioka, Ny-Ålesund, Onsala, Shanghai, RAEGE, ...)
- VGOS Twin Telescopes in Wettzell, Ny-Ålesund and Onsala
- IVS evaluation of the ITRF2014 solutions:
 - 2 types of comparisons: (1) Regenerate 2013 products with ITRF2014, and (2) Compare EOP series from solutions where positions/velocities are fixed to ITRF2008, ITRF2014 (incl. PSD) and DTRF2014.
 - Seasonal models: IVS will request the models for AC evaluation
- X-Pole discrepancies between VLBI solution and IGS
 - Systematic difference in X-Pole between IVS Combination and IGS to be studied

Comments Zuheir Altamimi: Acknowledgment of the contributions by the Technique Centres to the ITRF2014.

Daniela Thaller: Make all three ITRF solutions as well as the final Techniques' input solutions publicly available at IERS ftp server.

New Action Items #62.07 Extend antenna serial number in SINEX format
 #62.08 Make Techniques' contributions to ITRF2014 publicly available at IERS ftp server
 #62.09 Make all 3 ITRF2014 combinations publicly available at IERS ftp server

Symposium on Earth Rotation 2016 Richard Gross presented the Symposium on Earth Rotation 2016 taking place on July 18–23, 2016 in Wuhan, China.

Report on new structure of IAU Richard Gross presented the new structure of IAU:
 In the old structure, Commission 19 "Rotation of the Earth" was organized by IAU Division I. The new structure required a re-application of the commissions followed by a selection process: Division A Fundamental Astronomy now hosts Commission A2 "Rotation of the Earth".
 S. Lambert: New Journées probably in 2017; OPAR is interested in continuing to organize the Journées.

EOP Products Earth Orientation Centre Sébastien Lambert reported on the latest activities:

- New C04 series: alignment to ITRF2014 with new weighting algorithm; not replacing the current C04 yet, but operational at OPAR website ftp://hpiers.obspm.fr/iers/eop/eopc04_14/

- Nutation comparisons: new C04 should be strictly the ITRF2014 with direct combination of dX,dY/IAU2000
- Open questions:
 - Replace C04 x,y pole coordinates by ITRF2014 solution over the interval 1993–2015 as proposed by Z. Altamimi?
 - When making it official?
- C04 2008 still available till the end of 2017
- IERS EOC website <http://iers.obspm.fr/eop-pc> with new web tools

Discussion:

T. Herring: Possibly use the Technique Centers' combinations.

T. Herring: IGS needs to prepare the new antenna models before switching to ITRF2014 (including EOPs); this is not expected to be finished before September 2016.

DB: Discuss C04 and decision on making it official at December 2016 DB meeting?

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

Christine Hackman reported on the latest activities:

- Mission, products, staff:
 - Mission: provide rapid-turnaround EOPs for real-time (highest quality)
 - Products: weekly, daily, sub-daily. Now also available on the CDDIS server (maia.usno.navy.mil, toshi.nofs.navy.mil and [ftp://cddis.gsfc.nasa.gov/pub/products/iers](http://cddis.gsfc.nasa.gov/pub/products/iers))
- Status eVLBI to Kokee Park Geophysical Observatory:
 - Restored at Kokee → increased latency impacted UT1–UTC estimate/prediction accuracy
- Products 2015:
 - Values downloaded to 26859 unique IP addresses (2014: 18025)
- Other items:
 - NAVGEM v1.3 replaced v1.2 in operations
 - Test NTP UT1 service set up at NIST

Decision Wait until the techniques are ready before switching to C04 ITRF2014.

New Action Item #62.10 Decide on switch to C04 ITRF2014 at DB meeting in December

IERS Technical Notes on ITRF2014 Schedule: e.g. end of 2016. Input from the Technique Centers needed first (the individual technique solutions and the validations of the 3 combined ITRF solutions).

New Action Item #62.11 Send an email to the Techniques' Analysis Coordinators

IAG Service Assessment Questionnaire How to handle the suggestions by the IAG Service Assessment (ISA) Team?

It is still not clear what the IAG expects the services to do. Suggestion by Z. Altamimi: He will bring up this question at the IAG Executive Committee meeting (the week after EGU).

Some comments in the ISA document seem to be a misunderstanding or a lack of information on the reviewers' side.

New Action Item #62.12 Clarify with IAG what the services are expected to do with the ISA

Next UAW or IERS Workshop Is there a need to organize an IERS workshop on a dedicated topic? Should the IERS hold a workshop independently from the UAW?

Discussion: The scale issues in ITRF2014 could be a topic. But investigations (see earlier discussions) need to be done first.

Detlef Angermann: For the next UAW it is important that people from geometry and gravity are present.

Decision No dedicated topic for a workshop at the moment.

ICRF3 status Bryan Dorland reported:

ICRF3 goals (e.g.)

- Competitive in precision with Gaia ($\sim 70 \mu\text{as}$)
- Improved southern coverage
- Complete ICRF-3 by 2018 (Gaia comparison)

P. Charlot took over as chairman of the WG from C. Jacobs.

ICRF3 WG status

- Most recent ICRF3 WG meeting at IVS GM in South Africa
- Work underway to assess radio/optical tie issues

- Gaia frame tie densification, K-band densification underway
- VLBA Cal Survey-II (VCS-II) re-observation completed

ICRF3 schedule: adoption of ICRF3 by IAU in July 2018 New ICRS

Working Group

- Division A “WG on Multi-waveband Realisations of International Celestial Reference System” (WG190) to investigate issues

To Action Item #61.02: Joint IAG/IAU WG: A. Nothnagel asked P. Charlot about this point, but got a negative response.

B. Dorland: Formal validation process? For ICRF2, a comparison was done internally in the working group (but it was a joint WG).

GGOS and WDS

WDS: Should more data be included in the IERS data base than described by metadata?

Bernd Richter reported on GGOS activities:

- GGOS Coordinating Office is transferred to the BEV (National Austrian Agency for Metrology and Surveying)
- CfP on Focus Area 2 (Early warning systems)
- GGOS participation in GEO (advocacy and outreach)
- GGOS support letter for E-GRASP Mission

GGOS committees and Working Groups

- Joint GGOS Committee / Sub-Commission 1.2 Working Group on Performance Simulations and Architectural Trade-Offs (PLATO)
- Committee on Data and Information
- Committee on Satellite Missions
- Committee on Contributions to Earth System Modeling
- Working Group on ITRS Standards
- Joint Working Group (JWG) on Strategy for the Realization of the International Height Reference System
- JWG on Establishment of the GGRF

Reports from Working Groups ***WG on Site Survey and*** ***Co-location***

Rüdiger Haas gave the presentation on behalf of S. Bergstrand:

- Resolution on the nomenclature of space geodetic reference points and local tie measurements

- One point of contact at each Technique Centre
- Local tie / site survey
- Comparison of IVS and IGS baseline with terrestrial and GNSS-based local ties
- No improvement at co-located sites for ITRF2014 combination
- Common terminology (within the IERS components) established for local tie measurements
- A Technical Note on Site Survey Guidelines is to be published (ready approx. June).

Issues for the Directing Board:

- Distinguish between Analytic and Surveyed Ties?
- How to give scientific credit for maintenance?
- Surveys should be repeated, not reinvented: How to ensure support for maintenance?
- Considering that the limiting factor for accuracy is the GNSS based 3D orientation, and that the GNSS antenna is the cheapest component. Development and manufacturing of ~ 100 customized core station antennas?

D. Thaller: Include IERS Central Bureau in the email distribution list.

***WG on Combination at the
Observation Level***

Detlef Angermann presented the status of the COL on behalf of Richard Biancale:

- COL objectives
 - Study methods and advantages of combining techniques at the observation level
- Last COL meeting in February 2016: closing of the WG proposed
- Proposal to join the IAG/GGOS PIATO WG as the topics are similar

Discussion and Decision: The IERS WG will be closed. The further activities will be included in the Joint WG PLATO. Results of the WG should be documented as a TN if possible.

WG on SINEX Format

Daniela Thaller reported that three activities are ongoing:

- IGS: extend the line length to include the antenna serial number; will circulate the proposal within the WG

- Add information on number of observations per parameter (e.g. source coordinates)
- ITRF2014 PSD modelling to be included in the SINEX format

New Action Items #62.13 Draft a TN on the results of the WG COL
#62.14 Publish TN on Site Survey Guidelines

Annual Reports Up to now: one contribution to the AR 2015 received (deadline was end of March).
An email was sent out to ask if AR contributions should change to $\LaTeX$. Most of the contributors agreed to contribute in $\LaTeX$; few contributors announced to continue to submit in Word format.

Decision Starting with AR 2016, the contributions should be submitted in $\LaTeX$.

New Action Item #62.15 Draft $\LaTeX$ template for AR contributions

Next IERS DB meeting The next DB meeting (half-day meeting) will take place on Saturday December 10, 2016 before the AGU in San Francisco. Changing from Sunday to Saturday will avoid the conflict with the IGS meeting.

New Action Item #62.16 Prepare IERS DB meeting #63

Meeting No. 63 December 10, 2016, Hotel Marriott Marquis, San Francisco, USA

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

Action items of DB meeting #62 The minutes of IERS DB Meeting #62 were distributed together with the agenda of DB Meeting #63.

Changes in IERS Directing Board, and election of the Chair New DB members:

- Conventions Centre representative: Christian Bizouard
- ICRS Centre representative: Jean Souchay

Other changes:

- IERS representative to IAG Commission 1 Steering Committee: Detlef Angermann

The IERS DB thanks the members who left for their work and contribution.

Re-election of the IERS DB Chair: Brian Luzum is willing to continue. No other persons were named. 10 voting members and 4 proxies (with voting rights) are present: 14 voting members (out of 18).

No objections. Brian Luzum will continue as Chair for 4 years.

Associate Members

Associate Members: no further comments on the list (list will be updated once a year).

Note: former DB members can stay Associate Member if they want. Functional constraints apply rather than geographical constraints.

Harald Schuh noted that Members at Large could also be nominated as a function of countries to help keep a geographic balance.

Reports from Technique Centres

IDS

Hugues Capdeville presented the IDS report:

Missions

Currently 6 DORIS missions in flight; several new missions planned starting in 2018. Proposal for E-GRASP/Eratosthenes (ESA Earth Explorer-9 mission) will be submitted to the new ESA/EE9 call in 2017.

Network

- 59 stations of which 11 beacons are out of order
- 2 new sites (Managua, Nicaragua and Wettzell, Germany) and one re-location at Kitab, Uzbekistan
- Several new stations planned

Analysis update

- Six active DORIS Analysis Centres
- Extension of combined series from 2014 doy 362 to 2016 doy 178
- Work in progress: implementation of DORIS RINEX data processing since the launch of Jason-3, Sentinel-3A; work on open points following the ITRF reprocessing (scale increase in 2012, scale issues on SPOT-5 and increase of DORIS residuals)
- Jason-2 and Jason-3 SAA sensitivity: impact on station position estimation. SAA minimization strategy is currently under development.
- Construction of a new DPOD2014 (DORIS cumulative position/velocity solution based on the IDS combined series) associated with ITRF2014. Will be provided by IDS CC to the IDS DPOD validation group for internal and external validation. Switch to ITRF2014 will

be adopted when the ACs use the DPOD2014 for submissions to IDS CC.

IDS news

- DORIS Special Issue (Adv. Space Research) published as Vol. 58, Number 12 on Dec. 15, 2016.
- IDS Newsletter launched in April 2016. 2 issues published since.

IDS meetings

- IDS Workshop 2016 (October 31 – November 01) in La Rochelle
- Next IDS AWG: May 2017 in London

Zuheir Altamimi commented: Discrepancies between the DORIS-to-DORIS tie vectors of larger than 5cm: not to be constrained too strong (only NNR, why not NNT).

IGS Paul Rebischung presented the IGS report:

IGS transition to ITRF2014

- Reference frame switch Igb08→IGS14
- Ground and satellite antenna calibration updates igs08.atx→igs14.atx
- IGS14 (subset of 252 well-suited RF stations from ITRF2014) & IGS14 core (51 primary stations) network design
- Impact on IGS daily frame alignments: re-combined daily repro2 AC solutions with satellite PCOs fixed to their igs14.atx values and daily combined solutions aligned to the IGS14 core network leading to notable improvement after 2010
- Impact on IGS EOPs and geocentre: pole coordinate differences entirely due to the RF change; pole rate and LOD differences insignificant; apparent geocentre coordinate differences mostly due to the RF change
- Impact on IGS terrestrial scale:
 - Mean scale: igs14.atx coincides with ITRF2014 scale at epoch 2010.0, but progressively diverges with time
 - Scale rate: closer to ITRF2008 scale rate than to ITRF2014 scale rate
 - Non-linear scale variations: non-linear, non-seasonal variations less scattered with igs14.atx

- Implementation schedule: preliminary IGS14/igs14.atx made available in July, waiting for IERS DB and IGS GB approval to set the date of the official switch and announce via IGSMail

IGS Workshop

Next workshop: First week in July 2017 in Paris. Workshops: review progress in the working groups and the facilities of the IGS, recommendations of last workshops, dedicated open meeting tomorrow from 9 to 11h (IGS Associate Members).

Miscellaneous

- Transition to RINEX 3 is making progress, not yet finished.
- Infrastructure for legacy stations, process finished in 2017.
- MGEX integrated into network.
- ITRF2014: ACs are prepared to use the data. Since October 2016, both solutions run in parallel. First evaluation did not show any surprises: IGS is ready to switch by the end of January 2017.

ILRS Erricos Pavlis presented the ILRS report:

Recent ILRS developments

- ILRS International Workshop was held 10-14 October, 2016 at GFZ Potsdam, Germany
- Review and update of ILRS Terms of References completed and approved by IAG
- Quality Control Board (QCB) meeting monthly by telecon. Plans the next phase of the implementation of near-real-time QC analysis tools

ILRS Network

- New initiatives in Russia; anachronistic mix of new and legacy technologies; expanded use of the newer technologies to move from legacy to new technology status
- New systems operational in 2016 in Wettzell and Sejong and rebuilt systems in Borowiec and Riga
- Activities in the Russian and Chinese network and in the NASA SGP
- New SLR systems underway; several sites are now working routinely at kHz rates

Mission News & Support

- Three 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 in progress
- Pilot Project on station systematics in progress
- New products related to near real-time system evaluation are in development stage

Effect of ITRF Switch on EOP

- 1,5 mas differences in x-pole between JCET and ILRSA
- ILRS EOP differences SLRF2008 – ITRF2014: ILRS has not implemented ITRF2014 yet

Conventional mean pole

- A climate driven polar motion has been observed. Suggestion: adapt the proposed subroutine in the IERS 2010 Conventions.
- Differences of the mean pole have been observed related to the download epoch

Meetings and Workshops

- Next ASC meeting: Saturday, April 22, 2017 prior to the EGU 2017 in Vienna
- Technical Workshop on Laser Ranging foreseen for fall 2017 in Riga, Latvia
- 21st International Workshop on Laser Ranging: November 4–9, 2018 in Canberra, Australia

Miscellaneous

- ILRS ACs: ITRF2014, Pilot Project, new products related to real-time system evaluation.
- An ILRS special issue is planned to appear in Journal of Geodesy

IVS Chopo Ma presented the IVS report:

Transition from ITRF2008 to ITRF2014

- Comparison of the two VLBI solutions of ITRF2008 and ITRF2014 (prepared by GSFC AC, Dan MacMillan): x-pole ripple visible and a small drift (NNR and NNT on station coordinates): frame rotation is reflected in EOP and EOP rates, rz rotation

**ITRF2014 and IERS Technical
Notes on ITRF2014: Status
and way forward
Report from ITRS
Combination Centre at DGFI**

Mathis Blossfeld reported on the activities of the DGFI ITRS CC:

Comparison of the three ITRF solutions

Parameterization of station coordinates:

1. expansion of the mathematical model by PSD model;
 2. improvement of the geophysical models (atmospheric and hydrological loading);
 3. estimating epoch reference frames
- Models do not always match well compared between the three solutions

DTRF2014 additional models are available for interested users. Solution specific systematics are raising questions:

- Are the ITRF realizations comparable?
- Does the IERS need common standards?

More comparisons needed between the three solutions.

**Report from ITRS
Combination Centre at JPL**

Richard Gross reported on the activities of the JPL ITRS CC:

JTRF2014

JTRF2014 results and comparisons were shown in the presentation:

- Three-Cornered Hat on (Tx, Ty, Tz) between JTRF, ILRS and geophysical inversion
- Annual components in amplitude and phase
- Semi-annual harmonics
- Inter-Annual Components Tx, Ty, Tz

Correlations in ground deformation

The objective is improving the geocentre location with sparse stations. The correlations in ground deformation is effectuated by longitudinal

limits in the correlation in long wavelength (nearby located stations; only based on ground deformation) and a translation caused by the deformation.

Joint TRF / CRF / EOP determination

Project started. The objective is to improve the consistency of TRF, EOP, and CRF using a Kalman filter CRF and jointly determine TRF/EOP/CRF.

Miscellaneous

- Work on a website to release the time-series is in progress.
- Journal article is in progress.

Tom Herring: no linear model

Report from ITRS Centre at IGN

Zuheir Altamimi reported on the activities of the IGN ITRS CC:

Summary on the ITRS Centre activities

- The new ITRF website is delayed to mid 2017
- Local survey operational entity (recognize as an official IERS entity): TN note will be ready by January–February. The operational entity should be recognized by the IERS as a fundamental component of the ITRS Centre.

ITRF2014 related activities

- ITRF2014 was published in January 2016
- An article in Journal of Geophysical Research was published in July 2016
- ITRF2014 plate motion model will be released: work in progress
- Update of Chapter 4 of the IERS Conventions

IERS Technical Notes

- TN1: On the official ITRF2014: will be ready by January 2017
- TN2: Evaluation of the three ITRF solutions ITRF, DTRF, and JTRF. Techniques Centres are also invited to contribute. Deadline is end of March 2017.
- The ITRS Centre started an evaluation/comparison of DTRF2014 & JTRF2014. Results will be available by Jan.–Feb. 2017.

DORIS, SLR & VLBI scale issues

- Reason for DORIS scale differences understood (see presentation on IDS: DORIS scale is 0.4 ppb higher than VLBI); no significant drift between the solutions, but offset visible.
- Impact of SLR range bias on the scale: VLBI-SLR = -1.37 ppb; VLBI-DORIS = 0.48 ppb

Harald Schuh noted that an external evaluation would be useful. Proposal: use ITRF2014 EOP series and not wait for IERS 14 C04.

Daniela Thaller noted that the timeline for TN2 is too short, because first the comparisons have to be done; the deadline should be at least end of May 2017.

Comparisons regarding scale issues

Tom Herring reported on SLR/VLBI scale differences DTRF vs ITRF:

- Idea: Directly compare the scale differences between the DTRF and ITRF realizations of the SLR and VLBI frames.
- DTRF to ITRF comparison: SLR scale difference 0.63 ppb; VLBI scale difference 0.11 ppb
- Scale rate difference between DTRF and ITRF: SLR 0.018 ± 0.007 and VLBI 0.00 ± 0.01 ppb/yr

Decisions

Deadline for TN2 for the inter-comparisons by May 2017. All ITRF Combination Centres are listed as co-authors.

External evaluation should be done after an internal evaluation is done (time frame still to be decided).

Generate and publish accumulated solutions (coordinates + velocities) in SINEX format by each Technique Centre

New Action Items

#63.01 Send out an email to the Analysis Coordinators of the Technique Centres, and the ITRS Combination Centres asking for contributions to the TN2 on ITRF validations and comparisons.

#63.02 Ask Technique Centres to publish global solutions (coordinates + velocities) in SINEX format. At least for their input to ITRF2014, better also in an operational manner (as IGS does).

#63.03 Draft TN1 on the ITRF2014 (follow-on AI to #61.03 and #62.03)

#63.04 Draft TN2 on the evaluation of the three different ITRS realizations (DTRF2014, ITRF2014, JTRF2014).

EOP Products (esp. update for ITRF2014) Report from Earth Orientation Centre

Sébastien Lambert provided information on the EOP products:

EOP 14 C04 series consistent with ITRF2014 and ICRF2?

- 08 C04 pole coordinates consistent with ITRF2014? → A bias in the Y-pole can be observed when comparing 08 C04 to ITRF2014 and also in comparison to IVS and IGS Final EOP
- Consistency with ICRF2? → Inconsistencies can be observed after 2010, as well.

14 C04: an improved procedure

- dX / dY (with respect to IAU 2000 Precession-nutation model) are directly combined; paper in preparation
- Network effects visible in trends of individual series – guide series are modeled by continuous piecewise linear function
- Re-computation since 1984

Results

- Improvement for dX, dY: 30/40 μas (instead of 60 μas)
- Improvement for UT1: 4 μas (instead of 14 μas)
- 14 C04 better reproduces IVS (UT1, dX, dY) and ITRF2014 (x, y) series, confirmation by Allan Deviation analysis 1993–2015

Recommendations and roadmap

- Adopt 14 C04 on February 1st, 2017
- Full description to be published in Journal of Geodesy 2017
- Unchanged directory for downloading from Paris Observatory server
- 08 C04 will be produced until February 2018, but moved into another directory

Notes: 14 C04 epochs are at noon and ITRF2014 epoch at midnight (should be zero; interpolation?).

Rapid Service / Prediction Centre

Christine Hackman reported on the Rapid Service / Prediction Centre:

Mission, products, staff

- Mission: provide rapid-turnaround EOPs for real-time users
- USNO RS/PC estimates use the IERS final product C04 as a benchmark and are designed to follow it at long time periods.

- Products (different formats; IAU1980 & 2000): Weekly (Thursday): IERS Bulletin A; Daily (~ 17:30 UTC): estimates, predictions; Sub-daily (21:00, 03:00, 09:00) estimates, predictions
- Download: [maia.usno.navy.mil](ftp://maia.usno.navy.mil) (ftp, http); [toshi.nofs.navy.mil](ftp://toshi.nofs.navy.mil) (ftp, http); <ftp://cddis.gsfc.nasa.gov/pub/products/iers>
- Staff: C. Hackman (primary scientist), N. Stamatakos (production director; lead project scientist), M. S. Carter, N. Shumate, M. Davis

RS/PC procedure for IERS ITRF transition

- RS/PC products aligned to OP C04
- OP C04 aligned to ITRF
- RS/PC thus transitions to 14 C04 (and hence ITRF2014) as follows
 - Compute new systematic corrections between each input data source (e.g., VLBI, GNSS) and 14 OP C04 (takes place before OP officially switches to 14 C04, but as close to official switch as possible); use measurements from MJD 50000 (10 Oct. 1995) forward
 - Implement new system in Bulletin A on Thursday following C04 transition (Bulletin A predictions and estimates going back 365 days are directly computed in new system using new systematic corrections; estimates older than 365 days are aligned to new system using line fit)
 - Implement in daily/subdaily solutions on C04 transition day

Expected transition discontinuities

- Bulletin A: evaluate Dec./Jan. due to Feb. 2017 proposed C04 transition date (using one file before the switch and another after the switch)
- Experience from transition 05 C04 to 08 C04 (1 Feb. 2011):
 - RMS 76, 70 μ as for PMx, y
 - RMS 6.8 μ s for UT1–UTC

Decisions

Replace TN planned for 08 C04 by TN on 14 C04.

Ask C. Bizouard how the interpolation is done and where the differences between 14 C04 and ITRF2014 EOP come from.

Adopt 14 C04 in February 2017.

New Action Items

#63.05 Announce switch to 14 C04 via IERS Message

#63.06 Draft TN on 14 C04

How to switch to ITRF2014:	The DB proposed January 28, 2017.
Status and way forward	IDS: will not be ready to do the transition before February 2017. IGS: needs to resolve the remaining inconsistencies between ultra-rapid, rapid and final products. Transition foreseen for February 2017. Earth Orientation Centre: preliminary version has to be checked → The Technique Centres need to provide their solutions ~2–4 weeks ahead.
Decision	Central Bureau write this up and send an email to the Technique Centres.
New Action Item	#63.07 Document the plans for switching to ITRF201 and send an email to the Technique Centres
Potential upcoming modifications to the IERS Conventions 2010	Nick Stamatakis reported: Chapter 7 software implementing the leap second Updating W0 Update mean pole definition. Zuheir Altamimi: will provide Chapter 4 update. Modify the Conventions to make them easier to read and to change less frequently to address the concerns of the users. An example of such a revised chapter will be presented at the next DB meeting.
Decision	Update Chapter 4 of IERS Conventions (see also Action Item #62.04).
Report on Symposium on Earth Rotation 2016, Wuhan	Richard Gross reported on the GAGER2016 symposium: Proceedings will be published as a Special issue of Geodesy and Geodynamics (Elsevier). Furthermore, a Journées-like meeting will take place on September 25–27, 2017 in Alicante (Spain) on the theory of Earth rotation and reference frames and other Journées-like subjects. IAU General Assembly: a Symposium on earth orientation and reference frames has been proposed for 2018. 2019: 100th anniversary of the Commission A2 (“Earth Rotation”) of IAU; a dedicated symposia is planned to be held in Brussels.
UAW 2017	The UAW 2017 will take place on July 10–12 in Paris hosted by IGN at Université Paris Diderot, jointly organized by IAG and GGOS. The topics will be: • Technique-specific data & products: technique-specific biases & systematic errors; model improvements

- Combined data & products: progress towards combination at observation level; possible new combined products
- Reference systems and frames: limitations in current approaches; limitations of data & products used to determine TRF; progress towards a unified height system
- Standards, conventions & formats: inclusion of metadata; SINEX format extensions

Feedback is expected by end of December (January) related to experts and topics. UAW 2017 is planned as a closed workshop (each Service can nominate 5–6 technical experts, also gravity service and GGOS).

New Action Item #63.08 Send out a reminder for nominating IERS delegates and topics with the slides to the DB members.

IERS Workshop The IERS will have its 30th anniversary in 2018. An IERS Workshop is planned to be celebrate this event. A host and topics should be identified by the next DB meeting.

New Action Item #63.09 Identify possible hosts and topics for an IERS workshop in 2018

Status of ICRS/ICRF and IAU Working Group

Bryan Dorland gave an ICRF3 status update:

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 ICRF-3 by 2018 (Gaia comparison)

ICRF3 Schedule

- ICRF3 is scheduled to be ready by January 2018 and will be adopted by the IAU by October 2018.

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
- K-band densification
- X/Ka data continues to be taken and processed.
- 100 μ as zonal declination errors being investigated for all bands: S/X, K, X/Ka
- Images available for S/X and K-bands

VCS-II Observations

- 2400 sources observed within the VCS-II campaign

X/Ka and K-Band densification

- K-band existing (Lany+, Charlot+)
- Data completing full sky from (Australia – South Africa) being processed
- De Witt et al. VLBA program underway to densify the north. Expecting > 500 sources total

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) – Sept. 2016; DR2+ ~Nov. 2017, approximately yearly thereafter
- Tying reference frames: ongoing work to look at Gaia optical-to-ICRF radio reference frames

Summary and Future Work

- Candidate catalogs in S/X, K and X/Ka compiled (under evaluation now for possible inclusion in ICRF3)
- Next step: preparation of final component catalogs
- Single wavelength vs. multiwavelength?
- On-track for 2018 adoption

- First Gaia data release received; evaluating Gaia accuracies and resultant reference frame
- Potential increased use of VLBA to support ICRF3 work
- Additional work to be done in 2017 on imaging database (i.e., source structure)

Annual Reports Annual Report 2015: Most of the contributions have been received. The AR 2015 will probably be published by the end of 2016.
The AR 2016 will be prepared in $\LaTeX$ format.

Next DB meeting The next DB meeting will be an all-day meeting and will take place on Sunday, April 23, 2017 before the EGU.

New Action Item #63.10 Prepare next DB meeting #64 in Vienna

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. 62, April 17, 2016, at Technical University of Vienna, Austria, and No. 63, December 10, 2016, at Hotel Marriott Marquis, San Francisco, California, 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: 9th IVS General Meeting, European Geosciences Union General Assembly 2016 (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”), the conference “The Science of Time: Time in Astronomy & Society, Past, Present and Future”, 20th International Workshop on Laser Ranging, and AGU 2016 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 2016 the web site was continually updated, several new pages and documents were added. New pages include a compilation of tools provided by all IERS components. 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 and added some new documents to these pages. In an internal area, accessible for DB members and IERS Associate Members, all presentations given at IERS DB meetings since 2000 were made available.

The IERS Annual Report 2014 was printed and distributed. The CB edited the IERS Annual Report 2015 and published it online in December 2016. 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, and drafted a report of the Working Group on Site Coordinate Time Series Format. Starting with the report for 2016, the CB will use $\text{\LaTeX}$ instead of InDesign for formatting the IERS annual reports. For this a $\text{\LaTeX}$ template was developed.

The contribution of IERS to IAG’s “The Geodesists’ Handbook 2016” was submitted in June 2016 (open access: <https://link.springer.com/article/10.1007/s00190-016-0948-z>).

During the year 2016, 33 IERS Messages (Nos. 287–319) 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 2016 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. In connection with the leap second at the end of 2016, the CB received several requests from newspapers and radio stations. Also public popular talks about the leap second and its background were given.

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 was also a member of the UN Working Group GGRF (Global Geodetic Reference Frame) and contributed to the “Roadmap for the Global Geodetic Reference Frame for Sustainable Development”, endorsed by the UN-GGIM 6th session in August 2016. 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 2016 further developments of the IERS DIS concentrated on the new system for data management, the development and improvement of interactive tools, and some improvements to the address management.

Together with a software company, a concept for improving the management system for IERS data was developed and the implementation of a first draft of the new system was installed within a testing environment. In addition, the parsers used in the existing system and the data download were optimized.

For higher security, the IERS web server was moved from http to the https protocol. Improvements were made to the Content Management System used for the IERS web site.

Further improvements of the IERS DIS included the following:

- The different output formats of the IERS products were homogenized.
- XML schemes for IERS Bulletins C and D were written.

- The search for users in the address management system by the system managers was enhanced.
- Guiding external users through the address management system was improved.
- The EOP Reader was connected with the IERS Plot Tool for better service.
- New IERS web services for EOP, leap seconds and time scales were developed.
- A tool to manage the lists of acronyms used in the web site and in the IERS annual reports was created.

In preparation to a forthcoming major change of BKG's IT infrastructure, a detailed description of all components of the DIS (hardware, software, interfaces) was prepared.

Staff in 2016

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

Wolfgang R. Dick, Daniela Thaller, Sonja Geist

3.3 Analysis Coordinator

Introduction

In this report, we outline the activities of the Analysis Coordinator during 2016. The main activities were an investigation into the scale differences between the ITRF2014 and DTRF2014 systems for the VLBI and SLR stations, and preparations for the Unified Analysis Workshop (UAW) to be held in 2017. The organization of the 2017 UAW is being led by GGOS.

VLBI/SLR scale differences between ITRF2014 and DTRF2014

Preparations for the transition from ITRF2008 to ITRF2014 are well underway and the IGS will transition on January 29, 2017 (GPS week 1934 day 0). For the IGS, there are two major changes associated with this switch: (1) A new set of coordinates, velocities and, for some stations, post-seismic deformation models are being adopted for the core set of IGS sites that define the IGS realization of the ITRF2014 system; and (2) the antenna phase center models are being changed for the GPS satellites and for some GPS ground antennas. The changes to the IGS antenna calibration models were mostly due to the introduction of Earth albedo and antenna thrust models that effectively increased the altitudes of all the GPS satellites resulting in a small terrestrial scale change of ~ 0.3 ppb. The GPS terrestrial scale was aligned to the ITRF2014 scale by systematic changes of the radial coordinate of the GPS satellite antenna phase center relative to center of mass. The small -0.02 ppb scale difference between ITRF2014 and ITRF2008, at epoch 2010.0, was also included in the change to the satellite antenna phase center positions. There is however a scale rate difference between ITRF2014 and ITRF2008 of 0.03 ± 0.02 ppb/yr and this rate difference can clearly be seen in the IGS comparisons between ITRF2014 and ITRF2008 with ITRF2008 showing little difference in scale rate. The only way this rate difference can be accommodated in the GPS analyses is to introduce rates of the satellite antenna phase center locations. The scale rate will result in the IGS scale differing by 0.21 ppb when ITRF2014 is adopted at the beginning of 2017. This difference is similar to the total scale change introduced by incorporating Earth albedo and antenna thrust models suggesting that to absorb this scale rate through changes in force models would require an accumulated effect over a decade of the same magnitude of the total force. It seems unlikely that a force with such a high rate of change (i.e., for Earth albedo the force would, depending on the sign of the time interval, either need to double or go to zero over a decade) could have been neglected in IGS orbital modeling by all analysis groups.

The ACC has also been looking at the scale difference between ITRF2014 and DTRF2014 reference frames by a direct comparison of the position estimates of collocated VLBI and SLR stations in the

SINEX files available for ITRF2014 and DTRF2014. We can compare the SLR and VLBI coordinates from the DTRF and ITRF solutions for the collocated sites that are separated by <10 km and whose baseline length between the VLBI and SLR sites have an uncertainty (at the reference epoch of the SINEX files, 2005.0) of less than 10 mm. Figure 1 shows the velocity estimates at the collocation sites from the two ITRF solutions. Table 1 gives the site codes and DOMES numbers of the sites within 10 km of each other. Not all these sites are used in the comparisons. There are large differences in the velocities at many sites especially at those sites with large post-seismic signals. These differences arise from the different parameterizations used by the two ITRFs. These differences in velocities complicate the comparison of the average differences in site positions because the difference becomes dependent on the epoch of the comparison. For the comparison here, we compare at the reference epoch of the ITRF (2005). In addition to these differences in velocities, there are some sites that have very large differences in position and standard deviations between the two ITRFs. We have excluded sites with large standard deviations and large differences between the ITRFs. Some of these differences arise because the discontinuity lists are not the same between the two solutions. Our analysis requires quite a lot of editing of the position estimates due to large differences despite the two ITRFs sharing the same input SINEX files.

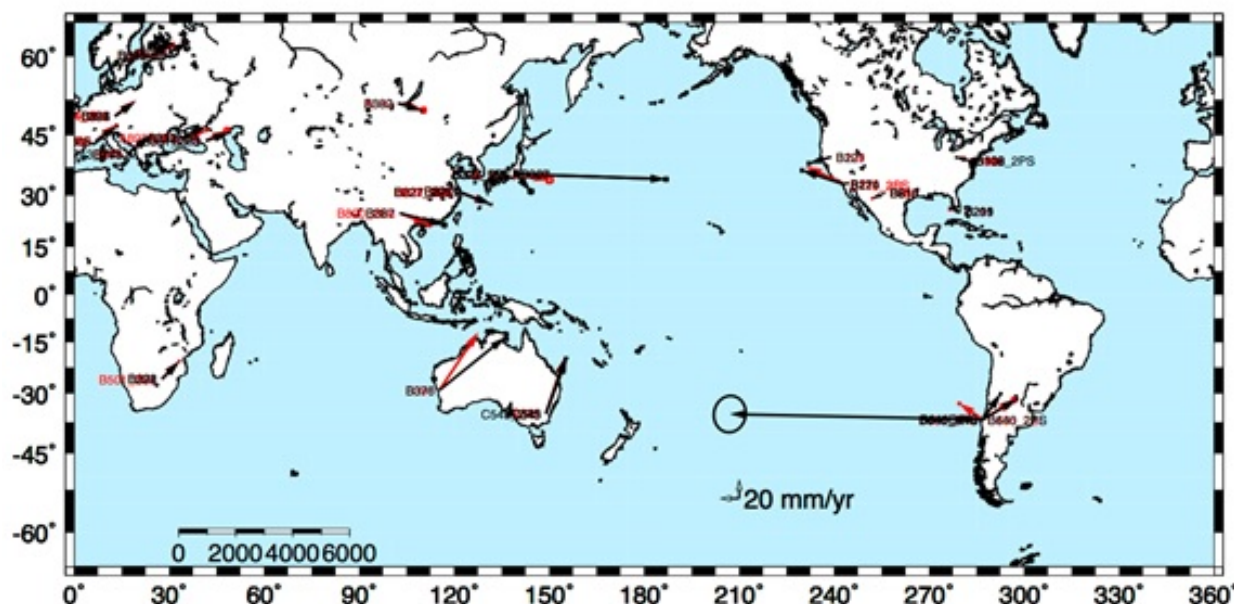


Fig. 1: Comparison of the velocity estimates for ITRF2014 (red vectors) and DTRF2014 (black vectors). DTRF2014 uses piecewise linear functions to represent postseismic motions and as a result some sites affected by large earthquakes have very large short term velocities. Sites shown here have separations < 10 km and length uncertainty between VLBI and SLR sites less than 10 mm. Velocity differences between ITRF2014 and DTRF2014 make comparison of scale difference difficult.

Table 2 gives the results of the average scale differences between the SLR sites (35) and VLBI sites (23 sites) as given the ITRF2014 and DTRF2014 SINEX files. These differences in scale estimates are consistent with the expectation that DTRF2014 sees little difference in scale between VLBI and SLR while ITRF2014 shows a difference of ~ 1.4 ppb. As an additional comparison for the VLBI sites we include a comparison with a combined VLBI solution available from the BKG/IVS ftp site. No combined SLR SINEX file is available from the ILRS. The BKG solution, compared at just 9-10 VLBI sites, falls between the two ITRFs. Since the scale difference arises from the application of local survey ties the difference in the TRFs must arise from the weight given to the survey ties and the number of such ties used. If the survey ties are given very low weight, the VLBI and SLR parts of the combined solutions would each adopt the scale inherent in the technique and there should be a ~ 9 mm (1.4 ppb) mean difference between the observed tie and those inferred from the difference between the SLR and VLBI site positions. When looking at individual stations, the weighted RMS scatters of the height differences (after the mean is removed) are 2.1 mm (35 sites) and 5.4 mm (23 sites) for SLR and VLBI, respectively. We also compared the scale rates between ITRF2014 and DTRF2014 and found scale rate differences of 0.018 ± 0.007 ppb/yr for SLR and 0.00 ± 0.01 ppb/yr for VLBI. The SLR scale rate difference is two-thirds of the ITRF2014/ITRF2008 scale rate difference.

There are number of steps that can be taken to improve this type of comparison. Fully combined solutions for the VLBI and SLR solutions, generated by the respective services, would make comparisons of this type easier e.g., the IGS already generates such as solution and it is updated weekly by the IGS combination center. For the comparison here, we used such a VLBI solution generated by BKG. There are large differences in the standard deviations of the position between the two TRFs and the relationship is not a simple scaling. Some of these differences arise from the difference in post-seismic motion modeling but some of the differences also arise from different discontinuity lists used in the two TRF solutions. (The BKG solution has a different set of discontinuities to both ITRF2014 and DTRF2014). In future, a consistent, common discontinuity list should be adopted by all combination centers. The scale differences between VLBI and SLR and between ITRF2014 and DTRF2014 are still not understood. There needs to be continued analysis of these scale differences. This topic will be addressed at 2017 UAW as it was at 2015 UAW.

Table 1: Collocated sites between VLBI and SLR that are within 10 km of each other. For a site to be used in our comparisons, the standard deviation of the baseline length between the SLR and VLBI site must be less than 10 mm so not all sites in this table are used in the comparisons shown in Table 2.

4-char CODE	VLBI DOMES #	VLBI Name (from IVS combined SINEX file)	SLR DOMES #
7108	40451M125	GGAO7108 ORION MV3 at Greenbelt, MD, USA	40451M105 40451M114 40451M117 40451M120 40451M116
7216	40442S003	HRAS 085 HRAS at Fort Davis, TX, USA	40442M001 40442M006 40442M008
7221	40433M004	QUINCY, USA	21605S001 21605S010
7227	21605S009	SESHAN25 Shanghai, China	21605S001 21605S010
7274	40497M003	MON PEAK mobile Monument Peak	40497M001 40497M002
7327	21704S004	KOGANEI 11-m Keystone at Koganei, Japan	21704S002 21704M001
7332	12337S008	CRIMEA Simeiz, Ukraine	12337M001 12337S003 12337S006
7380	12350S001	SVETLOE Svetloe, Russia	12350S002
7613	40442S017	FD-VLBA VLBA at Fort Davis, TX, USA	40442M001 40442M006 40442M008
7640	41719S001	TIGOCONC TIGO at Concepcion, Chile	41719M001
7102	40451M102	GORF7102 ORION MV3 at Greenbelt, MD, USA	40451M105 40451M114 40451M117 40451M120 40451M116
7201	40499S019	MIAMI20 Miami, FL, USA	40499M002
7219	40499S001	RICHMOND Richmond, FL, USA	40499M002
7224	14201S004	WETTZELL Wettzell, Germany	14201S002 14201M004 14201S018 14201M005
7232	30302S001	HARTRAO Hartebeesthoek, South Africa	30302M003
7243	12734S005	MATERA Matera, Italy	12734S001 12734M005 12734M004 12734S008
7367	21609S003	KUNMING 40-m antenna at Kunming, Yunnan, China	21609S002

7376	50107S012	YARRA12M 12-m at Yarragadee, Australia	50107M001 50107S009
7378	30302S009	HART15M 15-m antenna at HartRAO, South Africa	30302M003
7381	12351S001	ZELENCHK Zelenchukskaya, Russia	12351S002
7382	12338S003	BADARY Badary, Russia	12338S004
7385	10503S002	METSAHOV Metsahovi, Finland	10503S001 10503S014
7593	14201S100	TIGOWTZL TIGO at Wettzell, Germany	14201S002 14201M004 14201S018 14201M005
7601	10503M002	METSHOVI mobile Metsahovi, Finland	10503S001 10503S014
7605	10002M003	GRASSE mobile Grasse, France	10002S001 10002S002

Table 2: Comparison of the scale differences for the SLR and VLBI sites which are collocated and that appear in ITRF2014 and DTRF2014. The list of sites has been reduced to remove sites with large differences and large standard deviations at the 2005.0 epoch of the solutions. The BKG solution is a VLBI only combination.

Technique	Scale difference (ppb)	± (ppb)
SLR (35 sites) DTRF to ITRF	0.63	0.04
VLBI (23 sites) DTRF to ITRF	-0.83	0.19
BKG to DTRF (9 sites)	0.11	0.07
BKG to ITRF (10 sites)	-0.48	0.18

Preparations for the 2017 Unified Analysis Workshop

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). The UAW in 2017 will be 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.

The 2017 Unified Analysis Workshop will be held in Paris, France during July 10–12, 2017 following the IGS Workshop and like the IGS Workshop. Both workshops will be hosted by the Institut National de

l'Information Géographique et Forestière (IGN). Both the IGS workshop and UAW will be held at the University of Paris-Diderot (15 rue Hélène Brion 75013 Paris). The previous UAW was held in Pasadena, California, USA in 2015 and was largely organized by the IERS in collaboration with the IGS. The organization of 2017 UAW will be led by GGOS through its science panel chair Richard Gross.

The attendance at the UAW will be by invitation only with each of the IAG Services, as well as GGOS, selecting 5 to 6 experts to participate in the workshop. The Analysis Coordinators for each of the services are expected to be one of the delegates from each Service. The Service Chairs and Central Bureau Directors are also welcome and will not count towards the limit of 5-6 experts from each Service.

The sessions at the UAW Workshop will focus on:

- Systematic errors and biases in GNSS observations
- Systematic errors and biases in VLBI observations
- Systematic errors and biases in SLR observations
- Systematic errors and biases in DORIS observations
- Site survey and co-location
- Reference systems and frames
- Conventional mean pole
- Standards, conventions, and formats
- Interoperability of portals and metadata

As in previous UAWs, the geometric services of the IAG will be well represented and there will be little representation or discussion of unifying the analysis methods and models of gravity field services with the geometric services.

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 numerous 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 2016 that are of interest to IERS are summarized within this report. The information herein was compiled from the 2016 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 2016. 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, making 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, or the full set of potential signals/measurements for all available GNSS. IGS tracking data, which is held by each of the four global Data Centers on permanently accessible servers, increased in volume over the last year by more than 2 Tb (20 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 to the so-called IGS product on an operational basis and assure their quality. Nearly 1.4 Gb IGS final, rapid, and ultra-rapid product files (GPS and GLONASS) as well as 28 Mb IGS real-time products are made available weekly; additionally, ionosphere (4 Mb per day) and daily troposphere files (3 Mb per day) for more than 300 stations are also produced.

The interest of users in IGS products is documented by the download statistics that records typically over 940 000 files (140 Tb) downloads per day (CDDIS statistics). The Central Bureau assumes responsibility for day-to-day management of the service, interaction with station operators, and answering to a typical number of 150–200 questions and requests from users per month. All these activities are performed all year and day-by-day, with high redundancy and reliability based on the pooled resources of more than 200 institutions worldwide.

Network Status

The Central Bureau monitors a globally distributed network of 505 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 systems. Approximately 189 IGS stations provide real-time data streams so support the IGS Real Time activities.

The IGS has been using the IGB08 realization of the ITRF2008 reference frame for its products since GPS week 1709 (7 October 2012). This contains coordinates and velocities of 232 stations, where only a globally well distributed subset of 91 stations are used as so-called core sites for the datum definition when generating the IGS products.

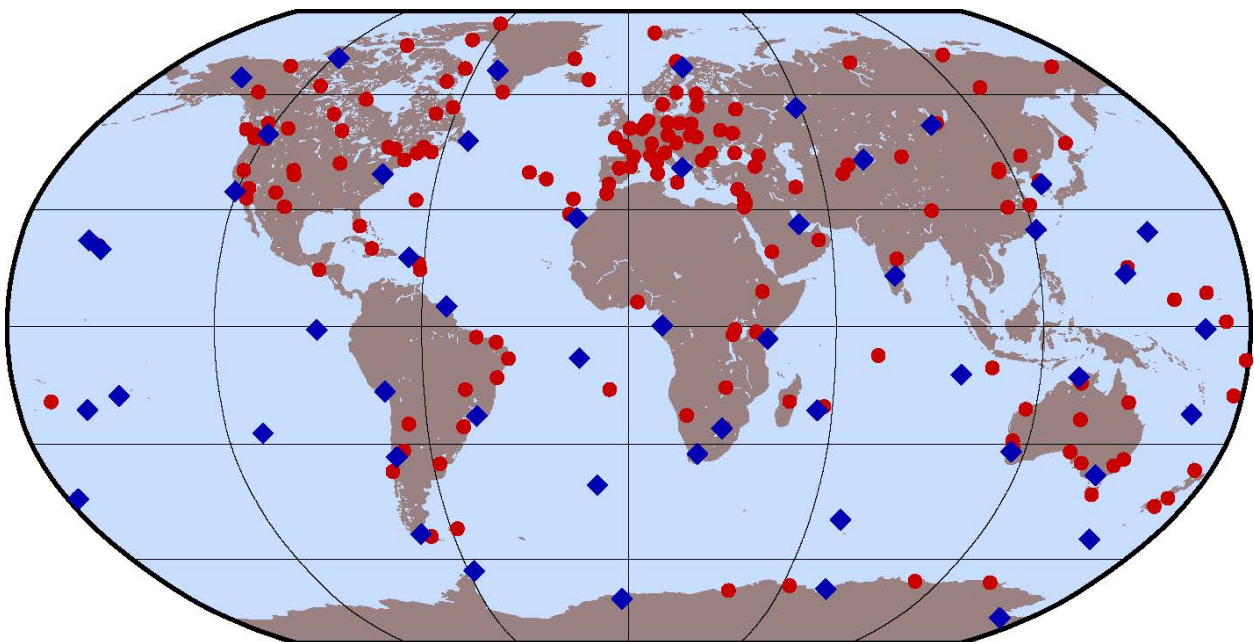


Fig. 1: Geographical distribution of the stations with given coordinates and velocities in IGS14 realization of the ITRF2014 reference frame. The blue diamonds indicate the location of the 51 core stations to be used for the datum definition when generating the IGS products.

Within the year 2016 the new IGS14 realization of the ITRF2014 reference frame has been prepared. It contains the coordinates and velocities for 252 stations. 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. In October 2016 most of the Analysis Centers started to generate an additional product series in order to verify the impact of the new reference frame realization on the IGS products. Starting with GPS week 1934 (29 January 2017) all IGS products are related to the new reference frame.

Analysis and Core Product Generation

The IGS core products have continued to be routinely combined and delivered to users in a timely manner through 2016. To ensure continued production of high-quality IGS products, the Analysis Center Coordinator (ACC) performed high-level oversight and quality control of Analysis Center (AC) products, combination performance, and maintenance of the ACC website with updated plots. Also performed was coordination among ACs to assimilate changes made by them and to ensure that the best analysis models and procedures are used, along with coordination among the other relevant IGS components, preparation of component reports.

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 within the Analysis Center Coordinator Section of the IGS Technical Report.

To establish 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 RT 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 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 10cm 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), considered a key project that will enhance IGS capabilities to support the emerging satellite navigation systems, has proceeded with high priority since its launch in February 2012. At the Governing Board meeting in February 2016 it became the status of a Pilot Project. In order to keep the well established acronym it was renamed to *Multi-GNSS Extension (MGEX)*.

As decided at the IGS 2014 workshop in Pasadena, California, USA, the related dataflow of RINEX 3 files with an extended set of observations into the operational structures is successfully 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). Nowadays, about 40% of the IGS stations deliver their data in RINEX 3 format using the 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 strategies. More information on the current status can be found on the webpage www.igs.org/mgex. This page also contains some 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/development in the MGEX Pilot Project) are currently under discussion.

Governance

Since beginning of 2015 Gary Johnston is the chair of the IGS Governing Board. Other members of the Governing Board have been replaced for

various reasons during the year 2016. 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 2016: first on 07 February, for a business meeting prior the IGS Workshop in Sydney, Australia; a second business meeting on 17 April, during the EGU General Assembly in Vienna, Austria; and finally on 11 December for its regular end-of-year meeting prior to the AGU Fall Meeting in San Francisco, California, USA. The IGS Executive Committee – consisting of Rolf Dach, Gary Johnston, Chuck Meertens, Ruth Neilan, Chris Rizos, and with regular participation of Steve Fisher and of WG Chairs as required – met several times in 2016 by teleconference.

Strategic Planning

The current IGS Strategic Plan covers the period 2013–2016. During the year 2016, three dedicated sessions of the governing board with interested guests were organized in order to discuss the future vision of the IGS. The visions and other concerns brought up in these meetings will be reflected in the next IGS Strategic Plan 2017–2020.

IGS Workshop

The IGS 2016 Workshop was hosted by Geoscience Australia, Land Information New Zealand, and the University of New South Wales in Sydney, Australia. More than 178 participants from more than 21 countries attended the workshop. The main theme “GNSS Future” was well reflected in the scientific program that did review the history and also provided an outlook into the future of the IGS. The workshop presentations, posters and recommendations can be found on the IGS website at <http://www.igs.org/presents/workshop2016>.

The next IGS Workshop will be held 3–7 July 2017 in Paris, France, and hosted jointly by l'Institut national de l'Information Géographique et Forestière (National Institute of Geographic and Forestry Information) and Le Centre National d'Études Spatiales (National Centre for Space Studies).

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	Orbits	15 min	≈5 cm	predicted	4x daily at	95%

(predicted half)	Sat. clocks		≈ 3 ns RMS ≈ 1.5 ns SDev		03, 09, 15, & 21 UTC	
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	≈ 200 μ as ≈ 300 μ as/day ≈ 50 μ s	predicted	4x daily at 03, 09, 15, & 21 UTC	95%
Ultra-Rapid (observed half)	PM PM rates LoD	daily	≈ 50 μ as ≈ 250 μ as/day ≈ 10 μ s	3-9 hours	4x daily at 03, 09, 15, & 21 UTC	95%
Rapid	PM PM rates LoD	daily	≈ 40 μ as ≈ 200 μ as/day ≈ 10 μ 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%

Outreach The IGS is well 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, and by participating in the planning for the international GNSS Monitoring and Assessment System (iGMAS). The latter activity resulted for instance in the common working group between IGS and iGMAS. 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 are numerous IGS-related publications released in 2016. Please visit <http://www.igs.org/library> for the directory as maintained by the IGS Central Bureau and based on the input information from the components.

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 2016.

Network The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2016 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 a few stations doing significantly better. Nearly all stations deliver normal points 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. Examination of the tracking over the past year indicates that the tracking of targets increased by 10%, with a similar increase in the number of tracking sites, with the combined effect resulting in a 20% increase of the annual data yield of the network (Table 1 and Figure 7). 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. 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. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of the SLR. This addition will eventually improve tremendously the tie between the SLR-, GNSS-, and VLBI-implied frames.

Table 1: *ILRS Network Tracking Statistics for 2016*

Site Name	Station	Number of Pass Segments			
		Low	LAGEOS	High	Grand Total
Altay	1879	142	383	2,224	2,749
Apache Point	7045	0	0	259	259
Arequipa	7403	2,844	275	0	3,119
Arkhyz	1886	402	346	1,000	1,748
Badary	1890	1,563	230	77	1,870
Baikonur	1887	37	274	902	1,213
Beijing	7249	703	225	469	1,397
Borowiec	7811	443	230	18	691
Brasilia	7407	398	472	1,299	2,169
Changchun	7237	10,743	2,371	8,820	21,934
Grasse	7845	1,114	638	835	2,587
Graz	7839	3,539	957	3,089	7,585
Greenbelt	7105	5,961	1,629	1,377	8,967
Haleakala	7119	2,212	734	0	2,946
Hartebeesthoek	7501	1,204	411	129	1,744
Herstmonceux	7840	8,684	2,546	7,561	18,791
Irkutsk	1891	697	396	568	1,661
Katzively	1893	1,423	416	61	1,900
Kiev	1824	474	76	0	550
Komsomolsk	1868	69	341	2,165	2,575
Matera	7941	1,611	1,050	1,785	4,446
McDonald	7080	323	42	15	380
Mendeleevo	1874	127	136	244	507
Monument Peak	7110	6,328	900	1,112	8,340
Mount Stromlo	7825	12,555	3,392	5,186	21,133
Potsdam	7841	5,722	1,441	788	7,951
Riga	1884	493	212	59	764
San Fernando	7824	104	4	2	110
Sejong	7394	879	279	115	1,273
Shanghai	7821	1,926	523	2,126	4,575
Simeiz	1873	1,205	367	91	1,663
Simosato	7838	945	407	24	1,376
Svetloe	1888	996	389	107	1,492
Tahiti	7124	919	291	613	1,823
Wettzell	7827	3,254	1,452	4,526	9,232
Wettzell	8834	2,912	702	2,635	6,249
Yarragadee	7090	20,757	4,321	8,544	33,622
Zelenchukskaya	1889	595	300	291	1,186
Zimmerwald	7810	4,542	1,249	680	6,471
Totals:	39 stations	108,845	30,407	59,796	199,048

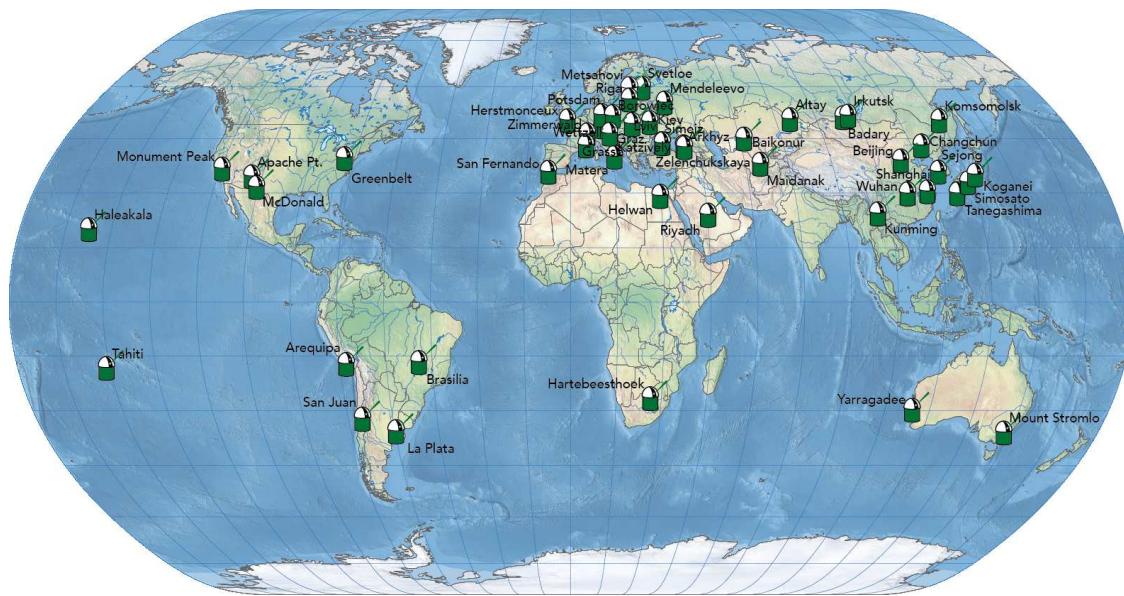


Fig. 1: The global network of SLR stations (status early 2017).

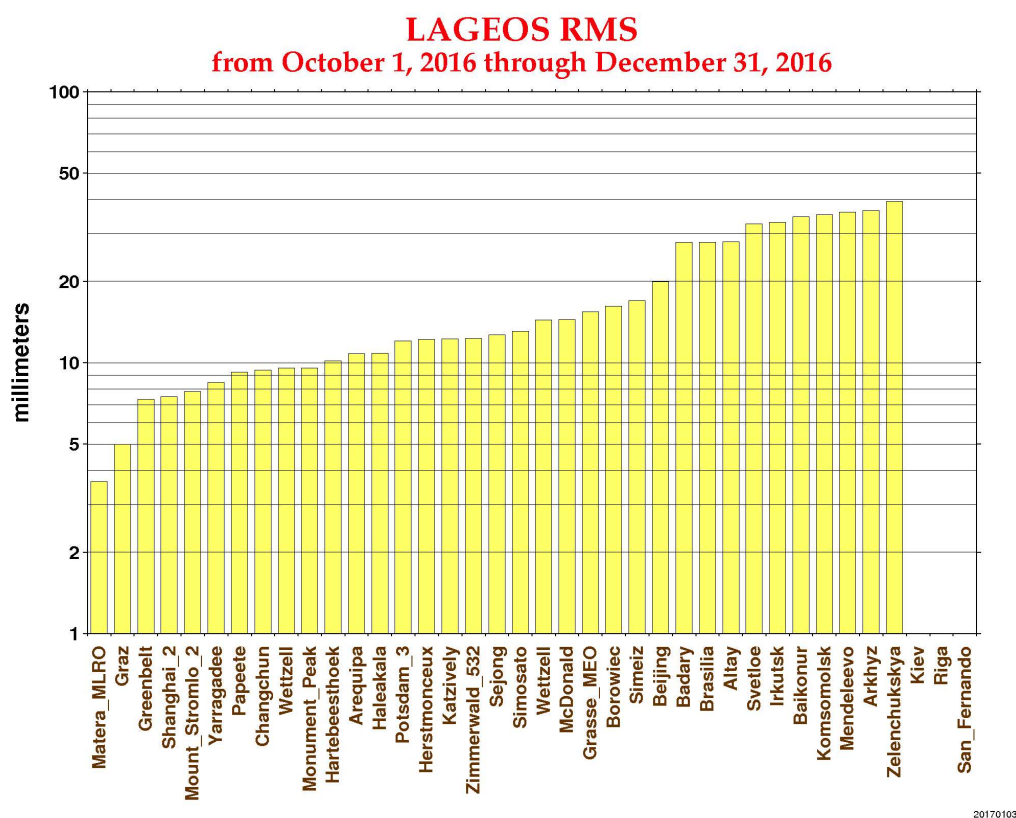


Fig. 2: Performance of the global network of SLR stations on LAGEOS (last quarter of 2016).

Statistics of the SLR data collected as pass segments during the calendar year 2016 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, GIOVE-A/B, Galileo, BeiDou, IRNSS and the Moon.

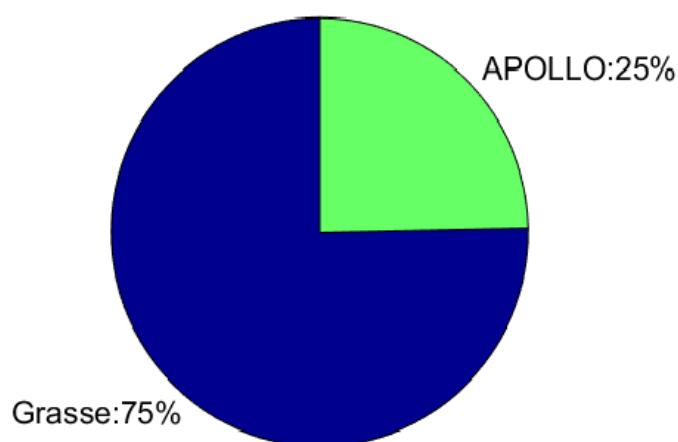


Fig. 3: Observatory statistics in 2016.

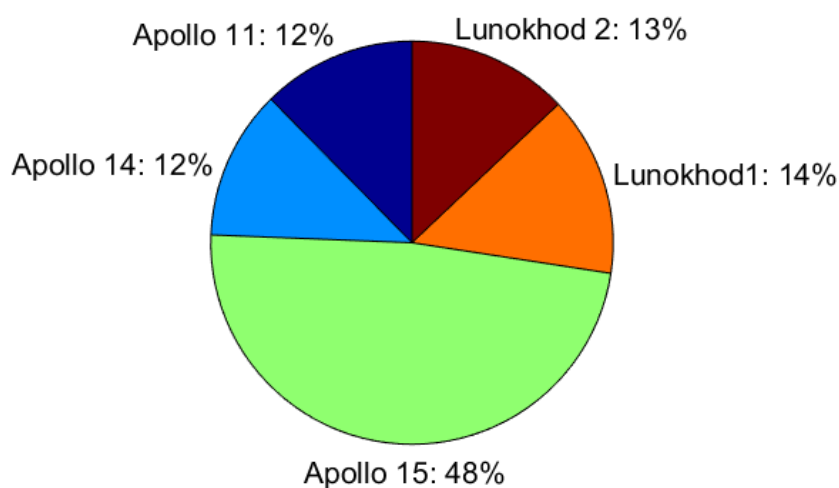


Fig. 4: Retro-reflector statistics in 2016.

Currently there are only four Lunar Laser Ranging (LLR) capable stations within the ILRS network of about 39 laser ranging stations. These LLR stations are also SLR capable (except for APOLLO located in New Mexico, USA) in addition to being technically equipped to track the

retro-reflector arrays placed on the surface of the Moon or retro-reflector equipped spacecraft orbiting the Moon. The other three LLR capable stations 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 McDonald Laser Ranging Station (MLRS) in Texas, USA. During 2016, LLR data from only one of these four sites (MeO, 52 normal points (NP)) were uploaded to the Crustal Dynamics Data Information System (CDDIS) although APOLLO data were also available. The quantity of data for 2016 was slightly less in comparison to 2015. In 2015 MLRS returned to service after one year without any lunar measurements, contributing only two successful lunar tracks, but without any contributions during 2016. Since the latter part of 2014 the Grasse LLR system MeO has ranged at infrared wavelength (1064 nm), and these data are available at their website (<http://www.geoazur.fr>) and included in the statistics shown in Figures 3 to 5. Most of the MeO LLR data are now obtained with infrared instead of green wavelength (532 nm) laser pulses.

Further development of LLR capabilities at McDonald in the future depends on decisions to be made following the establishment of a new generation SLR system at McDonald, through NASA's Space Geodesy Project-SGP, the SGSLR. The support for the LLR component is unclear at this time, but it is likely to be discontinued. This discontinuation will be a disappointment as the McDonald station has been a major contributor to LLR data over a long period of time.

The measurement statistics of 2016 (Figure 3) indicate that 75% of all LLR data have been collected at the French MeO site near Grasse and 25% at APOLLO. Figure 4 illustrates the statistics for the observed retro-reflectors, nearly half the data (48%) were obtained from the Apollo 11 reflector array, with the balance made up, nearly equally, by the other four reflector arrays. Figure 5 reflects the entire LLR data set from 1970 to 2016 indicating the amount of data collected by each of the active LLR sites in each year. There are more than 22,000 normal points in total. After several years of low data production with fewer LLR normal points, the last two years (2015, 2016) indicated a higher productivity, although the active number of stations declined. These numbers do not contain quite new measurements carried out in infra-red at the French site. Data from the APOLLO station was last released to CDDIS in 2014, which means that all data are not yet available in the archive.

LLR data analysis is carried out at a few major LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; and 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 Stud-

ies (SOKENDAI), Japan, increased their LLR data analysis activities. Some interest towards this end have also been shown by the Hartbeesthoek Radio Astronomy Observatory (HRAO), South Africa, where an ex-Observatoire de la Côte d'Azur 1-m aperture telescope is being prepared for LLR use.

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 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.

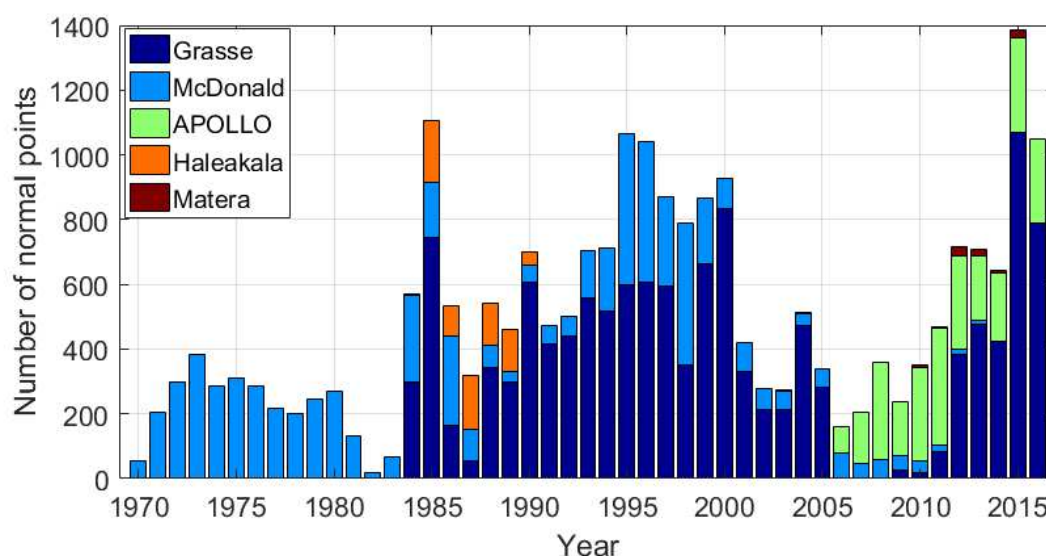


Fig. 5: Data yield of the global LLR network of stations (up to 2016). Note the increasingly significant contribution of Grasse's MeO system upon its return to operations in 2011.

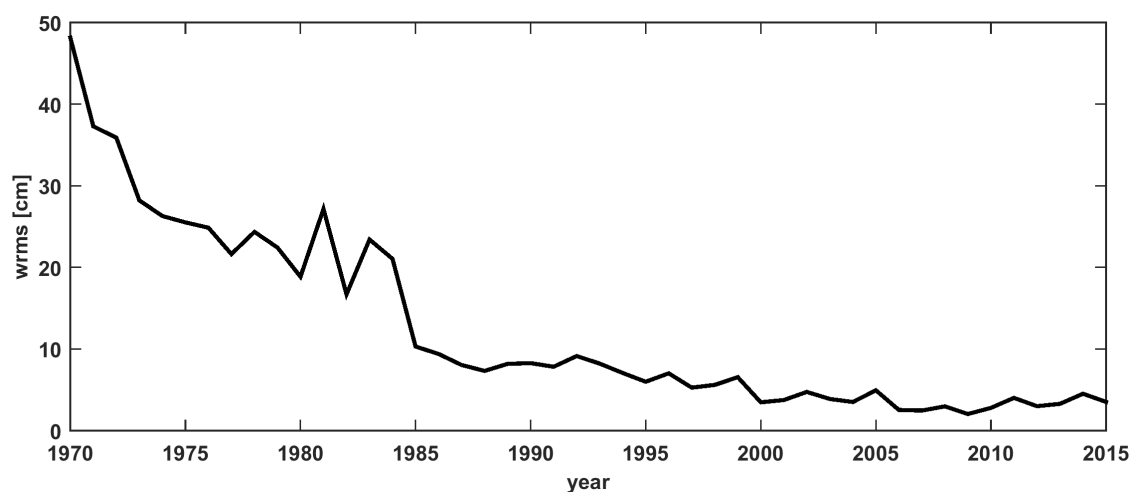


Fig. 6: LLR residuals, annual WRMS.

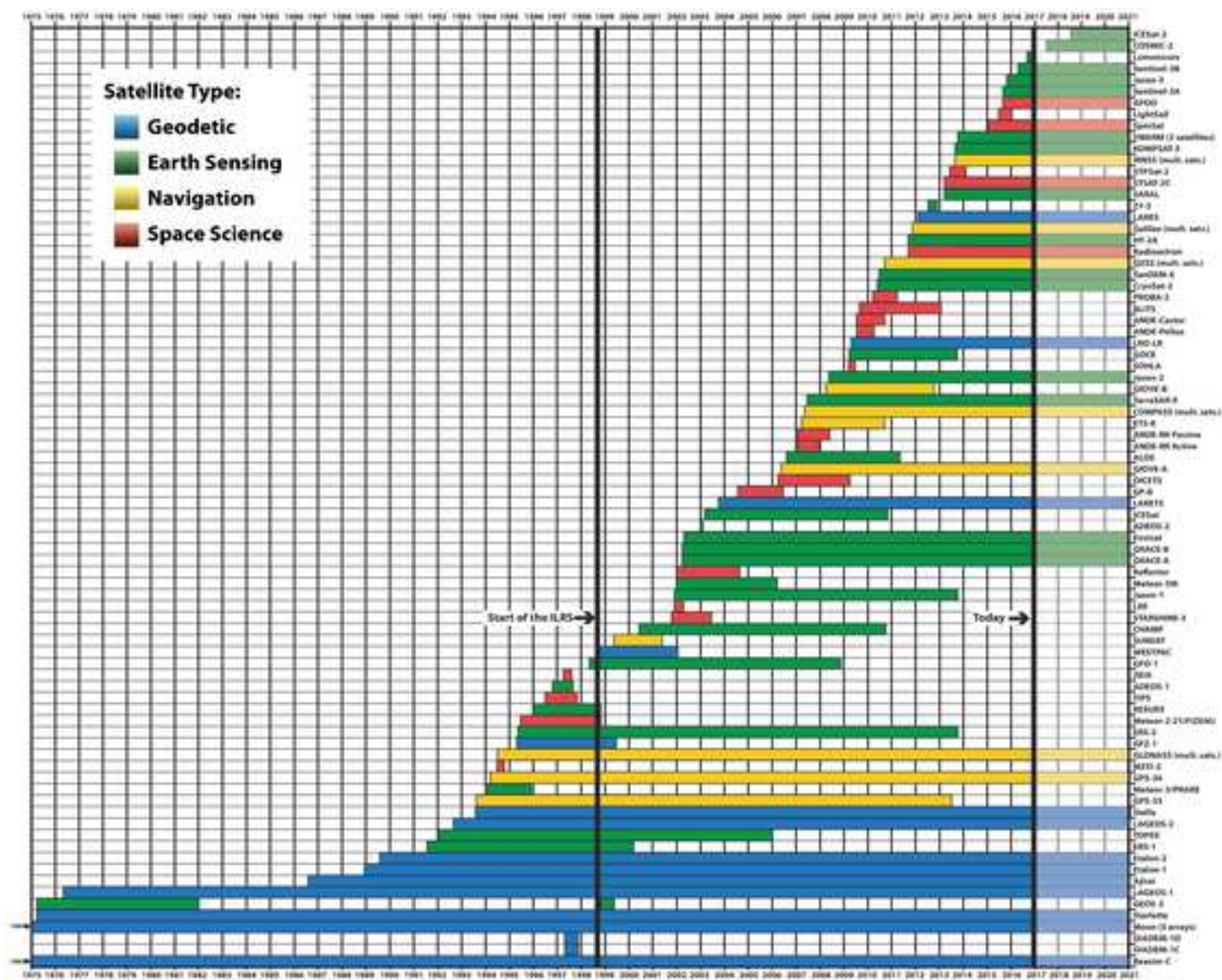


Fig. 7: The currently tracked SLR missions (status as of late 2016).

Missions In 2015, a total of 38 missions including the Moon (over 70 targets!) were being tracked by SLR/LLR (Figure 7). Of these, only about 1/3 are geodetic type targets (cannonball satellites), about one half are navigation satellites and the rest are mainly Earth Observation missions, along with a small number of experimental space science missions. In 2015 the steady increase of tracking multiple GNSS targets continued for a fifth 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 further increase in data yield from such missions.

Table 2: *ILRS Supported Missions Launched or Initiating Tracking in 2016*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (sec)	Altitude (Km)	Inclination (°)	First Data Date
Galileo-212	1606902	7212	41860	9	300	23,220	56 ± 2	2017-Feb-20
Galileo-213	1606903	7213	41861	9	300	23,220	56 ± 2	2017-Feb-20
Galileo-214	1606904	7214	41862	9	300	23,220	56 ± 2	2017-Feb-20
Galileo-207	1606901	7207	41859	9	300	23,220	56 ± 2	2017-Feb-16
GLONASS-136	1603201	9136	41554	9	300	19,140	65	2016-May-29
IRNSS-1F	1601501	3306	41384	9	300	35,786	5	2016-May-26
COMPASS-I6B	1602101	2012	41434	9	300	35,677	55.5	2016-Mar-29
Galileo-210	1603002	7210	41550	9	300	23,220	56 ± 2	2016-Jun-12
Galileo-211	1603001	7211	41549	9	300	23,220	56 ± 2	2016-Jun-12
Jason-3	1600201	4379	41240	3	15	1336	66	2016-Jan-20
IRNSS-1E	1600301	3305	41241	9	300	35,786	29	2016-Jan-20
Sentinel-3A	1601101	8010	41335	3	15	814.5	98.65	2016-Apr-01

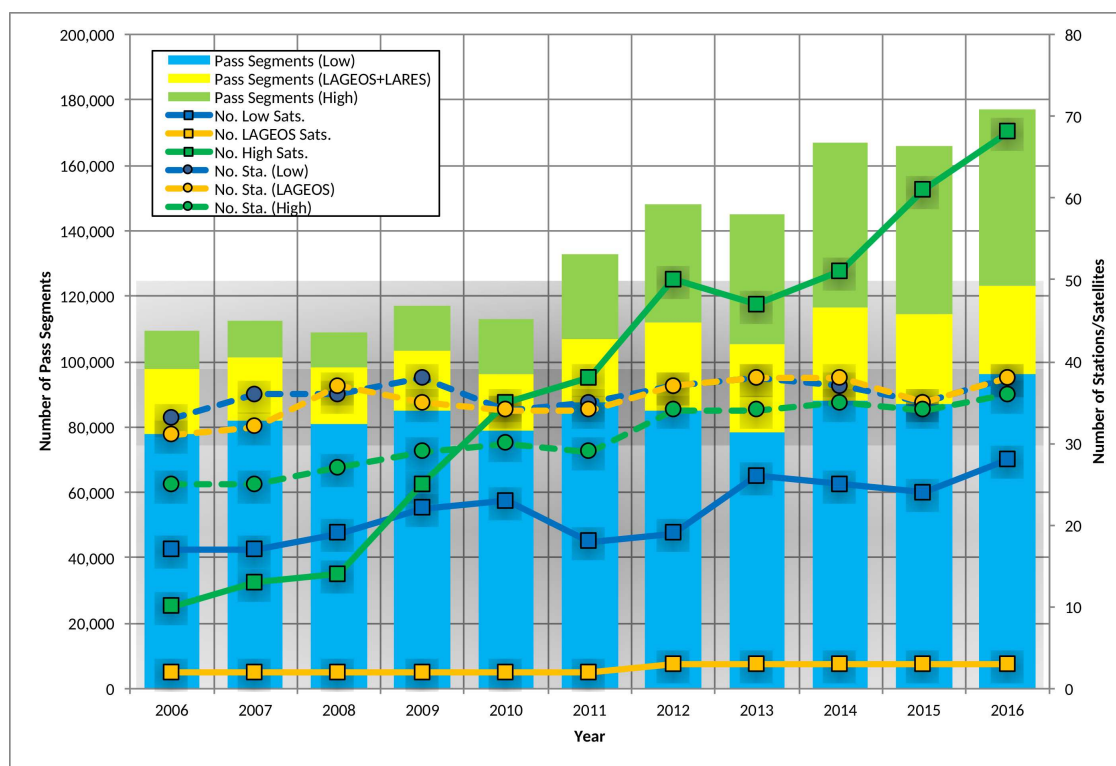


Fig. 8: ILRS network data yield by target type since 2006 (by end of 2016).

During 2016 the new missions that were launched are shown in Table 2. They were mostly spacecraft of GNSS Constellations. Notably though, we also had the launch of the new oceanographic mission Jason-3 and that of ESA's Sentinel-3A mission.

Despite the increase in the number of targets in 2016, the ILRS network has increased its productivity tremendously (by 20%) for an improved data yield this past year (Figure 8). A major contributor in the recent years' data yield increase is the fact that several stations upgrade their capability to track all GNSS satellites whose numbers are steadily increasing these past 3–4 years.

Analysis and science

The Analysis Standing Committee (ASC) based on the final version of the ITRF2014 developed SLRF2014 to include additional ILRS sites that were not part of the official ITRF2014 release or came online after its completion. The expanded TRF model will become the new official ILRS model once the validation of the contributions from all ACs is completed, sometime in early 2017.

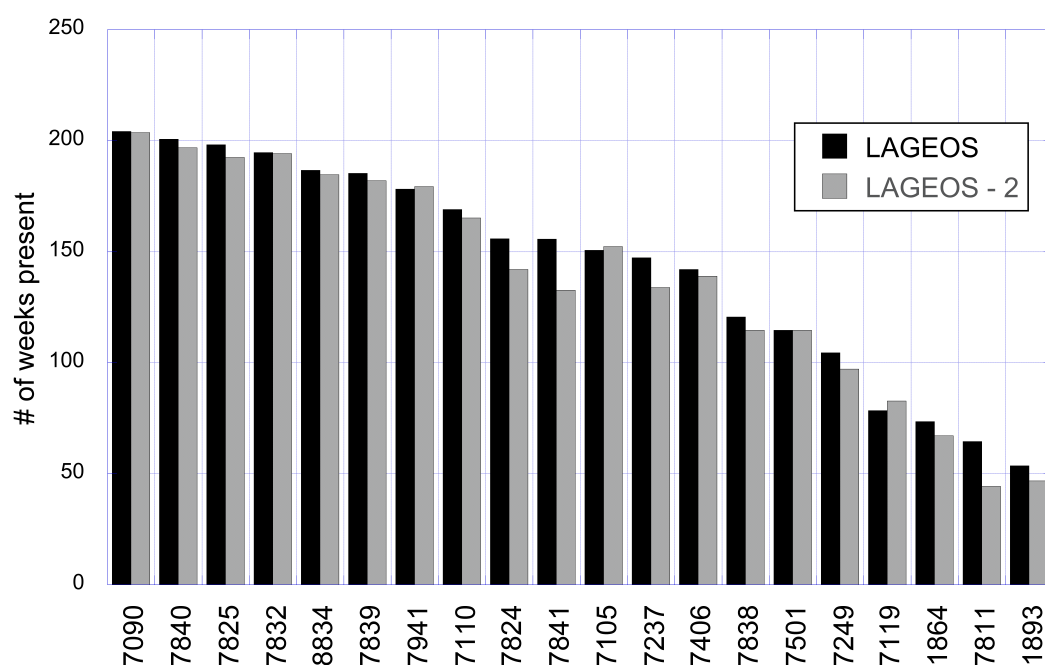


Fig. 9: The number of weeks that ILRS stations contributed to the SSEM Pilot Project over the period 2005–2008 (out of a maximum of 208 weeks). Stations averaging less than 50 weeks per target are not shown.

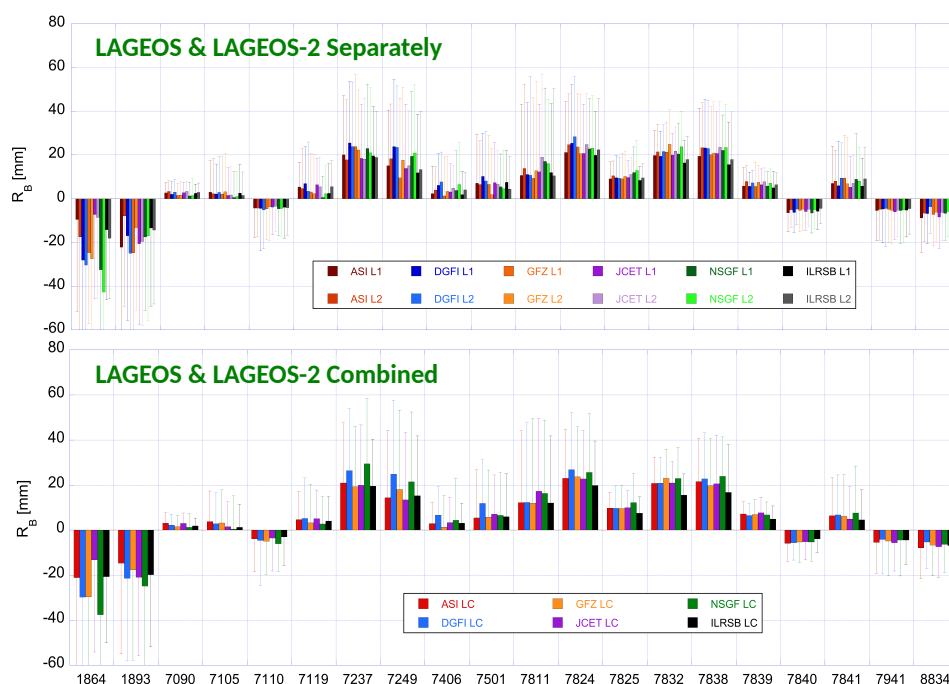


Fig. 10: The averaged systematics for twenty ILRS stations, for each target separately (top) and in combination (bottom), based on the Station Systematic Error Monitoring Pilot Project results (averaged over the period 2005–2008).

The effort to identify, mitigate and monitor systematic errors in the ILRS data has continued over the past year with many new initiatives. The Pilot Project to develop a strategy for a combined product that delivers estimates of station systematics on a regular basis was executed with success, with the participation of most of the ILRS ACs. The results indicated the best practice would be to monitor separately the systematics on each of the main ILRS targets (LAGEOS and LAGEOS-2, eventually including LARES), and to allow for long-term averaging of the results of weekly estimates. This is now being transitioned to an operational product, which will become available in 2017, once a trial period with the participation of all ILRS ACs is successfully completed. The pilot project was restricted to the time-period 2005–2008, delivering estimates of the systematic errors of the entire network while simultaneously allowing the estimation of the stations' coordinates. The results are therefore by and large independent of the underlying TRF or any errors it may inherently possess. The selected period comprised a robust set of data for most of the stations (Figure 9). The weekly estimates were averaged over the 4-year period to obtain more reliable mean estimates for each target separately as well as a combined estimate for both, LAGEOS

and LAGEOS-2. These averaged results are displayed in Figure 10 for the twenty most prolific stations over that period.

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_v200+v210/configuration.php

A sample page with the comparison of several AC results for LAGEOS and throughout the test period 2005–2008 is displayed in Figure 11. Note that the results are all very close to each other, indicating the high degree of consistency between ACs' analysis, and to the combined estimate indicated by the black dashed line.

The next step 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 need to develop a long history of systematics for each station separately. This is a task to be completed in 2017, after the adoption of the new SLRF2014 model by all participating ACs.

Matera 7941

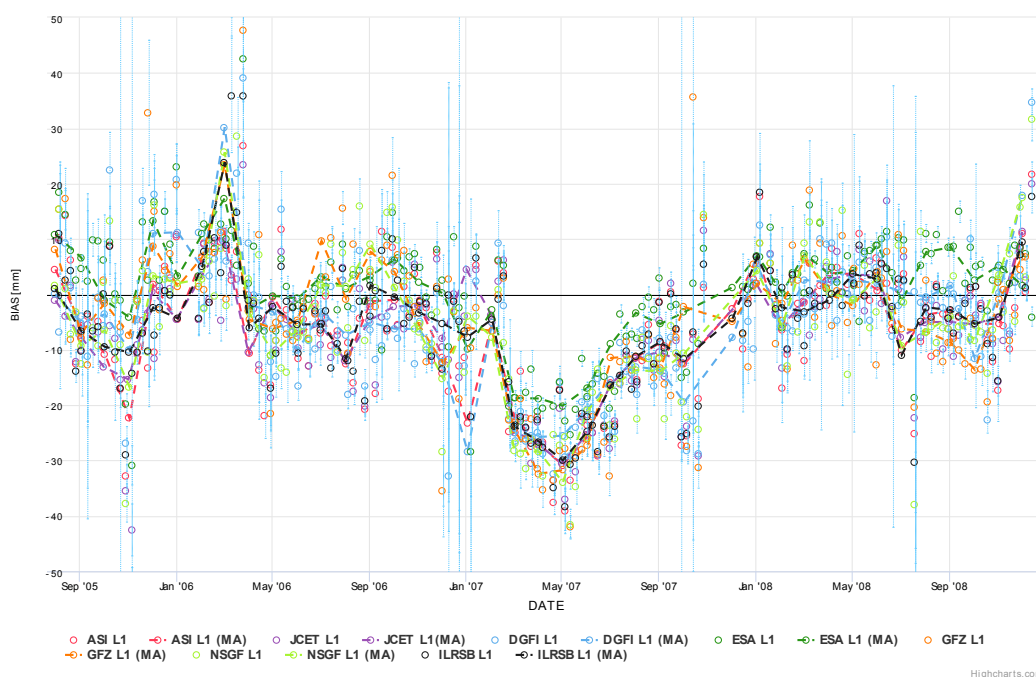


Fig. 11: Weekly estimates of the systematic error for the Matera, Italy MLRO system (7941). The circles indicate the weekly results while the dashed lines a “moving average” estimate (MA). The black color results are the combination of the individual AC contributions.

Meetings

In 2016 the 20th International Laser Workshop was held at GFZ Potsdam, Germany, during the week of October 9–14, co-sponsored by the Helmholtz Center Potsdam – GFZ German Research Centre for Geosciences and the ILRS. The theme for this workshop was: “The Path

Toward the Next Generation Laser Ranging Network” and the topics that were addressed:

- Advances in laser ranging technology and new applications;
- Co-locations and other intra- and inter-technique calibrations;
- Strategies and priorities for laser ranging;
- Understanding and addressing SLR station systematics;
- Progress in laser ranging analysis;
- Current trends in lunar ranging;
- SLR tracking of space debris;
- Automation of laser ranging systems;
- Interplanetary ranging and time transfer; and
- Advances in retroreflector arrays and their modeling.

The workshop was very well attended with over 170 participants from 25 countries, 80 oral presentations and over 60 posters. The ASC held two meetings in 2016, one during the EGU General Assembly, on April 22, and one prior to the Potsdam Workshop, on October 8. The ILRS Governing Board met once in 2016, prior to the Potsdam workshop on October 8. The ILRS will hold in 2017 an ILRS Technical Workshop that will take place in Riga, Latvia, co-hosted by Institute of Astronomy at the University of Latvia, October 2–5. For more information see:

<http://www.ilrstw2017.lu.lv>

The topic of the 2017 Workshop is: “Improving ILRS Performance to Meet Future GGOS Requirements”.

Publications

Access all the presentations, posters, and proceedings papers presented at the 20th International Laser Workshop at GFZ Potsdam, Germany from the official ILRS page for the workshop:

<https://cdsis.nasa.gov/lw20/Program/>

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.2016.html>

Erricos C. Pavlis, Ludwig Combrinck

3.4.3 International VLBI Service for Geodesy and Astrometry (IVS)

IVS Organization and Activities

During 2016, 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:

- Based on discussions at the 2015 IVS Retreat, the IVS Directing Board developed a Strategic Plan for the Period 2016–2025. The main goal is to provide overall planning guidelines and to give the stakeholders and IVS Associates reasonable indications for the investments and activities needed. In the period 2016 to 2025 the IVS will enter the era of the VLBI Global Observing System (VGOS), which will be composed of a transition period and subsequent full VGOS operations.
- The IVS published three IVS Newsletters in April, August and December, keeping the community informed about IVS activities. In the fall of 2016 the Proceedings volume of the 9th IVS General Meeting was published.
- The 2nd VLBI Training School was organized at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa. The purpose of the School was to help prepare the next generation of researchers to understand VLBI systems and inspire them in their future careers. A large group of attendees included students from different countries in Africa with the aim to develop expertise in geodesy and especially VLBI as part of an effort to build new stations in Africa and integrate them into the global VLBI network.

Table 1: *IVS meetings in 2016.*

Event	Location	Date
2nd VLBI Training School	Hartebeesthoek, South Africa (ZA)	March 9–12, 2016
9th IVS General Meeting	Johannesburg, ZA	March 13–17, 2016
17th IVS Analysis Workshop	Johannesburg, ZA	March 18, 2016
35th IVS Directing Board meeting	Johannesburg, ZA	March 19, 2016
1st International Workshop on VLBI Observations of Near-field Targets	Bonn, Germany	October 5–6, 2016
5th International VLBI Technology Workshop	Westford, MA, USA	October 12–14, 2016
36th IVS Directing Board meeting	Westford, MA, USA	October 15, 2016

Network Stations and observing sessions

A total of 190 geodetic/astrometric 24-hour sessions were observed during the year 2016. The number of observing sessions coordinated by IVS was about ~ 3.6 days per week, which is about the same level of observing as for the year 2013. The increased number of sessions for the observing years 2014 and 2015 (~ 4.7 days/week and ~ 4.5 days/week) was mostly due to the high number of regional AUSTRAL sessions in that time period; because of budget constraints this is back to pre-2014 numbers. However, there was an increase of about 8% in the number of station days from 2013 to 2016. As the number of stations was more or less constant, this increase can mostly be attributed to the stations providing more observing days, that is on average the observing networks were larger in 2016. The major observing programs during 2016 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 Tsukuba (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 Tsukuba (Japan).
- IVS-T2** Bi-monthly sessions coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn, Germany, with 16–18 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 2016.
- VLBA** The Very Long Baseline Array (VLBA), operated by the National Radio Astronomy Observatory (NRAO) and, since October 2016, by the Long Baseline Observatory (LBO), allocated six observing days for astrometry/geodesy. These sessions included the 10 VLBA stations plus up to 5 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 2016.

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 2016 six OHIG sessions were observed.

APSG The Asia-Pacific Space Geodynamics (APSG) program operated two sessions in 2016.

AUSTRAL In 2016, 21 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 6 sessions during 2016.

IVS-R&D Thirteen research and development sessions were observed in 2016. The goals of the 2016 R&D sessions included the observation of link sources between *Gaia* and the ICRF2, the improvement of the scheduling technique of the Intensives and the observation of the Chang'E-3 lander with VLBI.

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

Transition to Multi-tone Phase Calibration

In VLBI measurements the measured delays are corrupted by unknown and unstable phase shifts in the signal as it travels down the signal path from the front end to the sampler. Many of these effects can be removed through the use of phase calibration. The most common approach is to inject a calibration signal near the front of the signal chain. The calibration signal consists of a set of tones ('phase-cal tones') equally spaced in frequency and derived from the station frequency standard. These signals are extracted during the correlation process and used to adjust the phases prior to fringe-fitting. Since the spurious phase shifts are frequency dependent, each frequency channel is calibrated independently. Historically, only a single phase-cal tone was used in each frequency channel.

Due to the ever broader channel bandwidth and advances in correlator software, for the past several years the correlators have been able to use multiple phase-cal tones in each channel. This latter approach is called multi-tone phase-cal. Naively, the use of multiple phase-cal tones should reduce the noise. A verification by correlating the CONT14 data set with both multi-tone and single-tone phase calibration revealed that multi-tone was generally slightly better than single-tone. On average, the multi-tone sessions had 1% more observations. The session fit was slightly better, again on the 1% level, indicating that the data within a session was less noisy and more consistent. Lastly, the RMS baseline scatter across all of the CONT14 sessions was generally lower. All of these are arguments for using multi-tone phase-cal. However, it also turned out that for Zelenchukskaya there was a difference of 8 mm in the vertical position (3-sigma level) depending on whether you used multi-tone or single-tone phase-cal. There are differences for other stations, but none of these are greater than 1-sigma. The IVS Directing Board decided to switch over to multi-toned phase-cal for all sessions observed on or after 1 January 2017. It is expected that this will yield an improvement in the quality of the data; but it may also introduce a discontinuity in some station positions.

Technology Development

The main focus of the IVS technology development was placed on the build-out of the next-generation VLBI system (VLBI Global Observing System, VGOS) network and achieving operational readiness with the various installations of the signal chain realizations. Figure 1 shows the currently available VGOS broadband stations (inverted blue triangles)

as well as the stations expected to become VGOS capable by the year 2020. That is, over the next several years a number of new VGOS stations will come online. Operational readiness for the existing VGOS stations was worked on in a series of test sessions of 1-, 2-, 6-, and 24-hour lengths. These tests uncovered a number of smaller and larger issues of high-level, low-level, and transient nature that were successively ironed out or identified and actively being worked on. In the near future the focus is likely to shift from the station side to the data transport and correlation parts of the processing chain. Here the use of cloud services and distributed correlation to deal with the large amount of data are aspects that will be investigated.

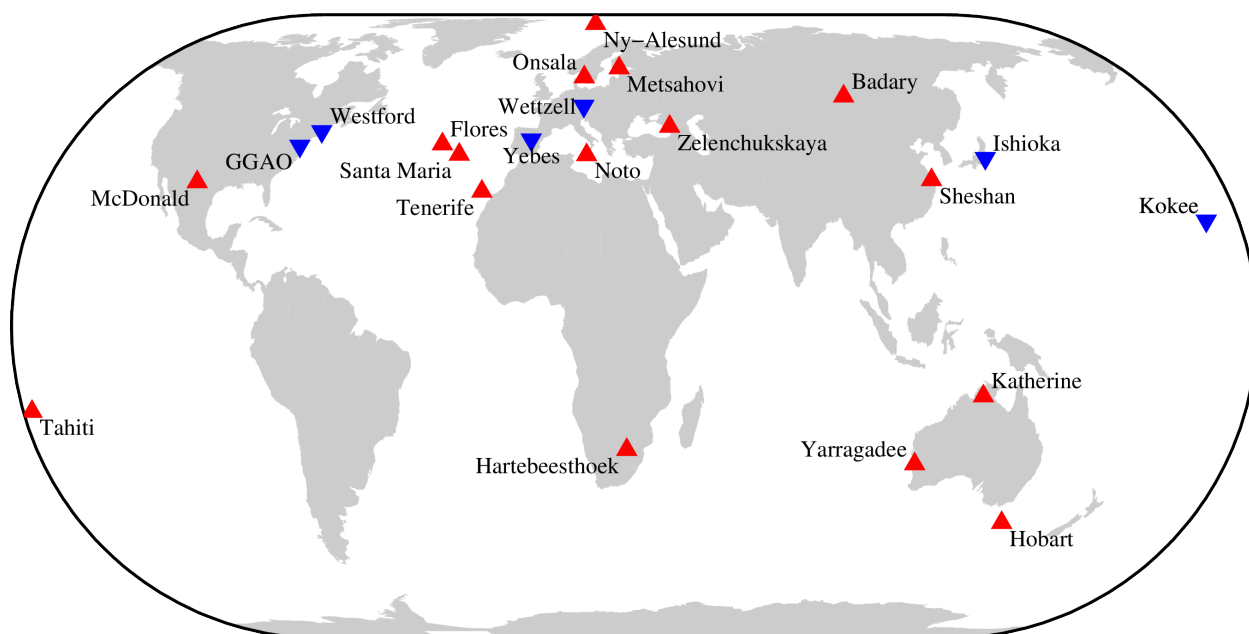


Fig. 1: *Evolution of the VGOS broadband network. By the year 2020 a network of 22 VGOS sites is anticipated to be operational. By the end of 2016 there were six stations (inverted blue triangles) participating in the VGOS test sessions. The other sixteen stations (red triangles) are expected to realize their VGOS signal chains in the next few years.*

Publications

- D. Behrend, K.D. Baver, K. Armstrong (editors): IVS 2016 General Meeting Proceedings, NASA/CP-2016-219016, Greenbelt, MD, USA, 2016, online: <https://ivscc.gsfc.nasa.gov/publications/gm2016/>
- A. Nothnagel, T. Artz, D. Behrend, Z. Malkin: International VLBI Service for Geodesy and Astrometry – Delivering high-quality products and embarking on observations of the next generation. *Journal of Geodesy*, Vol. 91, pp. 711–721, DOI 10.1007/s00190-016-0950-5.

Dirk Behrend, John Gipson

3.4.4 International DORIS Service (IDS)

Overview The current report presents the different activities held in 2016 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 (2016), the number of DORIS satellites has increased to six (see Table 1).

Table 1: *DORIS data available at IDS Data Centers. As of December 2016*

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

Two new satellites were launched in early 2016: Jason-3 and Sentinel-3B, both using the new 7-channel DG-XXS DORIS receiver on-board

the satellite. The DORIS constellation then steadily increased, including currently six satellites at altitudes of 720 and 1300 km, with almost polar or TOPEX-like inclination (66 deg).

The DORIS system was 26 years old in 2016 and its performance remains unbeatable thanks to permanent enhancements to the system and its components. Thirteen DORIS receivers have flown on various Earth observation and altimetry missions since 1990, and many future missions currently under preparation should guarantee a constellation of DORIS contributor satellites up to 2030 and beyond:

- Sentinel-3B, Sentinel-3C and -3D (ESA/Copernicus) are under development, and expected for end 2017, 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.
- HY-2C and HY-2D (CNSA/NSOAS), two Chinese missions flying DORIS, are planned for 2019 and 2020 respectively. A further four missions (HY2-E, -F, -G and -H) are pending approval and planned from 2024.

DORIS network DORIS has a globally distributed network of 56 permanent stations dedicated for orbitography and altimetry. Two additional DORIS stations are used for other scientific purposes: Grasse (France) and Wettzell (Germany).

The new DORIS station at the Geodetic Observatory Wettzell started work on September 27, 2016 with shifted frequencies to avoid internal jamming with the nearby stations of the permanent network. The most challenging requirement was to manage interferences with VLBI. After some months of intensive tests carried out on site, a compromise to minimize the constraints for both systems has been found. Greenbelt and Wettzell are now two examples of core sites complying with the GGOS requirements with the four space geodetic techniques (co-located DORIS/GNSS/SLR/VLBI).

Another main event of 2016 is the newly installed DORIS station at Managua, Nicaragua. Fully integrated within the data coverage map, this new station is also well located to provide reliable information on

the Caribbean tectonic plate motion when combined with the DORIS station data of 'Le Lamentin'.

This new DORIS site compensates for the decommissioning of Santiago with regard to the number of beacons of the permanent network, remained stable: 56 including 4 master beacons and 1 time beacon.

The extensive outage of 3 stations is to be noticed: Mahé, Santa-Cruz and Socorro. Nevertheless, the DORIS network provided a very reliable service 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: 8 failed beacons and 1 failed antenna were replaced and 2 antennas were relocated.

The development of the 4th DORIS beacon generation continued with the preliminary design review in July and everything is going according to the provisional schedule: detailed design review and manufacturing of a prototype in 2017, technical appraisal and testing in 2018 and start of the deployment in 2019.

The network monumentation was the subject of a global assessment in the DORIS Special Issue of 'Advances in Space Research' performed by Saunier (2016) and based on three methods: mechanical laboratory study to see the behavior of the metallic structures, field measurements on the existing monuments, evaluation chart in order to have a grading and scoring of each monument. Elastics deformations for the standard monuments are less than one millimeter when undergoing extreme climatic conditions. Two thirds of the network monuments are compliant with standards. The field checks conducted in the last 15 years showed that 80% of the monuments are stable within a mm.

Co-location has always been a major objective for the DORIS network. We continuously increased the number of stations co-located with other space geodetic techniques and with tide gauges throughout the various phases in the network evolution.

In 2016 the following sites were visited:

- Managua, Nicaragua: new site
- Mariana Islands, USA: reconnaissance with a view to installing a new station
- Kitab, Uzbekistan: station re-location (200m South)
- Hartebeesthoek, South Africa: tracking oscillator replacement
- Wettzell, Germany: new site (IDS station)

Finally, the overall objectives for the next year are:

- Restarting at Socorro (Mexico) and Santa-Cruz (Galapagos, Ecuador)
- New stations at San Juan (Argentina) and Guam Island (USA)

- Re-location in Easter Island (Chile)
- Reconnaissance in Papenoo (French Polynesia), Manchuria (China) and Reykjavik (Iceland)

DORIS stations co-located with other IERS techniques

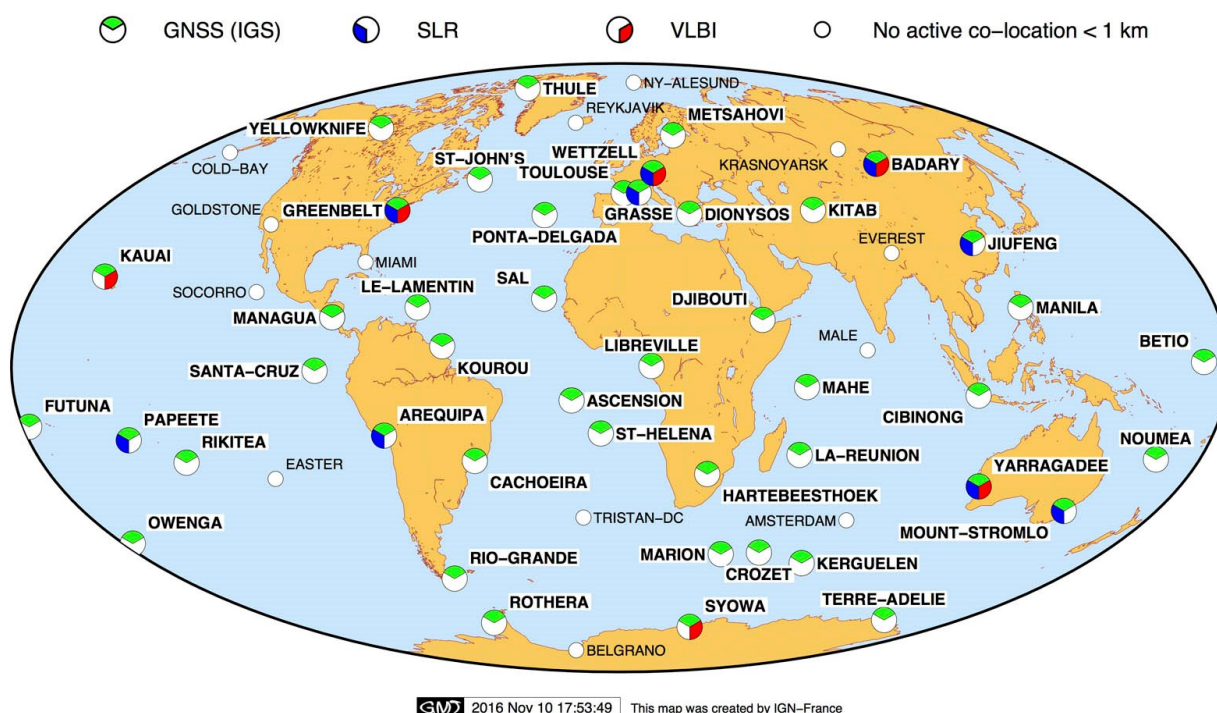


Fig. 1: *The permanent DORIS network – 56 stations – and co-location with other IERS techniques (as of Nov. 2016).*

IDS Governing Board

The term of three posts expired at the end of 2016. The holders of these posts are: Carey Noll as the Data Center representative, Pascal Willis as the Analysis Center representative, and Richard Biancale as one of the Members at Large. After the elections organized in fall 2016, the new members elected by the IDS Associates are:

- 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, the Board elected Frank Lemoine as the new Chairman from January 1st, 2017.

Table 2: *Composition of the IDS Governing Board (January 2015 - December 2016)*

Name	Institution	Country	Mandate
Richard Biancale	CNES	France	Member at large
Hugues Capdeville Jean-Michel Lemoine	CLS CNES	France	Analysis Coordination
Pascale Ferrage	CNES	France	System representative
Brian Luzum	USNO	USA	IERS representative
Guilhem Moreaux	CLS	France	Combination Center representative
Carey Noll	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
Pascal Willis (chair)	IGN/IPGP	France	Analysis Center representative
Marek Ziebart	UCL	UK	Member at large

IDS Central Bureau

In 2016, the Central Bureau (CB) participated in the organization of the AWG meeting held at the Faculty of Aerospace Engineering in Delft, Netherlands, on May 26 and 27, and of the IDS Workshop in La Rochelle, from October 31 to November 1. The CB documented the GB meetings held on these occasions. Between the meetings, the CB coordinates the work of the GB.

The CB managed the edition and publication of the 2015 IDS Activity Report. It also produced the IDS contributions to the 2015 IERS Annual Report, and to the Geodesist's Handbook of the IAG.

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. A draft was proposed in March 2016 by the Central Bureau to the Governing Board who accepted the concept. So, the IDS Newsletter is born. Three issues were published in 2016, #1 in April

2016, #2 in July, and #3 in December. The issues are distributed via email to the subscribers to the DORISmail and a number of identified managers and decision-makers. They are also available on the IDS website for downloading.

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 2016, this activity focused on:

- the delivery of Jason-3 data, auxiliary data and information related to this new mission.
- the delivery of Sentinel-3A data, auxiliary data and information related to this new mission.
- the delivery of the CNES orbits for Saral in GDR-E standards (file naming, store folders, description files). See [ftp CDDIS or IGN] [pub/doris/products/orbits/ssa/README_SP3.txt](http://pub.doris/products/orbits/ssa/README_SP3.txt)

The Central Bureau also interfaced with the CDDIS staff, SSALTO, and the IDS components during the transition phase to the new file upload system at CDDIS.

IDS Web and ftp sites

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

Besides the regular updates of pages and addition of documents, the website was enriched with new pages and received some changes. The main new features of 2016 are the Youtube IDS channel and the upgrade of the website.

The IDS video channel has been created on Youtube to host a set of existing videos for outreach. New videos were also included. They show DORIS-equipped satellites in orbit. These videos have been produced with the Visualization Tool for Space Data (VTS) free software from CNES.

<https://www.youtube.com/channel/UCiz6QkabRioCP6uEjkKtMKg>

A new 'Satellites' page has been added on the website. It provides access to a summary table of DORIS missions and satellite pages giving attributes, links to data files and VTS videos. The page also provides access to the VTS tool and predefined scenarios for DORIS missions, as well as directories of orbit files and quaternions.

<http://ids-doris.org/satellites.html>

A dedicated Newsletters page has been created. It contains the IDS Newsletters since April 2016.

<http://ids-doris.org/report/newsletter.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 2016 IDS Activity Report (<http://ids-doris.org/report/governing-board.html#activity>).

DOR-O-T, the IDS Webservice

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

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.).

The main events of the year are listed hereafter:

- Transition to the new CDDIS computer hardware was completed in late November 2016. This new system configuration now provides a more reliable/redundant environment (power, HVAC, 24-hour on-site emergency personnel, etc.) and network connectivity for CDDIS; a disaster recovery system is installed in a different location on the GSFC campus. The new system location addresses a long-time concern for the CDDIS, namely, the lack of consistent and redundant power and cooling in its existing computer facility. Multiple redundant 40G network switches are utilized to take full advantage of a high-performance network infrastructure by utilizing fully redundant network paths for all outgoing and incoming streams along with dedicated 10G network connections between its primary operations and its backup operations. The CDDIS transitioned the majority of its operation services to virtual machine (VM) technology for both multiple instance services in a load balancing configuration which allows additional instances to be increased or decreased due to demand and allows maintenance (patching, upgrades, etc.) to proceed without interruption to the user or any downtime. CDDIS now utilizes a unified storage system (100 Tbytes in size) to easily accommodate future growth of the archive and facilitate near real-time replication between its production and disaster recovery sites.
- One requirement of the new CDDIS computer system involved a change to the file upload process. In the old system, CDDIS

used ftp for delivery of data for the archive from both data centers and analysis centers. While this has worked well over the years, transition to the new system provided an opportunity to update this method to a web-based approach that can utilize a different user sign-on/authentication infrastructure. CDDIS developed a web-based application that allows users to use existing scripts without significant modification but also tie authentication into the NASA system. Staff worked with the groups who submit DORIS data and IDS products to CDDIS to transition their procedures to the new file upload system.

- CDDIS performed complete rewrite of its file ingest processing software in 2016. This rewrite incorporated numerous disparate programs developed over the years into a single, easily maintained software base which incorporates all the CDDIS requirements for data ingest while also allowing additional flexibility in meeting future metadata requirements. The software was initially modified for incoming GNSS files but will be extended to all incoming files, including DORIS data and products, in the near future.

IDS Analysis Centers and IDS Analysis Coordination

The activities of all the DORIS analysts of the past year 2016 have been dominated by the evaluation of the ITRF2014, taking into account that the most recent DORIS satellites Jason-3 and Sentinel-3A where DORIS data are only available in RINEX format, and the analyzing of the sensitivity to the South Atlantic Anomaly (SAA) effect of their Ultra Stable Oscillator (USO).

IDS meetings were held in Delft (The Netherlands) for an Analysis Working Group, May 26–27, 2016 (hosted by Technical University) and in La Rochelle (France) for an IDS Workshop, from October 31 to November 1, 2016.

All the IDS ACs have to take the standard routinely processing again by taking into account the news data available of all satellites. The IDS includes six ACs and ‘de facto’ three ‘associate analysis centers’ who use seven different software packages, as summarized in Table 3. We also note which analysis centers on a routine basis perform POD analyses of DORIS satellites using other geodetic techniques (c.f. Satellite Laser Ranging (SLR), or GNSS). The multi-technique analyses are useful since they can provide an independent assessment of DORIS system performance, and allow us to more easily validate model changes and the implementation of attitude laws for the different spacecraft, in the event spacecraft external attitude information (in the form of spacecraft quaternions) is not available. We note that a representative of the Norwegian Mapping Authority (NMA) expressed interest in analysis of DORIS data, and also in multi-technique analyses.

The participation of the NMA (Geir Arne Hjelle) and other potential IDS ACs should continue to be encouraged.

Following the DORIS processing for the realization of the ITRF2014, there were still many substantive issues that remained to be addressed, even with the current data already processed. Some issues as the jump in the DORIS scale (2012 and later) have been analyzed. The IDS scale jump in 2012 is fully explained by a variation in the number of low-elevation measurement included in the processing. Indeed, the increase of the scale factor for Jason-2 and Cryosat-2 is linked to the change of tropospheric model used by CNES in its POD processing (GDR standards): from CNET (GDR-C) to GPT/GMF (GRD-D). It causes a reduction in the amount of data marked as rejected in the doris2.2 file (input DORIS data file) and then, an increase of the data used considered to be good in CNES pre-processing. The larger number of data, especially at low elevation, could thus be the cause of the change we observe in the scale factor. The date of change is mission dependent. The scale increase of the multi-satellite solutions is due to the jump not at the same time of the Jason-2 and Cryosat-2 solutions but also of the HY-2A high scale. So, IDS ACs need to do their own pre-processing.

Table 3: *List of IDS Analysis Centers, Associated Analysis Centers, and other groups participating in the analysis activities in 2016.*

Group	AC	AAC	Other	Location	Contact	Software package	Multi-technique: DORIS +
ESA/ESOC	✓			Germany	Michiel Otten	NAPEOS	SLR, GNSS
Geodetic Observatory Pecny	✓			Czech Rep.	Petr Stepanek	Bernese	-
CNES-CLS	✓			France	Hugues Capdeville	GINS/DYNAMO	SLR, GNSS
NASA/GSFC	✓			USA	Frank Lemoine	GEODYN	SLR
IGN-JPL	✓			France	Pascal Willis	GIPSY/OASIS	-
INASAN	✓			Russia	Sergei Kuzin	GIPSY/OASIS	-

GFZ		✓		Germany	Sergei Rudenko Rolf Koenig	EPOS-OC	SLR, GNSS
CNES			✓	France	Alexandre Couhert	ZOOM	SLR, GNSS
TU Delft			✓	The Netherlands	Ernst Schrama	GEODYN	SLR

Since 2008, starting with Jason-2, satellites equipped with a DORIS receiver carry the new generation of receivers called DGXX which provides phase and pseudo-range measurements. They are distributed in a dedicated format, called RINEX/DORIS 3.0 derived from the GNSS RINEX format. One major advantage of these new measurements is that they are available with a very short latency. They also allow analysis centers to be less dependent on the CNES since the new data format provides the raw information that is necessary for computing the ionospheric delays and the precise time-tagging of the measurements. This was not the case for the former data format where this information was only given in a pre-processed form, following a pre-processing done by the CNES. While CNES supplies data files in doris2.2 and RINEX/DORIS 3.0 formats for the missions equipped with DGXX (Jason-2, Cryosat-2, HY-2A and Saral), only the latter format is available for the missions from Sentinel-3A and Jason-3 and following. Some recommendations on the practical implementation of the RINEX measurements in the POD software have been given at the last AWGs in 2016. A bug in time tagging from the PANDOR process inferred a high frequency noise in RINEX files. Another problem coming from DIODE was removed as well. The relativistic propagation correction should include not only GM but also the J2 effect. The ionospheric correction has to be computed from RINEX file. ACs should take care that the iono-free phase center is shifted from the 2 GHz phase center by 6 mm on board and 19 mm on ground, so 25 mm at all. Values of CoP–CoM vector and beacon phase center height are newly given for RINEX in an IDS available document. All differences between 2.2 and RINEX data are now explained and the necessary corrections have been applied.

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 (DGF) and JTRF2014 (JPL). While ITRF2014 and DTRF2014 are formally similar, differing only by the Post Seismic Deformation (PSD) model 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 editing criteria the JPL solutions 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 observation residuals, orbit overlaps and transformation parameters of the DORIS network. All TRF realizations represent a clear improvement over the previous realization, ITRF2008. Based on the different criteria used for evaluation, it has been shown this is the ITRF2014 which presents the best overall performance. It is this model that will serve as a basis for the operational processing of future DORIS data. For that purpose the ITRF2014 needs to be supplemented (new DORIS stations not present in the ITRF2014 solutions, if necessary correction of the position and velocity for the stations which had a short observation interval in the ITRF2014). This extension of ITRF2014 for the DORIS network is called DPOD2014: an update the position/velocity of all stations is performed and aligned on the ITRF2014, leading to possible minor adjustment of older stations. A version of the DPOD2014 will be submitted by IDS Combination Center to the evaluation of the users at the beginning of 2017.

The behavior of the various DORIS on-board oscillators in the vicinity of 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. Thanks to the extremely precise time-tagging of the T2L2 experiment on-board Jason-2, A. Belli and the GEOAZUR team showed that the DORIS on-board Ultra Stable Oscillator (USO) of Jason-2 is approximately 10 times less sensitive to the SAA than the one of Jason-1. IGN AC has shown that, thanks to the 'DORIS PPP method' on uncorrected Jason-2 DORIS data, the positioning error due to the SAA can reach up to 10 cm for some stations with this satellite. GRG AC and C. Jayles from CNES both showed that Jason-3 is also sensitive to the SAA, at a level which is lower than that of Jason-1, but still 4 to 5 times higher than that of Jason-2. The CNES POD team has shown that Sentinel-3A is also sensitive to the SAA. Using an original method based on the clock determination of the GNSS receiver on-board Sentinel-3A, they showed that it is possible with this method to obtain an accurate and continuous observation of the satellite's USO frequency excursions. One of the conclusions of these studies was that, while no noticeable effect of the SAA influence has been shown on POD or reference frame transformation parameters, there is an important impact on the station position estimation for some stations in the vicinity of the SAA area. Building accurate models of frequency variations in response to the temperature and to the SAA radiations for each DORIS

USO is therefore a task that is encouraged by the IDS community for the accurate position estimation of all DORIS stations.

ACs have to complete their DORIS/RINEX data processing implementation in order to consider the data from Jason-3 and Sentinel-3A (available first quarter of 2016). The IDS will switch to ITRF2014 for operational products when the DPOD2014 will be available. The next IDS Analysis Working Group and Workshop meetings will be held in London (UK), May 22–24, 2017 (hosted by the University College London).

IDS Combination

In 2016, in addition to the routine evaluation and combination of the IDS AC solutions, the IDS Combination Center mainly worked on the DPOD2014 solution as well as on the DORIS evaluation of the DGFI, IGN and JPL ITRF2014 realizations. These two studies, which were respectively presented at EGU 2016 and AGU 2016, must be completed and will be the subject of two forthcoming papers. In addition to its contribution to three papers of the DORIS special issue of *Advances in Space Research*, the IDS Combination Center finalized its study on the evaluation of the DORIS horizontal and vertical velocities by comparisons with two global plate models (GEODVEL and NNR-MORVEL56) and with the GNSS solution ULR6 from La Rochelle University (see Moreaux et al., 2016).

Meetings

In 2016, IDS organized a meeting of the Analysis Working Group on May 26–27 at TU Delft (Netherlands) and a Workshop in La Rochelle (France), on October 31 and November 1.

All the presentations from these meetings are made available by the Central Bureau on the IDS website at:

<http://ids-doris.org/report/meeting-presentations/ids-awg-05-2016.html>

<http://ids-doris.org/report/meeting-presentations/ids-workshop-2016.html>

Publications

IDS published the 2015 activity report that was broadly distributed to all DORIS participants and relevant services (see <http://ids-doris.org/report/governing-board.html#activity>).

All DORIS related articles published in international peer-reviewed journals are available on the IDS Web site <http://ids-doris.org/report/publications/peer-reviewed-journals.html>.

Conclusions

2016 was a year marked by the launches of two new DORIS instruments onboard Jason-3 and Sentinel-3A, increasing the DORIS constellation to six.

Two new DORIS stations were installed at Managua (Nicaragua), and Wettzell (Germany). Wettzell, with Greenbelt, are the two examples of

core sites complying with the GGOS requirements with the four space geodetic techniques (co-located DORIS/GNSS/SLR/VLBI).

The activities of all the DORIS analysts have been dominated in 2016 by the evaluation of the ITRF2014, taking into account Jason-3 and Sentinel-3A which DORIS data are only available in RINEX format, and by the analyzing of the sensitivity to the South Atlantic Anomaly (SAA) effect of their Ultra Stable Oscillator (USO). In addition to the routine evaluation and combination of the IDS AC solutions, the IDS Combination Center mainly worked on the DPOD2014 solution as well as on the DORIS evaluation of the DGFI, IGN and JPL ITRF2014 realizations.

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*Laurent Soudarin, Pascale Ferrage, Jérôme Saunier, Carey Noll,
Hugues Capdeville, Guilhem Moreaux*

3.5 Product Centres

3.5.1 Earth Orientation Centre

Revision of C04 In 2016 the Earth Orientation Center (EOC) has prepared a new C04, referred to as IERS EOP 14C04, aligned onto the most recent versions of the conventional reference frames (ITRF2014 and ICRF2). Additionally, the combination algorithm was revised to include an improved weighting of the intratechnique solutions. Over the period 2010–2015, differences to the IVS combination exhibit standard deviations of $40\ \mu\text{as}$ for nutation and $10\ \mu\text{s}$ for UT1. Differences to the IGS combination reveal a standard deviation of $30\ \mu\text{as}$ for polar motion. The IERS EOP 14C04 was adopted by the IERS Directing Board as the official reference series by 1 February 2017.

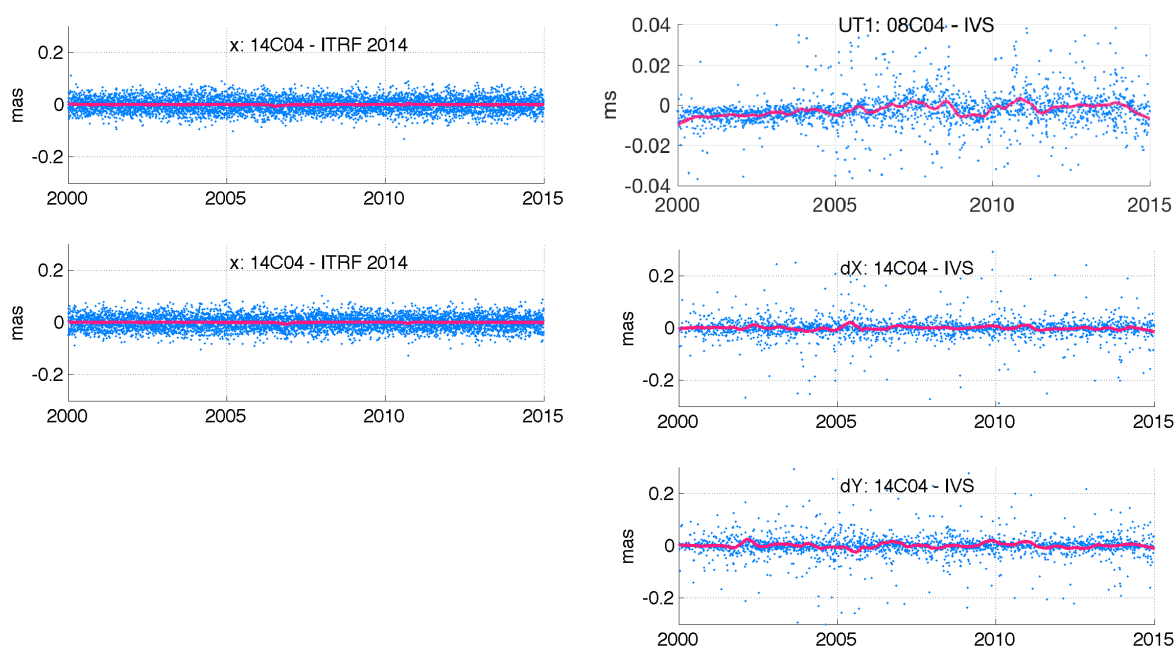


Fig. 1: Differences in (left) pole coordinates between 14C04 and ITRF2014, and (right) UT1/nutation offsets between 14C04 and IVS. The thick, red curve represents a 3-month smoothing.

Figure 1 displays the differences between 14C04 and the ITRF2014 EOP series. The bias of about $50\ \mu\text{as}$ affecting the y-component in the similar Figure 2 relevant to the 08C04 series does not show up anymore. The standard deviation of the differences has been divided by a factor of two with respect to 08C04.

Whereas no substantial change have been introduced in the input EOP series, the 14C04 series better match the intratechnique combined

solutions than the 08C04 version. This is evidenced by Table 1, where we report standard deviations of the differences between the C04 (both 08C04 and 14C04) and intratechnique and guide series. For pole coordinates the gain is about $10 \mu\text{as}$ with respect to the IGS solution from 2001 onward. For UT1 a gain of $3 \mu\text{as}$ is noticeable after 2001 with respect to the IVS solution. Nutation offsets evidence an improvement of about 30 to $60 \mu\text{as}$ from 1993 onward.

Moreover, a rigorous weighting of the input series allows to estimate for each combined EOP realistic formal uncertainties, for which the averaged values are given in Table 2.

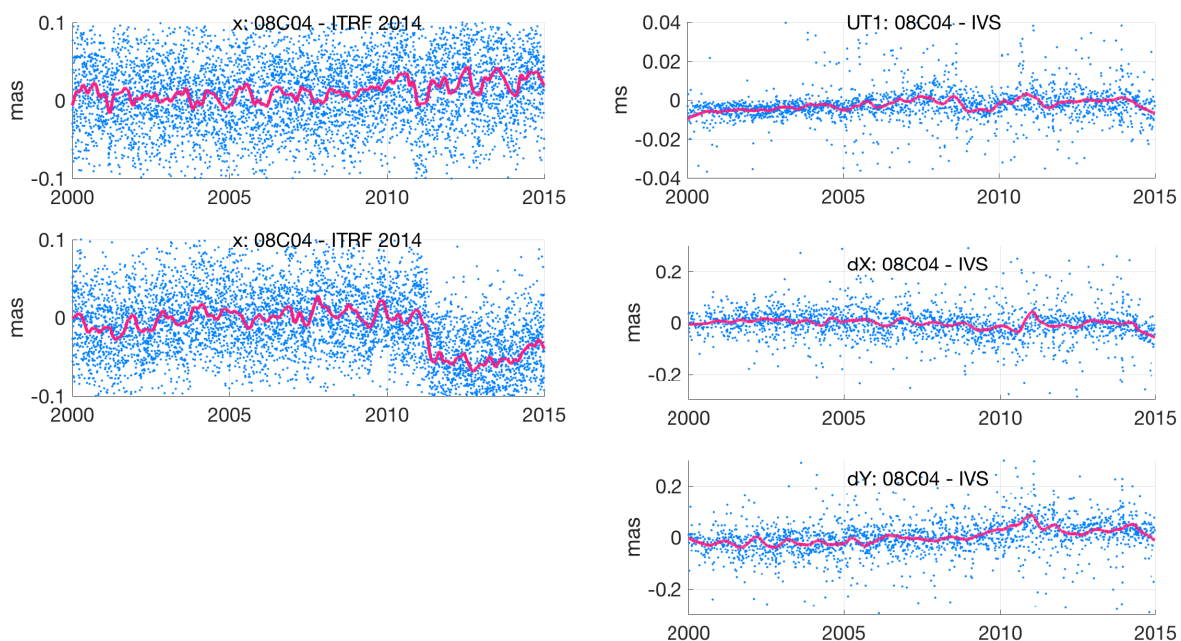


Fig. 2: Differences in (left) pole coordinates between 08C04 and ITRF2014, and (right) UT1/nutation offsets between 08C04 and IVS. The thick, red curve represents a 3-month smoothing.

Leap second on 2017 January 1

In July 2016 the EOC issued a leap leap-second through Bulletin C for 2017 January 1.

Other achievements

On the EOC web site <http://hpiers.obspm.fr/eop-pc/> interactive tools for visualizing and analyzing Earth orientation parameters have been strikingly improved. Now the page <http://hpiers.obspm.fr/eop-pc/index.php?index=analysis&lang=fr> permits an easier selection of the EOP to be represented or analyzed. On the web page <http://hpiers.obspm.fr/eop-pc/index.php?index=operational&lang=fr> comparison is no more limited to two series but can encompass several EOP series.

Table 1: *Standard deviation of the differences of C04 time series with IGS, IVS and ILRS combined series and ITRF2014. Unit is μas .*

		08C04						14C04					
		x	y	UT1	dX	dY	LOD	x	y	UT1	dX	dY	LOD
1984-1993	IGS												
	IVS	121	110	7.4	90	89		344	291	12.0	100	104	
	ILRS												
	ITRF2014	403	372	21.5				238	202	37.9			
1993-2001	IGS												
	IVS	103	95	9.4	67	60		70	55	4.4	34	37	
	ILRS												
	ITRF2014	65	60	10.9				45	38	10.3			
2001-2010	IGS	49	37				13	41	33				18
	IVS	73	71	8.3	43	47		68	66	3.3	34	41	
	ILRS	103	102				18	95	93				22
	ITRF2014	47	40	13.2				75	26	11.9			
2010-2015	IGS	42	36				11	31	27				10
	IVS	83	74	9.6	56	74		58	56	3.4	21	29	
	ILRS	107	94				16	77	74				16
	ITRF2014	49	49	11.9				27	25	10.1			

Table 2: *Averaged formal uncertainty of the 14C04 solution (second line) corresponding to four successive periods. Unit is μas .*

	x	y	UT1	dX	dY	LOD
1984-1993	274	238	22.0	178	193	31
1993-2000	108	96	6.8	51	45	18
2000-2010	62	59	8.5	38	37	21
2010-2015	48	44	9.1	54	45	14

**Earth Orientation Center
staff in 2016 and
functions**

Christian Bizouard, Astronomer, head
Olivier Becker, Engineer, daily tasks
Teddy Carlucci, System Engineer
Lambert Sébastien, Astronomer, deputy to IERS DB
Daniel Gambis, Astronomer, retired in 2015, adviser

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Christian Bizouard

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 2016. The accuracies of both the inputs (used in the generation of the IERS RS/PC results) and the IERS RS/PC combination and prediction results (as published in several formats that comprise the Bulletin A results) are provided. 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 discussions regarding results will not, in general, be discussed in this section; however, findings and explanations may be presented at the upcoming Journées 2017 Systèmes de Référence Spatio-Temporels conference (2017 Journées conference) or other future conferences.

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 based on their reported observational errors, which is referred to as a “weighted smoothing cubic spline” (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 2016 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 2016.

The EOPs consist of polar motion, UT1–UTC, and celestial pole offsets. 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 celestial pole offsets ($d\psi$, $d\epsilon$, dX , and dY), all the contributors (which have associated statistics in Table 1) provide direct measurements of these quantities. 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-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 length-of-day (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. The Atmospheric Angular Momentum (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 corresponds 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 spline, which combines the contributor inputs, uses the following as inputs: 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 to $d\psi$ and $d\epsilon$ in the combination process.

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.

Table 1: *Estimated accuracies of the contributions to the IERS RS/PC combination results for 2016 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	0.23	0.27	–	–	–
IAA SLR	0.19	0.22	–	–	–
MCC SLR	0.21	0.30	–	–	–
GSFC VLBI Intensive	–	–	0.013	–	–
USNO VLBI Intensives	–	–	0.010	–	–
GSI Intensives	–	–	0.015	–	–
GSFC VLBI	0.12	0.12	0.004	0.28	0.11
IAA ⁺ VLBI	0.19	0.14	0.010	(0.13)	(0.19)
IVS ⁺ VLBI	0.10	0.25	0.003	(0.06)	(0.06)
USNO VLBI	0.12	0.14	0.005	0.18	0.07
IGS Final	0.01	0.01	–	–	–
IGS Rapid	0.03	0.06	–	–	–
IGS Ultra*	0.04	0.05	0.103*	–	–
USNO GPS UT*	–	–	0.028*	–	–

⁺ 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.

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 08 C04 EOP solutions for 2016. 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	0.05
y	-0.02	0.04
UT1–UTC	0.001	0.030
Bulletin A Weekly Solution (finals.data)¹		
x	0.03	0.07
y	-0.01	0.06
UT1–UTC	-0.013	0.048
Bulletin A Daily Solution (finals.daily)		
x	0.02	0.05
y	0.02	0.04
UT1–UTC	-0.034	0.078

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

The 2016 UT1–UTC GSFC, USNO, and GSI VLBI Intensives Estimated Accuracy values are listed in Table 1. Comparing UT1 RMS values between the years 2015 to 2016, the GSFC intensives UT1 RMS value improved from 0.015 to 0.013 milliseconds (msec); the USNO intensives show no change; and the GSI intensives had larger residuals as compared to the corresponding 2015 values¹ (0.015 vs 0.010 msec, respectively).

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

¹The 2015 statistics are located in Table 1 of Section 3.5.2 of the IERS Annual Report 2015; located by clicking on the “Rapid Service/Prediction Centre” tab at: <https://www.iers.org/AR2015>.

from 2015, one can see over a 100% increase (0.103 for 2016 vs 0.046 msec for 2015). 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 increase are being considered; however, reasons for the increase 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 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 all partially used to determine this constant of integration. As will be discussed later, there was an apparent error in the UTGPS input or in the pre-processing of the UTGPS input before being used as an input to the EOP combination software. It is possible that this error in the constant of integration caused some of the increase in the larger IIULs residuals for 2016 than seen in previous years.

Table 2 shows the accuracies of Rapid Service/Prediction Center's combination solution for the running, weekly, and daily products compared to the 08 C04 series maintained by the IERS EOC for 2016; 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 2016 residuals between the daily rapid and the 08 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. There was a large residual at MJD 57424 in polar motion X whose value is not captured in the plot because the y-axis scaling of that plot was chosen so as to show the patterns and signal of the rest of the residuals. The value of polar motion X for MJD 57424 was 0.67 milliarcseconds (masec). If reasons for the large residual are determined, that information will be provided at the 2017 Journées conference or future conference.

As shown in Figure 1 and Table 2, the UT1–UTC residuals for 2016 were higher than those determined for 2015 – 0.068 for 2016 and 0.0546 msec for 2015; causes for this increase were investigated and mainly focused on days when the RS/PC solution did not initially converge. Occasionally, the RS/PC solution would not initially converge to a physically realistic solution in UT1–UTC. Prior to the beginning of 2016, this issue occurred approximately 5 to 10 times per year, and on most of those occasions, various recently observed non-VLBI inputs were removed until the combination solution converged. It was noticed that this issue occurred more often in EOP solutions computed at times other than 17:00 UTC – namely, at 21:10, 03:10, and 09:10 UTC; consequently, this problem had been already slowly investigated prior to the beginning of 2016.

Starting in 2016, it was noticed that this UT1–UTC convergence solution problem was occurring more often than in previous years. Consequently, more effort was made to determine the cause, and it was determined that a probable cause was that there were problems with the UTGPS inputs or the pre-processing of this input data before using it in the EOP combination. To partially confirm this probable cause, a simulation of 201 past days (during 2016) was created using a de-weighted UTGPS input to the weighted, smoothing cubic spline used in the combination. The RMS of the UT1–UTC residuals from the de-weighted UTGPS simulation was reduced to 0.045 msec; whereas, the operational RMS for the same 201 days during 2016 was 0.068 msec and for the 2015 UT1–UTC results the RMS was 0.055 msec. The de-weighting of the UTGPS input brought the RMS of the residuals more in line with what had been seen in previous years, thus indicating that there was a possi-

ble issue with the UTGPS contribution to the 2016 combination results. It is hoped that more investigation into the issue will be performed and presented at the 2017 Journées conference or a later conference.

The RMS of the polar motion residuals for 2016 are shown in Table 2, under the heading “Bulletin A Daily Solution (finals.daily)”; these results are comparable to those determined during previous years. In addition, polar motion and UT1–UTC residuals computed relative to the JPL SPACE EOP series were determined to be similar to those provided in Table 2, which were computed relative to the 08 C04 EOP series.

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 08 C04 series over the 365-day period covering 2016. The finals.data file used in computing these statistics was computed on January 14, 2017 (and also archived). Nominally, the last observational input data for the year (in this case, 2016) is processed and provided to the IERS RS/PC by January 14 of the following year (in this case, 2017); 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.

The “Bulletin A Weekly Solution” results shown in Table 2 are the statistics of the residuals obtained from the Bulletin A combination values for 2016 versus the 08 C04 series. These combination values for 2016 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 14, 2016 has EOP combination results from January 8 through January 14, 2016.)

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 2016, versus the respective 08 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.)

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 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

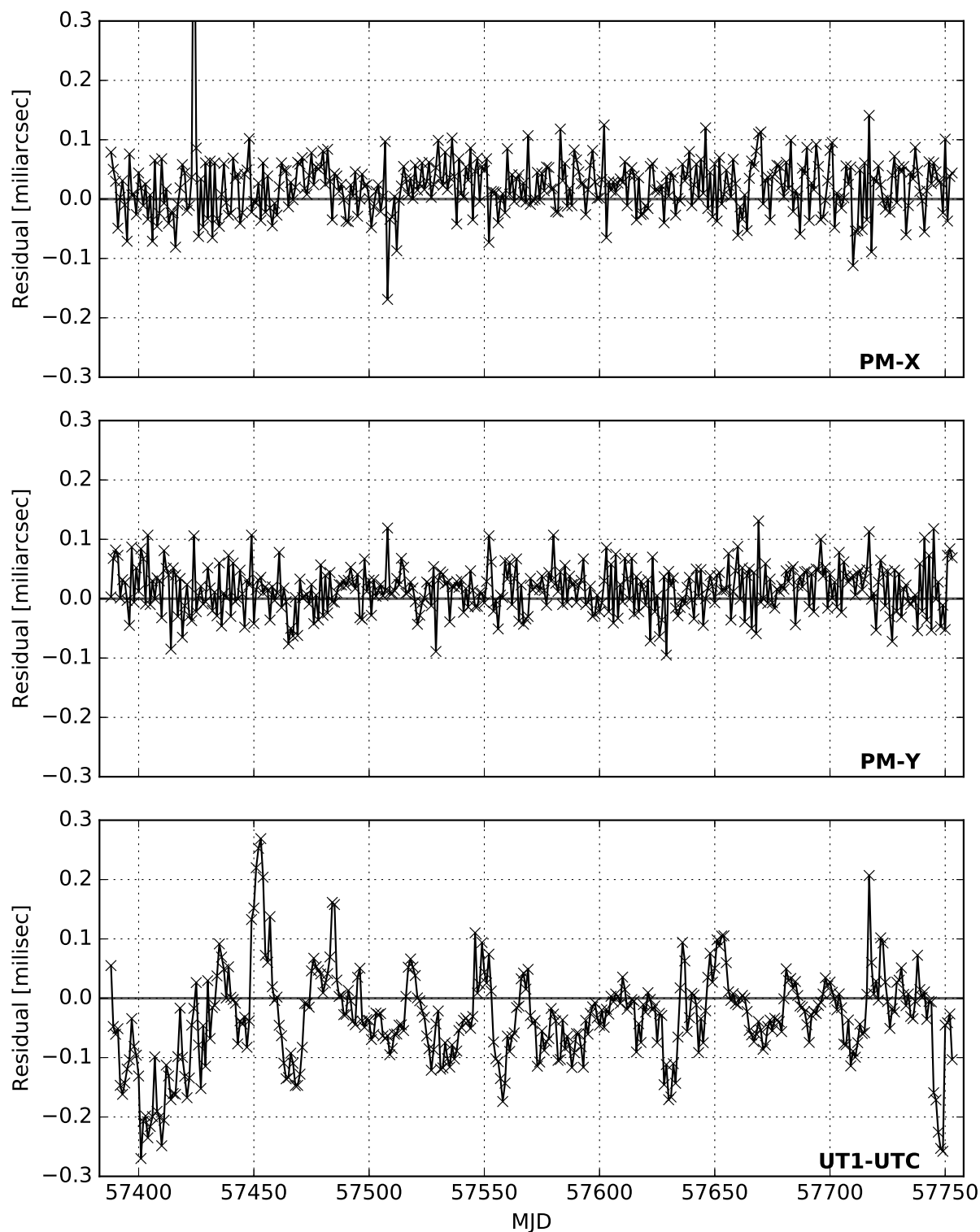


Figure 1: Differences between the EOP solution updated daily (called the “daily solution”) for 2016 and the respective 08 C04 series combination solution. The large (off-the-scale) outlier in Polar Motion X that occurred on MJD 57424 had a residual value of 0.67 masec. Earth Orientation Parameters shown are: a) Polar Motion X; b) Polar Motion Y; c) UT1–UTC.

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 UT AAM 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 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

GPS-based UT 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 sets of prediction days for 2016, the RMS of the residuals between USNO produced polar motion and UT1–UTC solutions and the 08 C04 series values are shown in Tables 3a through 3d. Prediction day “N” is defined as “N” days into the future from the current day that the EOP solution was updated. For example, prediction day 10 for the EOP solution that was updated on MJD 57662 (October 1, 2016) is MJD 57672 (October 11, 2016). Table 3a provides the RMS prediction errors for EOP solutions updated at 17:00 UTC; and Tables 3b, 3c, and 3d provide RMS prediction errors for solutions updated at 21:10, 03:10, and 09:10 UTC, respectively.

Unfortunately, for 2016 there was a noticeable increase in the RMS of the residuals for the UT1–UTC 0- and 1- day predictions when compared to previous years. The RMS of the 1-day prediction residuals shown in Table 3a was 0.131 msec for 2016; for 2015 the RMS was 0.073 msec. There are similar types of increases for the 5-day and 10-day values for 2016 versus for 2015. The exact reasons are under investigation; however, one possible cause is the previously mentioned issue with the UTGPS input or the pre-processing of the UTGPS input during 2016. A simulation was created with a de-weighted UTGPS input for a subset of 201 days of 2016 (as was mentioned in the Combination Processing Techniques and Results section), and the 1-day prediction RMS of the residual results improved to 0.065 msec. This reduced RMS is much closer to the RMS of the 1-day prediction for 2014 and 2015 – 0.056 and 0.073 msec, respectively.

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 08 C04 combination solutions for 2016. Note that the prediction length starts counting from the day after the date of the solution epoch.*

Days in future	PMx masec	PM _y masec	UT1 - UTC msec
0	.058	.042	0.085
1	.342	.248	0.131
5	2.09	1.36	0.223
10	3.52	2.49	0.663
20	4.95	4.50	2.004
40	7.52	8.16	4.521
90	7.94	15.2	9.125

Table 3b: *RMS of the differences between the EOP time series predictions produced by the 21:10 UTC daily EOP solutions and the 08 C04 combination solutions for 2016.*

Days in future	PMx masec	PM _y masec	UT1-UTC msec
0	0.05	0.04	0.082
1	0.29	0.22	0.190
5	2.00	1.31	0.324
10	3.46	2.47	0.726
20	4.93	4.51	2.066
40	7.50	8.13	4.543
90	7.89	15.02	9.131

Table 3c: *RMS of the differences between the EOP time series predictions produced by the 03:10 UTC daily EOP solutions and the 08 C04 combination solutions for 2016.*

Days in future	PMx masec	PM _y masec	UT1-UTC msec
0	0.06	0.05	0.077
1	0.16	0.09	0.120
5	1.96	1.22	0.218
10	3.62	2.38	0.669
20	5.18	4.45	1.989
40	7.75	8.13	4.479
90	8.07	15.24	9.089

Table 3d: *RMS of the differences between the EOP time series predictions produced by the 09:10 UTC daily EOP solutions and the 08 C04 combination solutions for 2016.*

Days in future	PMx masec	PM _y masec	UT1-UTC msec
0	0.06	0.05	0.075
1	0.08	0.08	0.118
5	1.73	1.22	0.215
10	3.39	2.38	0.666
20	4.97	4.43	1.987
40	7.56	8.10	4.476
90	8.09	15.00	9.102

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.

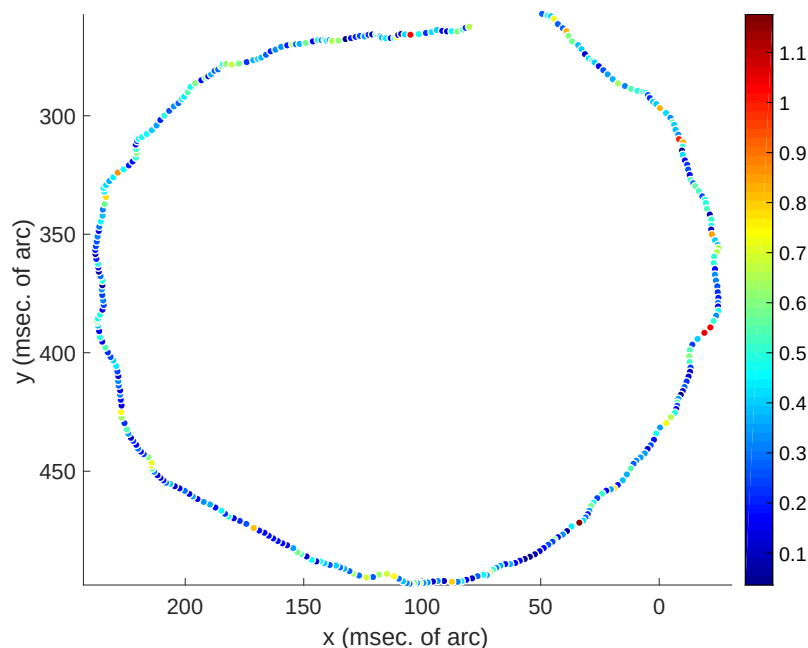


Figure 2: *Plot of the polar motion path for 2016 with corresponding 1-day prediction residual values versus the 08 C04. The residual is the RMS of the combined polar motion x and y residual values and is in units of msec. The residual values correspond to the color-coded vertical bar at the right ranging from less than 0.1 (dark blue) to greater than 1.1 (dark red) msec.*

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.

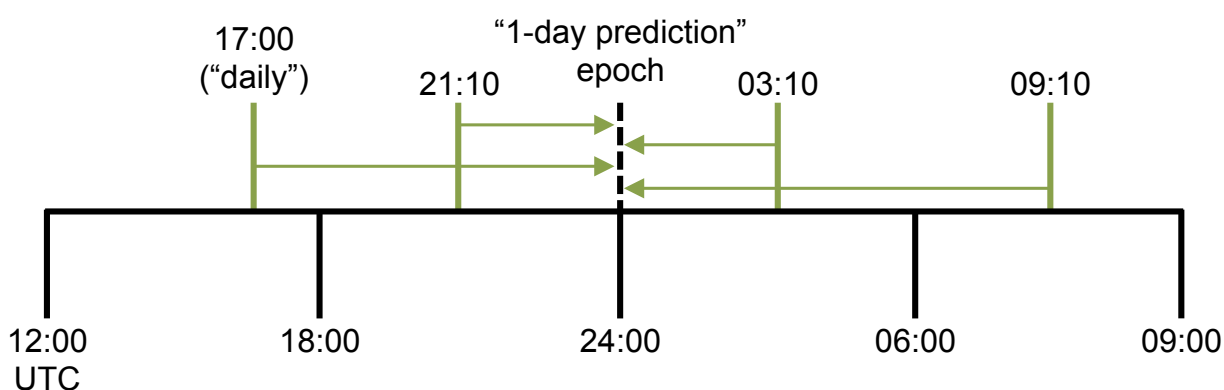


Figure 3: Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP “daily” solution produced at 17:00 UTC. Each EOP solution update time is shown by the vertical green lines at 17:00, 21:10, 03:10 and 09:10 UTC, respectively. At each of these times, the latest observations are obtained. 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.

Within each Nxdaily EOP solution file, which are located in separate sub-directories, there are EOP solutions for polar motion, UT1–UTC and celestial pole offsets. Each 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 00:00 <MJD+1> epoch.

The 0, 1, and 5-day UT1–UTC RMS residuals shown in Tables 3a, 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 3a values. However, the Table 3b values do not follow this pattern, and the reasons are under investigation. 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 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 08 C04 solution, is computed and applied to ensure consistency with the 08 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 08 C04 for 2016 are provided in Table 5.

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).

Center Activities for 2016

During 2016, several input data series to the EOP operational solution were upgraded. A list of these upgrades is as follows:

- a) the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) AAM input was upgraded from NAVGEM v1.3 to v1.4 in October 13, 2016;
- b) the GSFC 24-hour and intensive data series were upgraded from the gsf2015a to gsf2016a series on October 13, 2016; and
- c) the USNO VLBI 24-hour and intensive data series were upgraded from the usno2015a to usno2016a series on November 17, 2016.

In addition, just after the announcement in early July, 2016, of a pending leap second for December 31, 2016, had been made, several EOP codes and configuration files were successfully updated to accommodate the change.

Efforts continued in the following areas as well:

- a) using the Very Long Baseline Array (VLBA) estimates as additional UT1–UTC inputs to the EOP solution (Stamatakos *et al.*, 2012, AGU poster G51A-1084);
- b) studying combined AAM and OAM inputs to improve polar motion predictions (Stamatakos *et al.*, 2016);
- c) studying methods to better optimize the use of the UTGPS and IGS Ultra-rapid observations for LOD inputs to the EOP solution;
- d) upgrading the DataSim simulation environment to test changes to codes, input data series, and configurations to the EOP software and processing;
- e) creating code to combine celestial pole offsets using dX and dY formulation rather than $d\psi$ and $d\epsilon$ with respect to the 1980 precession and nutation formulations;
- f) 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; and

g) starting efforts to test other optimal estimation techniques to replace the smoothing, weighted cubic spline 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.).

The existing web-based, interactive EO matrix calculator² 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>.

²<http://maia.usno.navy.mil/t2c36e/t2c36e.html>

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	
<i>Contributor</i>	<i>Epoch at Midpoint*</i>	<i>Contributor</i>	<i>Epoch at Midpoint*</i>	<i>Contributor</i>	<i>Epoch at Midpoint*</i>	<i>Contributor</i>	<i>Epoch at Midpoint*</i>
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	
<i>Contributor</i>	<i>Epoch at Midpoint*</i>	<i>Contributor</i>	<i>Epoch at Midpoint*</i>	<i>Contributor</i>	<i>Epoch at Midpoint*</i>	<i>Contributor</i>	<i>Epoch at Midpoint*</i>
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 08 C04 combination solutions for 2016.*

Days in Future	dX mas	dY mas	d ψ mas	d ϵ mas
0	.12	.10	.26	.13
1	.12	.10	.26	.13
5	.12	.10	.27	.13
10	.12	.11	.28	.14
20	.13	.13	.29	.16
40	.14	.16	.33	.19

Table 6: *Predicted values of TT–UT1, 2017–2028.*
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)
2017 Oct 1	68.86	0.014
2018 Jan 1	69.0	0.02
2018 Apr 1	69.1	0.02
2018 Jul 1	69.3	0.15
2018 Oct 1	69.3	0.15
2019 Jan 1	69.5	0.15
2019 Apr 1	69.6	0.15
2019 Jul 1	69.7	0.15
2019 Oct 1	69.8	0.16
2020 Jan 1	69.9	0.16
2020 Apr 1	70.1	0.16
2020 Jul 1	70.2	0.16
2020 Oct 1	70.3	0.16
2021 Jan 1	70.4	0.16
2021 Apr 1	70.5	0.17
2021 Jul 1	70.6	0.17
2021 Oct 1	70.7	0.17
2022 Jan 1	70.8	0.17
2022 Apr 1	70.9	0.17
2022 Jul 1	71.0	0.17
2022 Oct 1	71.1	0.18
2023 Jan 1	71.2	0.18
2023 Apr 1	71.3	0.18

Table 6 (cont...)

2023 Jul 1	71.4	0.18
2023 Oct 1	71.5	0.18
2024 Jan 1	71.6	0.18
2024 Apr 1	71.7	0.19
2024 Jul 1	71.8	0.19
2024 Oct 1	71.8	0.19
2025 Jan 1	71.9	0.19
2025 Apr 1	72.0	0.19
2025 Jul 1	72.1	0.20
2025 Oct 1	72.2	0.20
2026 Jan 1	72.3	0.20
2026 Apr 1	72.4	0.20
2026 Jul 1	72.5	0.20
2026 Oct 1	72.5	0.20
2027 Jan 1	72.6	0.21
2027 Apr 1	72.8	0.21
2027 Jul 1	72.8	0.21
2027 Oct 1	72.9	0.21
2028 Jan 1	73.0	0.21
2028 Apr 1	73.1	0.21
2028 Jul 1	73.2	0.22
2028 Oct 1	73.3	0.22

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	✓	✓		✓				
USNO GPS			✓					
NCEP AAM			✓					
NAVGEN 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 Stamatakos	Project Director and Lead Scientist; Chief, EOP Combination and Prediction (EOP C/P) Division
Ms. Merri Sue Carter	Assists in daily operations and support; 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

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Stamatakos, 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.

Stamatakos, 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.

McCarthy, D., Stamatakos, N., “A Conventional Mean Pole,” G41A-1002 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2016.

Stamatakos, 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.

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.

Report contributors: Nick Stamatakos, Maria Davis, Nathan Shumate, Merri Sue Carter, Report reviewer: Christine Hackman

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). After years of dedicated service as a co-chair to the IERS Convention Centre, Dr. Gérard Petit of the BIPM has stepped down effective 23 June 2016. Moving forward, the US Naval Observatory has partnered with the Paris Observatory to share in the responsibilities of co-chairing the IERS Conventions Centre.

The Conventions Centre provides updated versions of the IERS Conventions in electronic form, after approval of the IERS Directing Board (DB). In the meantime, interim versions are also available by electronic means. In addition to the electronic releases, printed versions of the Conventions will be provided at less frequent intervals or when major changes are introduced.

Over 2016, the work accomplished or in progress includes the following:

Technical Content of the IERS Conventions

New IERS Conventions web and ftp sites were created in 2016 and 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 published 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>. Work started on the updates to the IERS Conventions (2010) soon after the publication of this new reference edition, and the electronic versions of the IERS Conventions (2010) update can be found at: can be found at the following sites: <http://iers-conventions.obspm.fr/updates/2010updatesinfo.php> and <http://maia.usno.navy.mil/conventions/updates/2010updatesinfo.php>.

Conventions Software

The following routines from Chapter 7, listed in the table on the next page, were updated to account for the leap second on 31 December 2016.

An updated CAL2JD.F, a subroutine of DEHANTTIDEINEL.F, was added from the 12th release of the SOFA package. Just as had been done in 2015, it was planned that IERS_CMP_YYYY would be updated for YYYY equal to 2016. However, due to expected changes in the definition of the mean pole that were to be proposed at the Unified Analysis Workshop (UAW), Paris France, July 8–10, 2016, the routine IERS_CMP_2016 was not published.

Function Name	Description
ETUTC.F	Difference between Ephemeris Time ET and Coordinated Universal Time UTC.
DAT.F	TAI–UTC at a given UTC date calculate.
DEHANTTIDEINEL.F	Computation of station tidal displacement.
HARDDISP.F	Reading time series of tidal displacements in the BLQ format.
CAL2JD.F	Gregorian Calendar to Julian Date.

Planned Changes Planned activities listed in the analogous section of 2015 IERS Annual Report were continued though 2016. Addressing customer feedback and comments with regards to the complexity and requirements of the Conventions remains an important consideration for the IERS Conventions co-chairs and associated staffs. Various discussions on how to address these concerns have taken place, and an update on these discussions was provided to the IERS DB just prior to the American Geophysical Union (AGU) Fall meeting, 2016.

Dissemination of Information 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
 Sébastien Lambert (OP)
 Maria Davis (USNO)
 Dennis McCarthy (USNO, retired)

Nick Stamatakos, Christian Bizouard

3.5.4 ICRS Centre

Paris Observatory ICRS Center activities during 2016

Analysis of recent VLBI catalogs Data sets

Six catalogs were submitted respectively by the Italian Space Agency (ASI; asi2016a), Geoscience Australia (aus2016a; aus2016b), the Federal Agency for Cartography and Geodesy (BKG Leipzig) and Institute of Geodesy and Geoinformation of the University of Bonn (IGGB; bkg2016a), and the US Naval Observatory (usn2016a). All these catalogs provide right ascension (α) and declination (δ) of extragalactic radio sources, as well as their respective uncertainties, the correlation coefficient between α and δ , and the number of sessions and delays. Note that bkg2016a and usn2016a catalogs were produced with the same geodetic VLBI analysis software package SOLVE developed at NASA GSFC. Solutions aus2016a and aus2016b were produced with OCCAM. The catalogs are displayed in Fig. 1 with color codes following the formal error on the source position.

Table 1: *Number of sources (total and in common with ICRF2 and the Gaia DR1 catalog) and median error (in microarc second). Values for right ascension, referred to as RA*, are corrected from the cosine of the declination.*

	No Sources			Median Err	
	Total	ICRF2	Gaia	RA*	Dec
asi2016a	1368	1339	958	56	92
aus2016a	3900	3284	2106	442	728
aus2016b	3917	3290	2109	432	700
bkg2016a	3507	3122	2029	234	428
usn2016a	4129	3412	2191	213	364

Table 1 displays the total number of sources of each catalog, as well as the number of sources in common with the ICRF2 (Fey et al. 2015) and the Gaia DR1 auxiliary solution (Mignard et al. 2016). Table 1 also reports the median error and reveals an error in declination larger than in right ascension by a factor of ~ 1.5 . The error is substantially smaller for SOLVE solutions compared to OCCAM, except the solution asi2016a whose smaller error likely originates in the fact that the solution considered a relatively small number of well observed sources with low positional standard error.

Figure 2 illustrates how the overall formal error, defined as the square root of $\sigma^2 \alpha \cos^2 \delta + \sigma^2 \delta + c^2 \sigma^2 \alpha \cos^2 \delta \sigma^2 \alpha \delta$ where σ is the formal error listed in the catalogs and c is the correlation coefficient between estimates

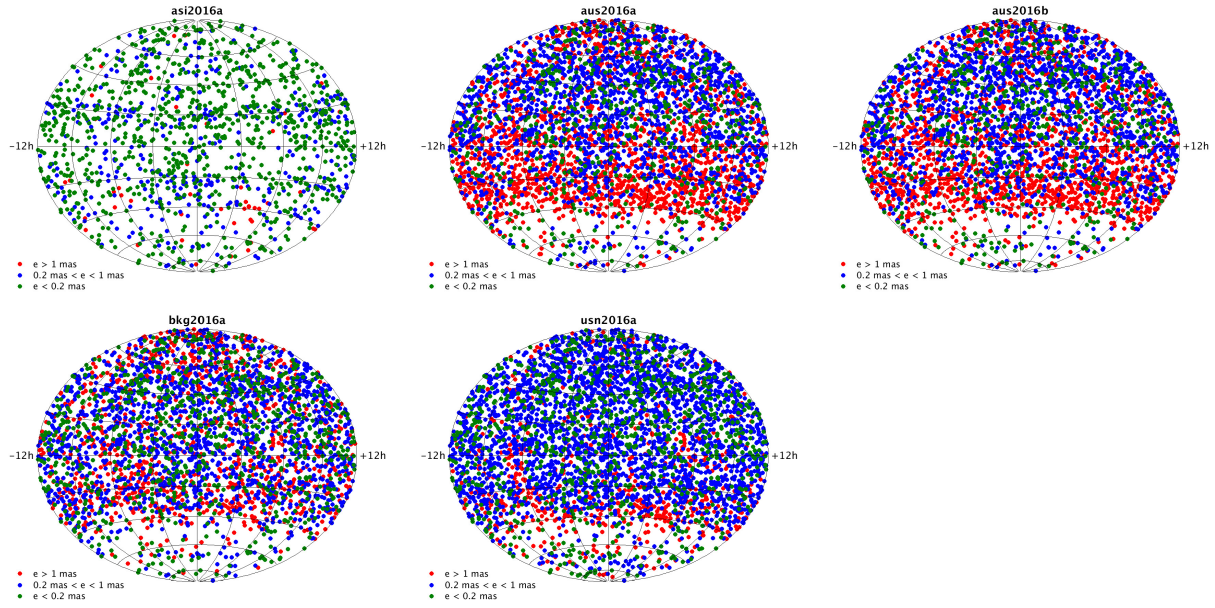


Fig. 1: *The source distribution on the sky.*

of α and δ as provided in the catalogs, varies with the number N of observations. The figure for aus2016b clearly shows that some sources have underestimated formal errors likely due to an overconstrained solution. (As stated in the technical document delivered with the catalog, a strong no-net rotation condition was imposed to these sources. A similar fact was pointed for solution aus2015a in the 2014 IERS Annual Report.) The formal error of the same sources in solution aus2016a, in which the no-net rotation condition is less severe, appears to be at a level comparable to other sources.

Frame deformation

We evaluate the consistency of the submitted catalogs with the ICRF2 and Gaia DR1 by modeling the coordinate difference (in the sense catalog minus reference) by a 16-parameter transformation including three rotations, a glide (three parameters), and a quadrupolar deformation (e.g., Mignard and Klioner 2012).

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

where R_1 , R_2 , R_3 are rotation angles around the X, Y, and Z axes of the celestial reference frame, respectively, D_1 , D_2 , D_3 represent the glide parameters, and $\Delta\alpha$ and $\Delta\delta$ are coordinate differences between the studied and the ICRF2 catalogs. All other parameters are relevant to the quadrupolar deformation. The parameters were fitted by weighted least squares to the coordinate difference of the common sources between the catalogs and the references. The covariance (weight) matrix included the a priori covariance information between the provided estimates of the radio source coordinates. A representation of the rotation and glide parameters is displayed in Fig. 3. The standard deviation and chi-squared of the offsets to the reference before and after removal of the systematics are reported in Table 2. Generally, the largest excursion from the ICRF2 shows up for the D_3 parameters expressing a poleward displacement of the sources. For Australian solutions, both rotation and glide parameters remain insignificant. Interestingly, the poleward deformation also shows up for the comparison against Gaia but with the reversed sign indicating that the 2016 VLBI catalog deformation lies somewhere between the ICRF2 and Gaia.

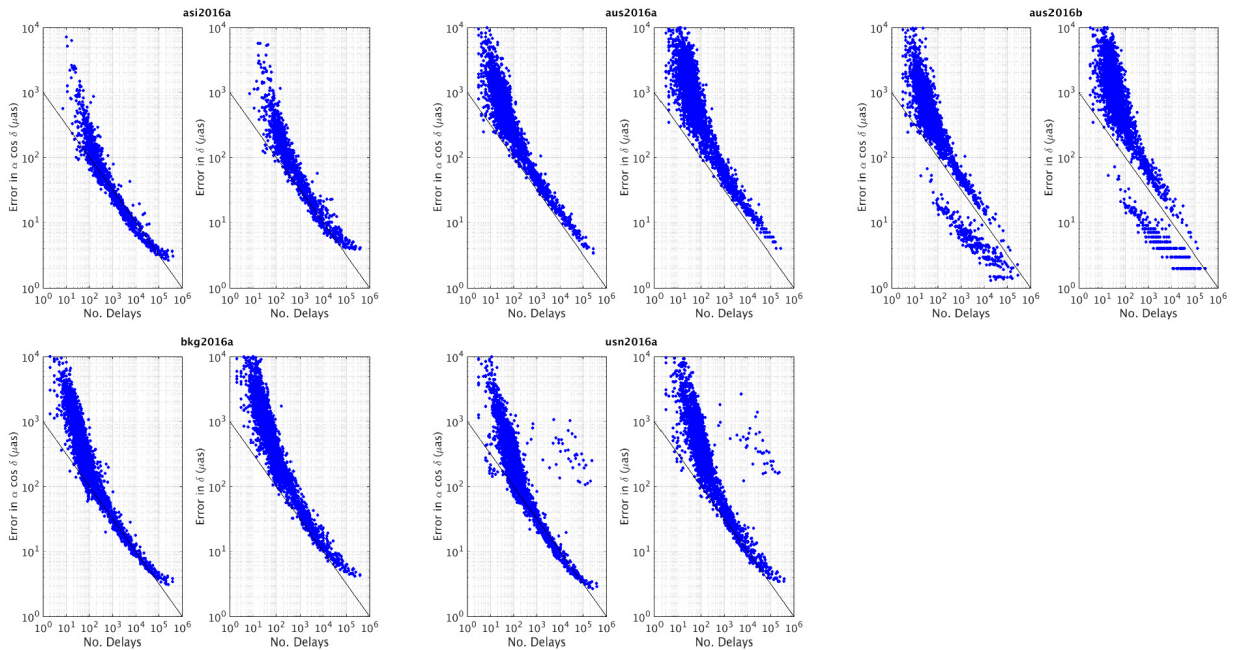


Fig. 2: The formal error as a function of the number of delays. See text for details.

Zonal errors

In Fig. 4, we plotted the differences in declination between catalogs and the reference averaged in ten bins of declination of equal width between -70° and $+70^\circ$. The systematics were not removed, so that the differences are direct differences between the catalogs and the reference. Data have been weighted using the total variance coming

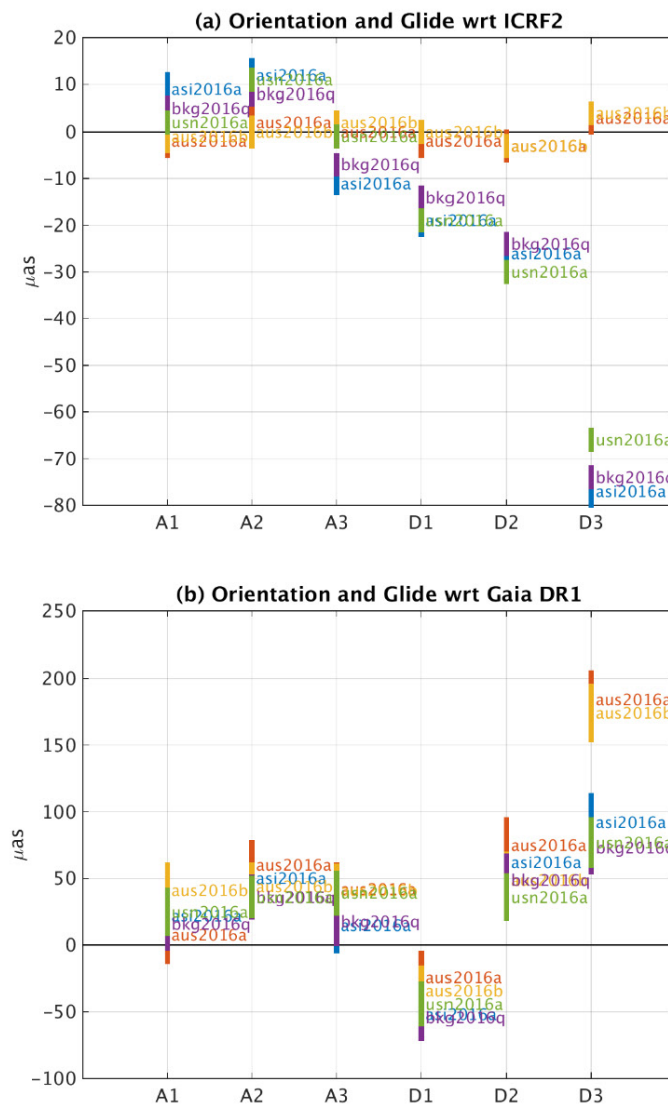


Fig. 3: The rotation and glide parameters between the catalogs and the reference that are (Left) the ICRF2 and (Right) Gaia DR1. Unit is micro-arcsecond.

from the errors in the two compared solutions. Comparison against ICRF2 (panel (a)) reveals that the differences are generally increasing in absolute value when going southern except for the Australian solutions, which is consistent with the estimated rotation and glide parameters (Fig. 3). If one consider that (i) zonal errors in VLBI catalogs can be expected because of the network north-south asymmetry and (ii) the Gaia catalog has no zonal error or, at least, smaller than for VLBI, plots of Figs. 3 and 4 can provide insights in how much VLBI catalogs have improved since the ICRF2 from the zonal deformation point of view. Especially, in the (b) panels of the figures, the deformation and declination difference values relevant to Australian solutions are similar to what one would have obtained by comparing the ICRF2 to Gaia. The 2016 ASI, BKG,

and USNO solutions appear therefore “closer” to Gaia for D3 and in terms of declination differences.

Table 2: *Crude and residual (i.e., after removal of systematics) differences between catalogs and references (ICRF2 and Gaia DR1). Unit is micro-arcsecond. Values for right ascension, referred to as RA*, are corrected from the cosine of the declination.*

Differences					Residuals				
		Stdev		Chi2			Stdev		Chi2
RA*	Dec	RA*	Dec	RA*	Dec	RA*	Dec	RA*	Dec
ICRF2									
asi2016a	83	102	0.85	0.91	80	94	0.79	0.78	
aus2016a	122	137	0.62	0.57	121	136	0.62	0.57	
aus2016b	108	123	0.54	0.51	108	123	0.54	0.51	
bkg2016a	89	113	0.44	0.49	87	106	0.42	0.43	
usn2016a	96	118	0.47	0.49	93	112	0.44	0.44	
Gaia									
asi2016a	363	461	1.88	1.47	357	457	1.82	1.45	
aus2016a	537	700	1.59	1.40	532	696	1.57	1.39	
aus2016b	519	696	1.59	1.41	516	694	1.57	1.41	
bkg2016a	493	627	1.77	1.49	490	624	1.75	1.48	
usn2016a	464	570	1.69	1.33	463	567	1.68	1.32	

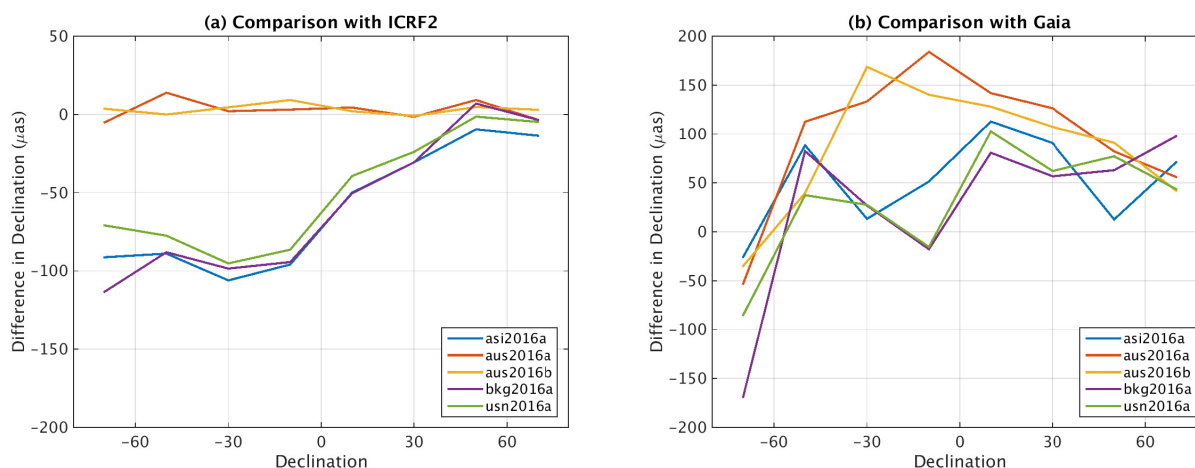


Fig. 4: *Difference in declination between catalogs and the references binned by interval of declination.*

Validation of the Gaia DR1 catalogue for QSOs

Members of the ICRS Center staff belong to the Working Group Package WP944 from CU9 of the Gaia DPAC. Our work was to validate the QSOs from the Gaia catalogue release using external QSO catalogues. In

summer 2016, we created and ran our validation tests (VTS) on the QSOs from Gaia DATA RELEASE 1 (GDR1) catalogue before the public release.

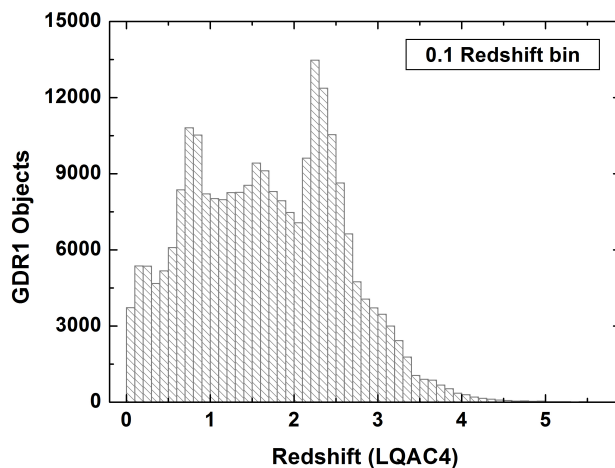


Fig. 5: Spectroscopic redshift histogram for the LQAC4 quasars found in the GDR1 with a search match radius of 1arcsec. The double peak – at about redshift 0.8 and redshift 2.2 - derive from the domineering number objects from the SDSS, either the classic north galactic cap plus the BOSS surveys.

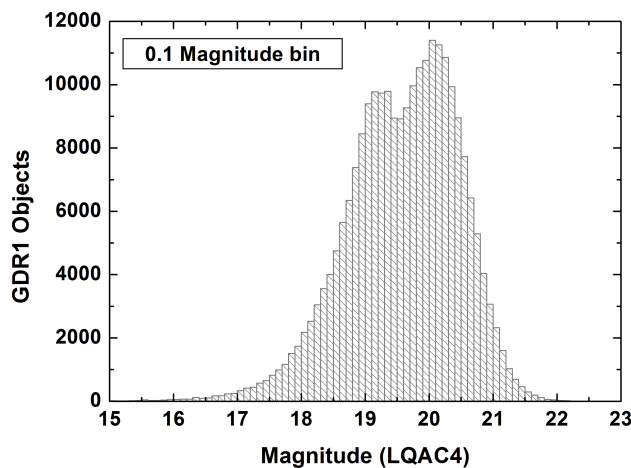


Fig. 6: Magnitude histogram for the LQAC4 quasars found in the GDR1 with a search match radius of 1arcsec. The magnitudes are from the LQAC4. The double peak – at about magnitude 19.3 and magnitude 20.1 - derive from the domineering number objects from the SDSS, either the classic north galactic cap plus the BOSS surveys.

Gaia DR1 contains a total of 1,142,679, 769 sources. The astrometric section of Gaia DR1 is built in two populations. The first one concerns the primary sources, which contain positions, parallaxes, and mean proper motions for 2,057,050 of the stars brighter than about magnitude $V = 11.5$ (about 80% of the total number of stars). This data set, the

Tycho Gaia Astrometric Solution (TGAS), was obtained through the combination of the Gaia observations with the positions of the sources obtained by Hipparcos (ESA 1997) when available, or Tycho-2 (Høg et al. 2000). The second population of the Gaia DR1 concerns the secondary sources, which contain the positions and G magnitudes for 1,140,622,719 sources brighter than magnitude $G = 21$.

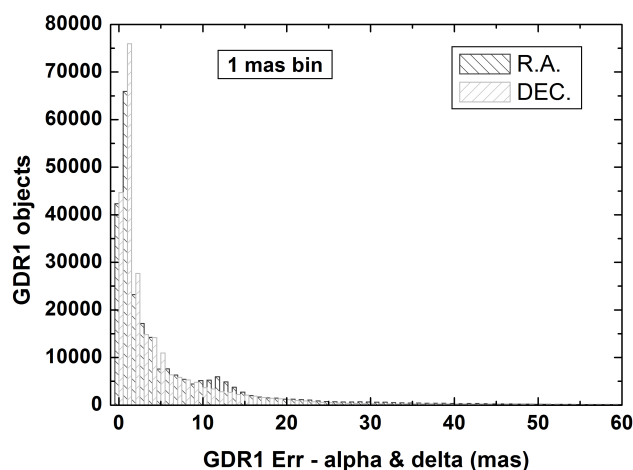


Fig. 7: Error histogram for the LQAC4 quasars in the GDR1, found using a search match radius of 1 arcsec. The right ascension and declination both follow well the expected distribution. The small departures of one distribution to another are non statistically significant.

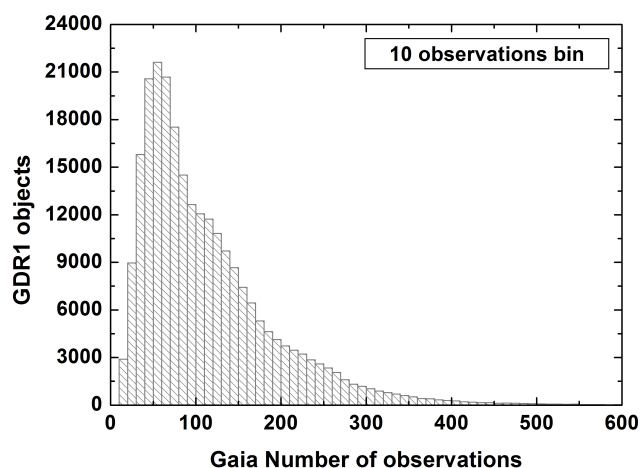


Fig. 8: Number of observations for the LQAC4 quasars the GDR1, found using a search match radius of 1 arcsec. The distribution is as expected from the satellite scanning law.

We have used the ESAC SVN to run our test written in Java and R languages. The main test (VTS 060_004) was the comparison between the ICRF2 catalogue and the second population of the Gaia DR1 catalogue by a crossmatch position within a 0.1 arcsecond radius. A total

of 2,292 ICRF2 quasars were found in the Gaia DR1. No significant rotation versus the ICRF2 was found, but a deformation (glide) lower than 0.2 mas was detected. It should be noted that this deformation is no longer significant if the cross-match radius is increased from 0.1 to 0.5 arcsecond, which adds 15 sources.

The residuals of the position differences normalized using the covariance matrix of both Gaia DR1 and the ICRF2 Rx show too many outliers, that is to say 10% of the sample with a p-value < 0.01 , i.e. 10 times more than expected and Rx is correlated both with the magnitude and with the number of observations.

In other tests (VTS 60_001 and VTS 60_002) we have verified that QSOs have been correctly observed and identified by Gaia. The first test compares Gaia DR1 QSOs with ground-based quasar compilations: the GIQC (Andrei et al. 2014), the LQAC-3 (Souchay et al. 2015), and the SDSS DR10 (Pâris et al. 2014) catalogues. This check stands for completeness, duplication, and magnitude consistency. While the QSOs were sometimes affected by duplicated sources the filtering seems to have removed them nicely. It was found that 81% of the GIQC, 53% of the LQAC-3, and 11% of the SDSS QSOs are present in the Gaia DR1, a ratio that reaches 93% for the LQAC-3 sources with a magnitude B brighter than 20. These tests results have been described in (Arenou et al., 2017) which accounts for the Gaia Data Release 1 Catalogue Validation.

Analysis of the Gaia GDR1 based on the LQAC-4 catalogue

From 2016 onwards, discovery and studies of quasars have been steadily progressing due mainly to the large synoptic optical surveys (for a recent comprehensive account see Mickaelian, 2016). The Pan-STARRS – a consortium of several institutes, collectively managed by the Pan-STARRS Project Office – lead to a total number of 3 billion sources, among which several hundred thousand of quasars can be matched. For instance, Hernandez et al. (2017) analyzed the light-curves of 104 highly variable quasars. The LSST – also a consortium of several institutes, collectively managed by the LSST Project Office – expects to find out ten million quasars among the several billion observed sources, through selection techniques based on colors, variability properties, and astrometric behavior (Ivezić 2016). This emphasizes the interplay between astrophysics, photometric, and astrometric techniques to characterize quasars and clearly, to the point here, to select those apt to form a Celestial Reference Frame.

The SDSS – a consortium of several institutes, collectively led by the Alfred Sloan Foundation – is the largest contributor of spectroscopically confirmed quasars. On top of that the Large Quasar Astrometric Catalog series (Souchay et al. 2015), now reaching its fourth version LQAC-4 (Gattano et al. 2017) compiles the SDSS quasars plus other confirmed

quasars of good astrometric quality. Finally, the Gaia data releases have already started (Lindgren et al. 2016). Although the number of quasars within its final catalog should be smaller than in the previously mentioned surveys, Gaia will provide important features for maybe half a million quasars: above-the-atmosphere observations, full sky coverage, more than one hundred individual measurements spread over 5 years, and remarkable astrometric quality in average as well as for the individual measurements. Although a combination of its own color, astrometry and variability data, has been proven capable of discerning quasars with high confidence, in its first release, GDR1, the quasars were found only by cross-matching with existing quasars catalogs.

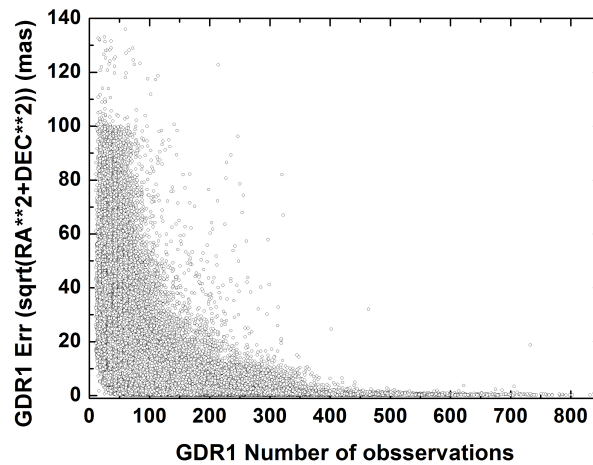


Fig. 9: *GDR1 compound error (quadratic mean from the right ascension and declination errors) according to the number of observations, for the LQAC4 quasars found using a search match radius of 1arcsec. A consequence of the dependence of the errors with the scanning law is highlighted in the text and in Fig. 10.*

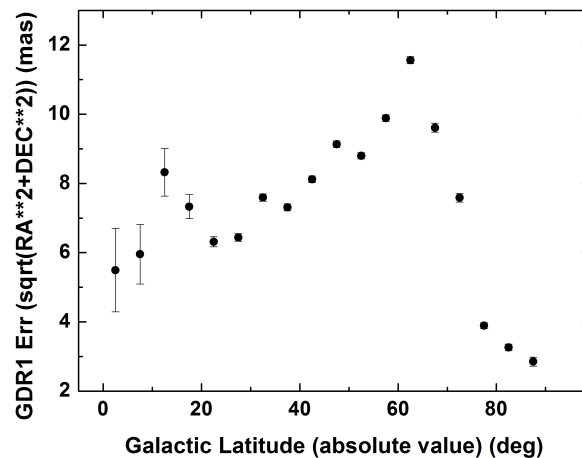


Fig. 10: *Apparent dependence of the GDR1 astrometric error with the galactic latitude, for the LQAC4 quasars found using a search match radius of 1 arcsec. A corresponding dependence appears in declination. They follow from the limited number of observations used to form the GDR1, and of the scanning law. The effect is asymptotic and should be all but vanished in the final Gaia catalogue.*

In the following, we report on the match between the GDR1 and the LQAC4, and present the main results.

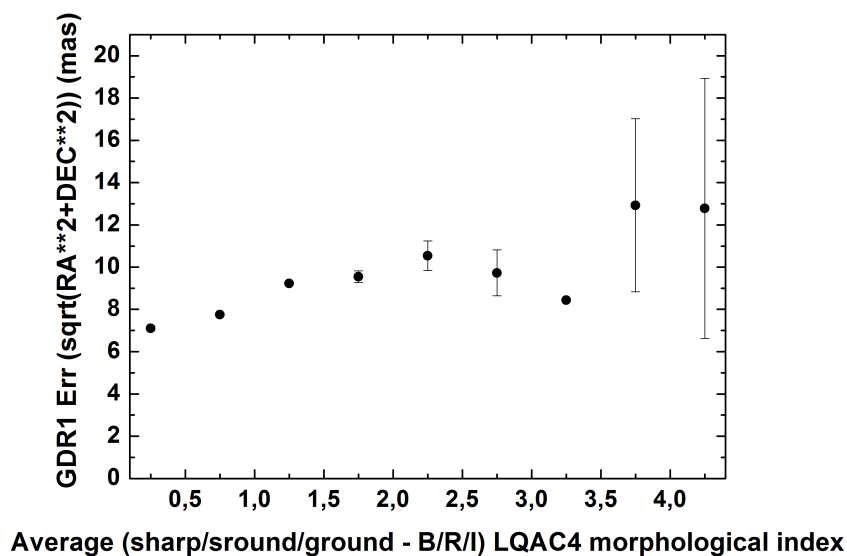


Fig. 11: *Dependence of the GDR1 quasars' astrometric error to the morphological index, obtained from the LQAC4. The main consequences of such dependence are examined in the text.*

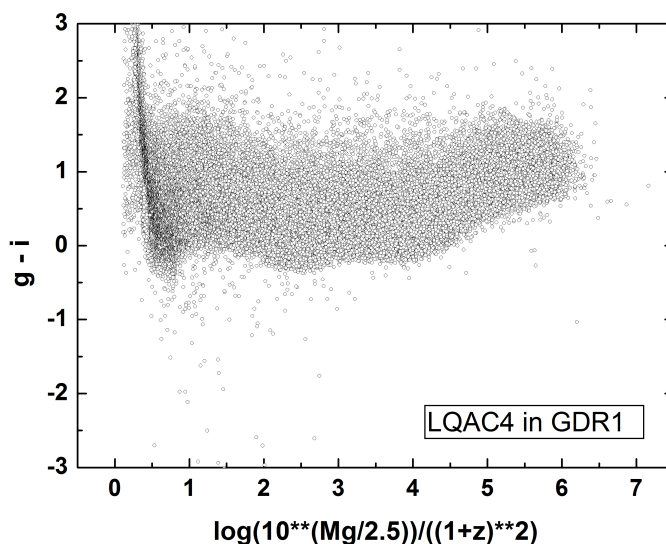


Fig. 12: *Loci of the GDR1 quasars, that is matched to the LQAC4 using a search radius of 1 arcsec, in the color versus magnitude plane. The color is the (g-i) color index taken from the SDSS entries. The magnitude is normalized accounting for the redshift, in order to provide a meaningful comparison to the fainter LQAC4 quasars not found among the GDR1 objects.*

There are 253,444 LQAC-4 quasars found in the GDR1 with a 2 arcsec search radius match. Of these, only 252 LQAC-4 quasars are matched to 2 GDR1 objects and only 1 LQAC-4 quasar is matched to 3 GDR1

objects. Although the matching is thus unambiguous, a more restrictive matching was made using a 1 arcsec radius match. In this case there are 249,071 LQAC-4 quasars found in the GDR1 and no case of double matching within the radius. The mean difference between the GDR1 magnitude and the LQAC-4 (average) magnitude is just -0.03 with a rms of 0.43. Moreover this difference exceeds 3 magnitudes for no more than 471 quasars. In the following, this set of LQAC-4 quasars matched with the GDR1 entries will be quoted as “LQAC4inGDR1”.

The redshift and magnitude distributions are shown in Figures 5 and 6. The double peaks, present in both histograms, derive from the dominant number of objects from the SDSS, either the classic north galactic cap plus the BOSS surveys. The correspondence between the GDR1 G magnitude and the nearest magnitude derived from the LQAC-4 data is also quite well behaved, but note the width around the line of perfect identity, indicating the quasars large photometric variability.

The histograms for the distribution of errors (combined RA and DEC) and the number of observations (transits), as well as the plot of errors versus the number of observations are shown respectively in Figures 7, 8, and 9. They follow what is expected from the mission accuracy goals. It is however worth mentioning that the known dependence of error to the number of transits reflects on larger errors near the galactic plane (but off its poles) and around the equator as can be seen in Fig. 10 with respect to the galactic latitude. The effect, although it may be enhanced by the quasars variability, is asymptotic and will drop at the end of mission. Nevertheless, given the relatively small number of VLBI sources available for the link between the ICRF and the GCRF, and the north-south asymmetry of the former, this issue must be kept under scrutiny.

The morphological indexes presented in the LQAC catalogues series are also included in the Gaia QSO Initial Catalog. Except in a handful of peculiar and very close quasars, the morphological indexes are due to isophotes of the underlying host galaxy. Although most of quasars are stellar-like objects, about 10% of the population present non-negligible apparent morphology on frames taken with ground-based telescopes. Gaia's astrometry instrument, working free from the atmosphere and flexure disturbances, is apt to be more sensitive than ground-based astrometric instruments. An extended structure – from 100 to 1,000 times fainter than the central source – would give rise to three kinds of disturbances: a larger astrometric error on the centroid because of poorer wings fit; an astrometric jittering due to an asymmetric underlying structure seen along different viewpoints on different with respect to each transit; a poorer fit to the corresponding VLBI-ICRF centroid because of the two previous points. Indeed, Fig. 11 shows a dependence

of the GDR1 reported astrometric errors to the ground based derived LQAC-4 morphological indexes.

There are also a large quantity of LQAC-4 sources that do not appear in the GDR1. For these we adopted an exclusion with a search radius of 2 arcsec. Notice that with such a positional limit the number of LQAC-4 objects with defective astrometry is very small. At total 190,201 LQAC-4 objects were not found in the GDR1, and this set will be here termed LQAC4notGDR1. The majority, 128,100 objects have (average) LQAC-4 magnitude beyond 21, therefore they might have been too faint for Gaia detection, at least during the time lapse corresponding to the GDR1. For the sake of comparison just 2.8 % of the LQAC4inGDR1 objects have a magnitude larger than 21.

The average magnitudes $\langle M \rangle$ and redshift $\langle z \rangle$ for the LQAC4notGDR1 and LQAC4inGDR1 sets are respectively:

LQAC4inGDR1 : $\langle M \rangle = 19.62 \pm 0.85$; $\langle z \rangle = 1.73 \pm 0.88$
 LQAC4notGDR1: $\langle M \rangle = 20.56 \pm 1.22$; $\langle z \rangle = 1.39 \pm 0.82$

These values are expected, for dimmer objects are more difficult to be seen by Gaia. But neither the magnitude difference, nor the redshift difference are themselves too large.

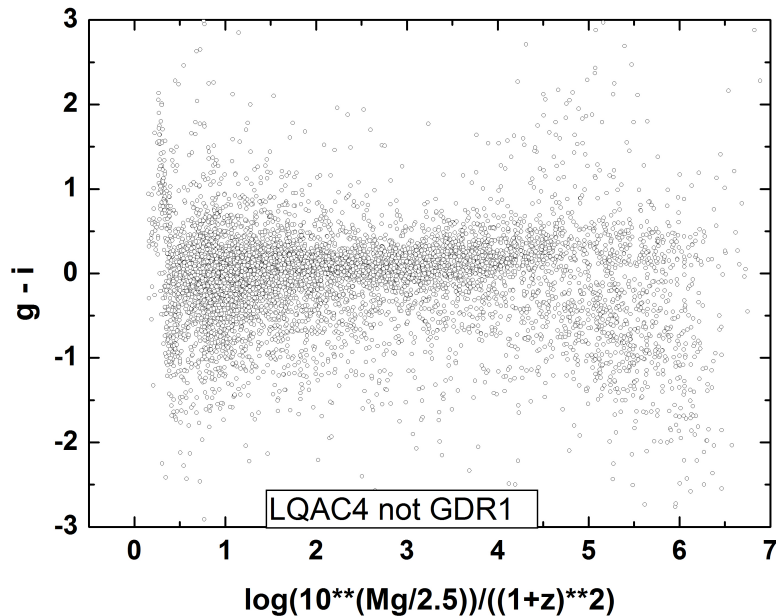


Fig. 13: Loci of the LQAC4 quasars, not matched to any GDR1 object using an exclusion radius of 2 arcsec, in the color versus magnitude plane. The color is the $(g-i)$ color index taken from the SDSS entries. The magnitude is normalized accounting for the redshift, in order to provide a meaningful comparison to the brighter LQAC4 quasars found among the GDR1 objects

On the other hand the morphological indexes distributions are indistinguishable in the LQAC4notGDR1 population from the LQAC4inGDR1 one. This is clearly shown in Fig. 11. The relationship between morphological indexes is clear there, but at a level around 10% or 20%, that is not enough to impede the detection of the strong central bright spot.

To progress further we investigated the color distribution. For this we used the (g-i) relative color present in the SDSS, from which most of the quasars of the both sets belong. A color magnitude plane was build. Since the mean magnitude and redshift are different, a reduced magnitude is built as $\log(10^{(M/2.5)})/((1+z)^2)$. Figs. 12 and 13 reveal that the loci of each set is separated in the color/reduced magnitude plane. The detected quasars are redder than the undetected ones. The coating of Gaia's mirror can offer an explanation. Remembering however that most of the undetected quasars are probably too faint, what should perhaps be learnt is that there are classes of quasars that would remain underrepresented even in the very complete Gaia catalog.

Photometric monitoring of quasars with a telescope network

As in the radio domain, it can be reasonably postulated that quasar optical flux variations can alert us to potential changes in their 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 2016 we used observations made by a set of nine optical telescopes to monitor the magnitude variations of quasars at the same time as Gaia (thanks to the Gaia Observation Forecast Tool). These observations were made in close collaboration with G. Damjanovic from Belgrade Observatory. The telescopes involved were:

- 1.40m and 0.60m telescopes in Vidojevica (Serbia),
- 0.60m and 2.00m Rozhen (Bulgaria),
- 0.60m Belogradchik (Bulgaria),
- LFOA 1.5m (Austria),
- 0.25m TAROT telescopes (France, Chile),
- TJO 0.8m (Spain).

The Allan variances, statistical tools, widely used in the atomic time and frequency community, were adopted to characterize the stability of the magnitude time series with the aim of quantifying the photometric quality of quasars. This method could help to select sources for the link between reference systems and will be the subject of a paper to be published in 2017.

Another program began in 2015 and was pursued in 2016, in collaboration with Z. Malkin from Pulkovo Observatory. It is devoted to the observation, with the TJO, of targets coming from the OCARS catalogue (http://www.gao.spb.ru/english/as/ac_vlbi/). Due to the very large number of targets (>5000), this program will be completed during the year 2017. The goal is to observe a set of targets that have been observed with the radio VLBI techniques but which are not very well known from the optical point of view. In this way, we can put limitations on the magnitudes/variability of the targets and then extend the list of those suitable to the link between the reference systems.

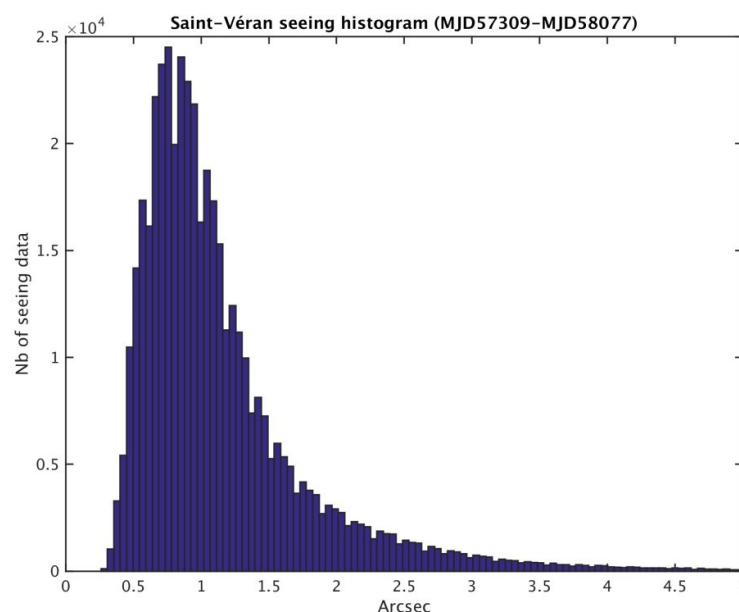


Fig. 14: *Saint-Véran seeing histogram*

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 (altitude 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 (see Figure 14) that the median value of the seeing is 1" (mode seeing is 0.7") which made this site a very good one (see Figure 15), 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 will be achieved in 2017.

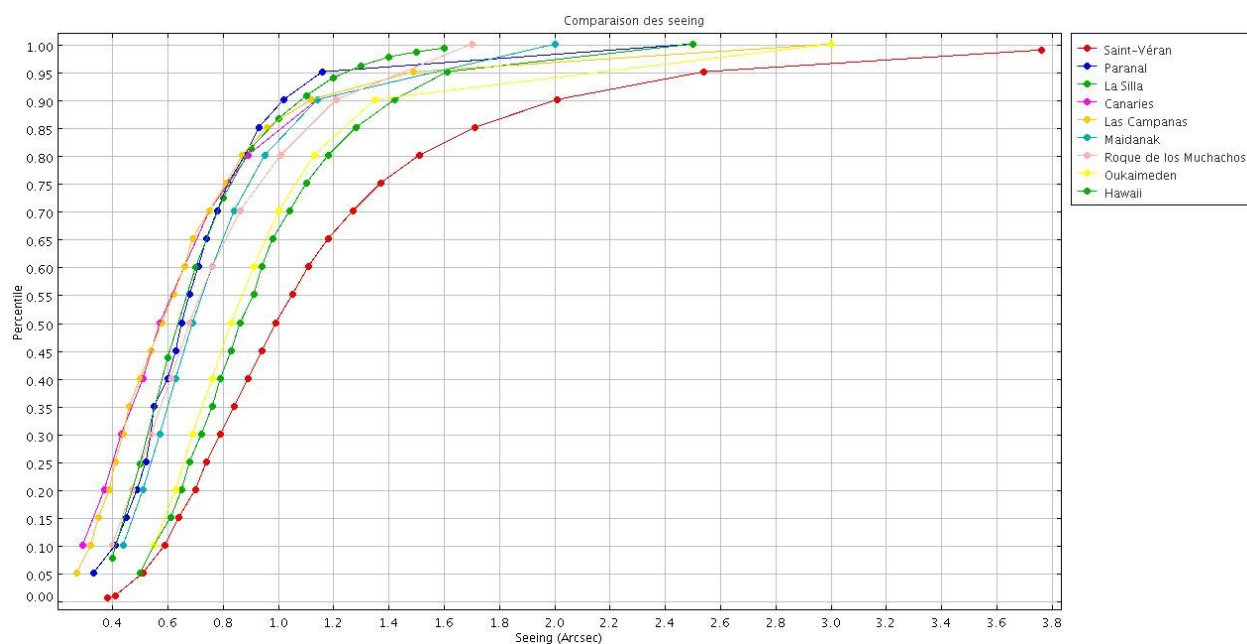


Fig. 15: Cumulative distribution of the seeing for Saint-Véran and for the best sites in the world. The curve for Hawaii is derived from <https://www.subarutelescope.org/Observing/Telescope/ImageQuality/Seeing/> and the other ones from: Frogel, J. A., 2002. Image quality at selected astronomical observatories V3.0. A memo prepared by Jay A. Frogel for the SNAP project at the Lawrence Berkeley National Laboratory, 1 February 2002.

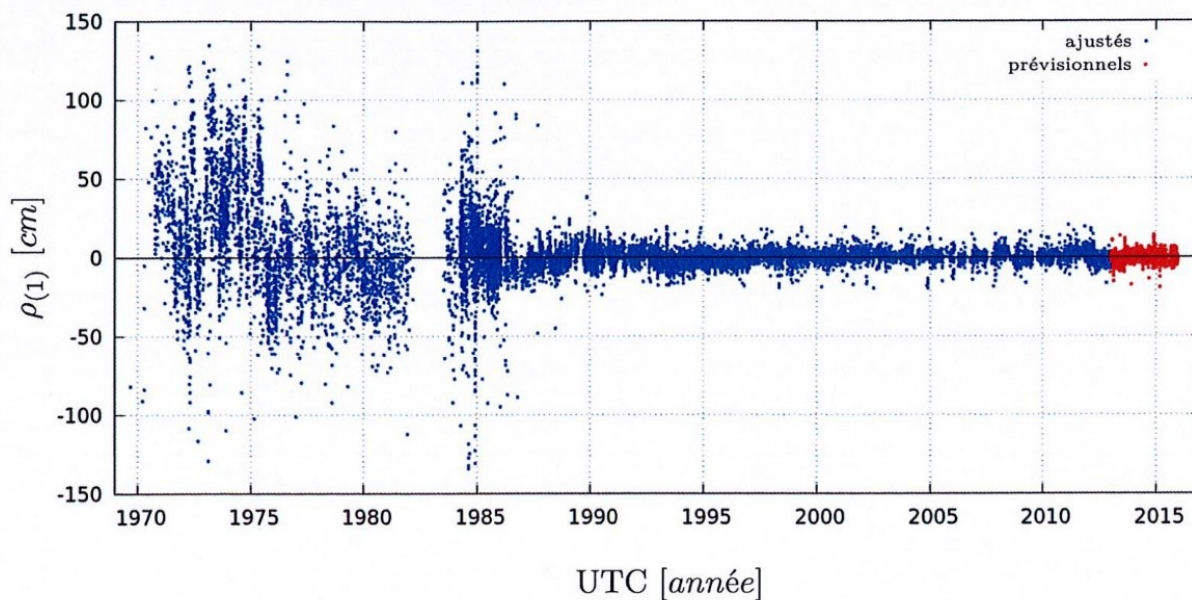


Fig. 16: Amplitude of the O–C residuals calculated starting from the reduction software CAROLL, by using the ELPN series. In blue the observations used to make the adjustments. In red the observations not used for adjustment.

Lunar Laser ranging (LLR) activities with POLAC

POLAC is the acronym of “Paris Observatory Lunar Analysis Center”. It represents one of the four LLR analysis centers reckoned by the ILRS (International Laser Ranging Service). In addition of its mission of collecting, filtering and distributing LLR data, it works continuously in close collaboration with the Laser ranging station Méo of the OCA (Observatoire de la Côte d’Azur) by furnishing in a daily basis the predictions of the LLR observations and a regular validation of the normal points. In addition, since 2013, it works with the SLR component of the GRGS (Groupe de Recherche en Géodésie Spatiale).

Table 3: Mean values μ and standard deviation σ (in meter), of the residuals obtained with ELPN for each LLR station. The numbers N and N_e represent respectively the total number of observations and the number of observations eliminated, for each station.

Stations LLR $\{l\}$	Période	$N_{\{l\}}$	$N_{e\{l\}}$	$\mu_{\{l\}}$ [m]	$\sigma_{\{l\}}$ [m]
McDonald 2.7m	1969-1985	3516	88	0.094	0.350
McDonald MLRS1	1983-1988	573	58	0.003	0.351
McDonald MLRS2	1988-2013	3284	386	0.006	0.097
Grasse Rubis	1984-1986	1182	6	0.056	0.176
Grasse Yag	1987-2005	8313	11	-0.004	0.045
Grasse MeO	2009-2013	993	6	-0.002	0.036
Haleakala	1984-1990	757	13	-0.004	0.101
Matera	2003-2013	79	11	-0.017	0.130
Apache-point	2006-2013	1806	8	0.001	0.038
Totalité	1969-2013	20503	587	-	-

The works achieved by POLAC in 2016 consisted of:

- Realization and the maintenance of the web service POLAC <http://polac.obspm.fr/PaV> which enables to the LLR observational team to prepare their laser shots on the lunar reflectors and to check the validity of their observations.
- Annual up-date of the LLR observations done at McDonald, Grasse, Haleakala, Apache Point and Matera since 1969 and coming from 5 different database with 4 different formats.
- Construction of lunar tables including the libration, to insert the LLR component into the multi-technique software GINS in order to product the parameters related to the EOP and to the Celestial reference Frames.
- Analysis of the ELP (Éphéméride Lunaire Parisienne) series by identifying their differences with the numerical ephemerides DExxx

and INPOPx, as well as the limits of these semi-analytical solutions (convergence and truncature problems, effects of uncertainties on physical parameters etc. . .)

In 2016, efforts have been made to reduce the disadvantages above by following two axes of investigation:

- The characterization of the limits of precision of the semi-analytical series ELPs by the intermediary of a rigorous analysis of the amplitude of the uncertainty of each underlying effect. For this purpose the ELP's series are compared with the results of numerical integration of the differential equations they include.
- The replacement of some of the ELP's series by numerical counterparts (when the series converge too slowly).

Moreover in the frame of these activities an alternative theory to the general relativity was tested, whose formalism is called SME (Standard-Model Extension). This theory is based on a parametrization of all the possible violations of the Lorentz symmetry. Thus the new lunar ephemerides, called ELPN, was implemented by taking into account the SME.

Fig. 16 represents the amplitude of the LLR O–C residuals calculated starting from the reduction software CAROLL by using ELPN. Finally, Table 3 shows the mean value and the standard deviation of the residuals obtained with ELPN from the various LLR stations.

USNO ICRS Center Activities During 2016

USNO concentrated on four primary areas of work in support of maintenance and improvement of the Celestial Reference Frame: (1) support to the ICRF3 working group, (2) processing of previously taken URAT Northern Hemisphere data, (3) operation of UBAD in the Northern and URAT in the Southern Hemisphere to collect bright star data, and (4) ingest and assessment of the Gaia data as a Gaia Affiliated Data Center (ADC).

ICRF3 USNO participated as a member of the IAU-sanctioned ICRF3 working group. Work included support for the execution of and analysis of the VCS-II S/X band observing campaign (see Gordon et al. 2016), and support for X/Ka band observations as candidates for inclusion in ICRF3.

URAT Parallax Catalog

The 2016 initial Gaia data release (DR1, see following discussion) included the “TGAS” catalog, which consisted of approximately 2 million

stars with the full set of five astrometric parameters. The remaining $\sim 99.8\%$ of the DR1 release were sources with positions (RA, DEC) only. In order to address this gap in proper motions, USNO released the URAT Parallax Catalog (UPC), a catalog of 112,177 parallaxes covering the magnitude range 6.56 to 16.93 in the URAT band-pass north of -12.752 deg declination, based on the URAT1 and follow-on observations (see Zacharias et al., 2015 for a discussion of URAT1). The UPC includes 56k parallaxes recovered from Hipparcos, and 59k new parallaxes.

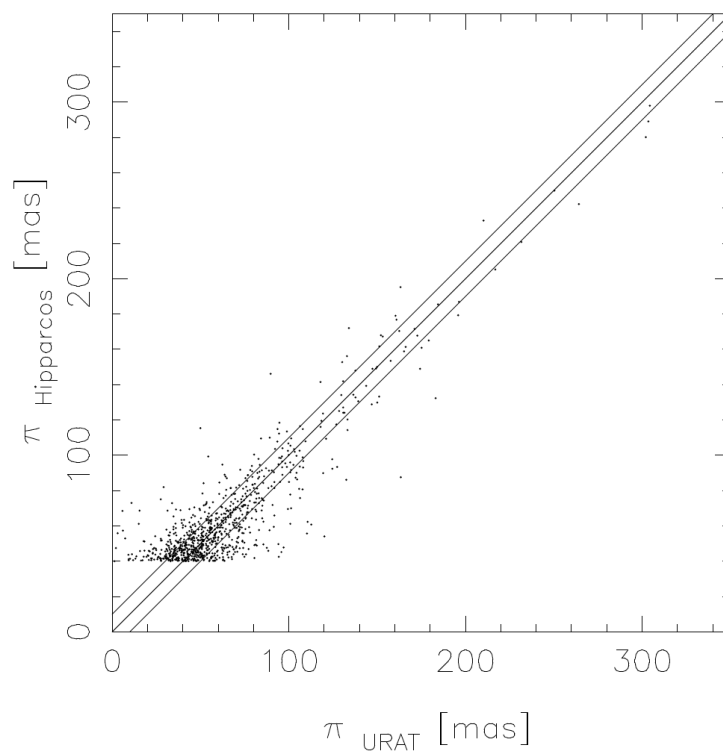


Fig. 17: Parallax comparison between URAT and the Hipparcos 25 pc sample north of $DEC = -10$ deg. The center line represents perfect agreement while the outer lines show a ± 10 milliarcsecond (mas) difference.

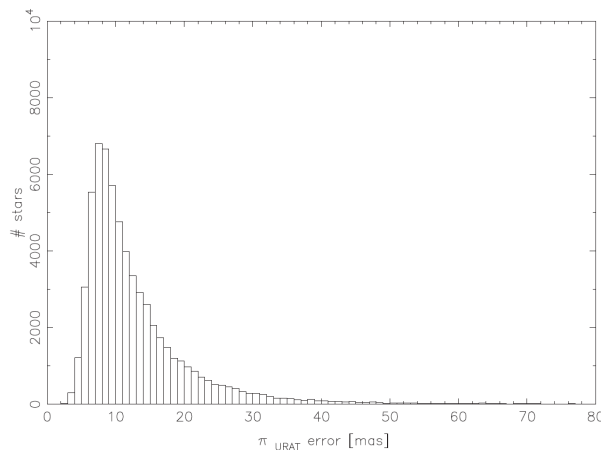
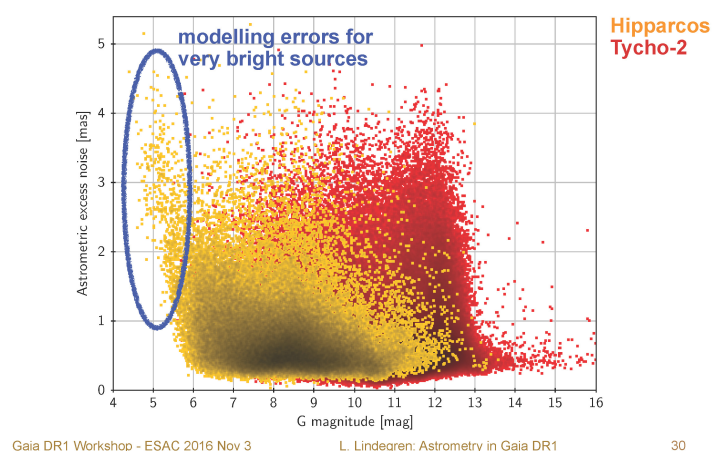


Fig. 18: Histogram of URAT parallax errors for Hipparcos same north of $DEC = -10$ deg.

Excess noise versus magnitude (TGAS)



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L. Lindegren: Astrometry in Gaia DR1

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Fig. 19: *Gaia* DR1 bright star results. Stars brighter than about $G = 6$ suffer from significant “astrometric noise”. There is currently (i.e., DR1) no authoritative method for measuring bright sources. Results are from the *Gaia* DR1 workshop.

The UPC contains 58,677 URAT parallaxes which have a match to either of those catalogs without implementing any extra cuts. For the stars with no prior published parallax, a set of stringent cuts to reduce possible erroneous parallaxes was implemented, resulting in over 53,000 new trigonometric parallaxes from URAT data alone with a high level of confidence. The average parallax precision is 10.8 mas and 4.3 mas for stars having a known parallax and stars without a prior known parallax respectively (see Figs. 17, 18) (Finch & Zacharias 2016a; Finch & Zacharias 2016b). This is the largest catalog of high-accuracy parallaxes released since Hipparcos, and will be definitive until superseded by *Gaia* DR2.

URAT Southern Hemisphere Bright Star Survey

The *Gaia* focal plane is configured in such a way as to saturate 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. As shown in Figure 19, the *Gaia* DR1 results show large levels of “astrometric noise” for sources brighter than about $G=6$. The *Gaia* data processing team is currently 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 Interamerican Observatory (CTIO) in October 2015 (see Fig. 20). 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. Figure 21 shows the southern hemisphere coverage through the end of 2016.

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.

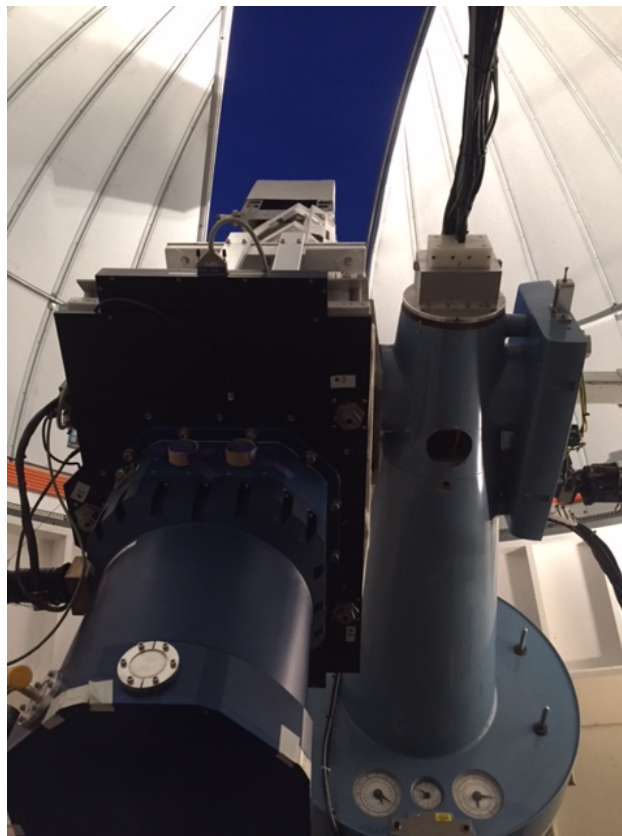


Fig. 20: *USNO Robotic Astrometric Telescope (URAT) deployed to and operating at Cerro Tololo Interamerican Observatory (CTIO) during 2016. URAT is being operating with both a full aperture grating and a neutral density spot that allows it to observe all the brightest stars in the Southern Hemisphere, up to a declination of DEC $\sim +25$ deg*

Ingest and Assessment of Gaia DR1 Data

USNO received the Gaia DR1 data as one of Gaia's Affiliated Data Centers (ADCs) in the US. The DR1 data was ingested and integrated into USNO's Celestial Reference Frame Database (CDB), where it is stored,

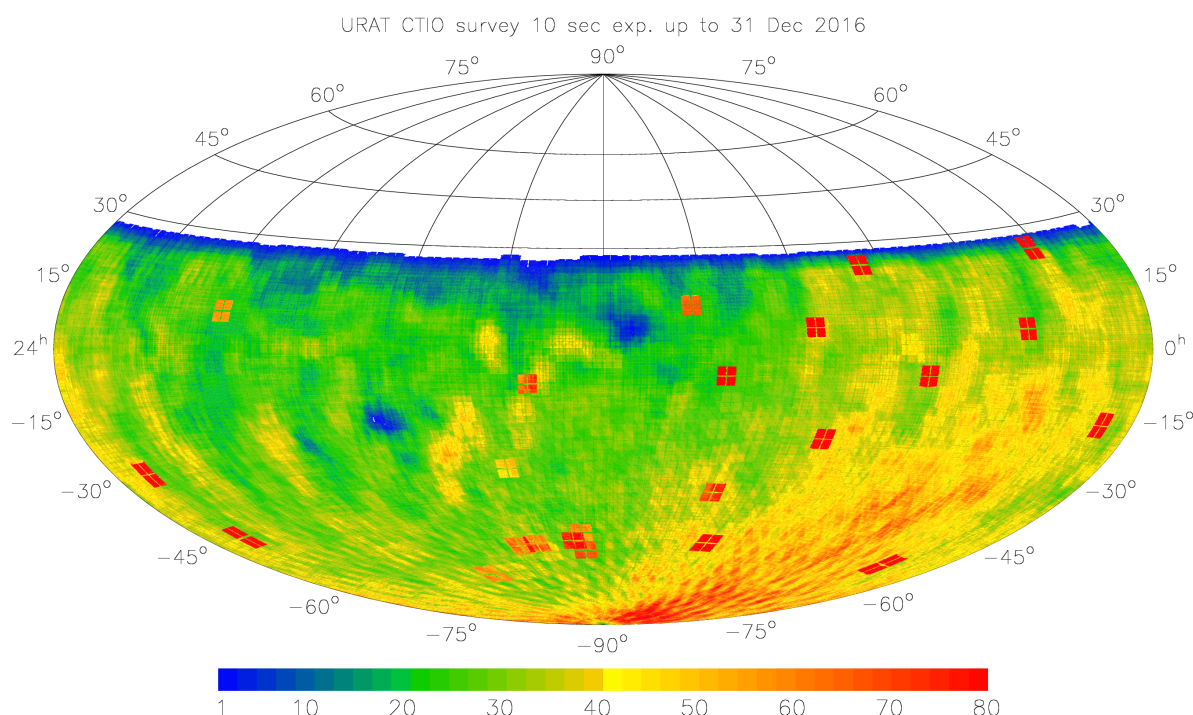


Fig. 21: *URAT Southern Hemisphere coverage through 31 December 2016. Scale along bottom indicates number of times location in sky has been observed. The visible red pattern is the projection of the focal plane on the sky. The identifiable patches that have been observed the most are locations of very bright stars that require dedicated pointings.*

along with data from numerous other programs, missions and catalogs, including Hipparcos, Tycho-2, UCAC4, URAT1, URAT2, Pan-STARRs 1, 2MASS, LQAC, WISE, MIRAGN, and ICRF2. The CDB supports source correlation and analysis across multiple input catalogs, wavelength and magnitude regimes. It is currently used internally at USNO, but may be made available in some form to the public in the future. The Gaia DR1 release immediately became the core, authoritative component of the CDB. Gaia data were validated as authoritative for optical sources from magnitude 6–20.7. Additional work will continue in 2017 in terms of validation of Gaia data and use of Gaia data along with other sources of data (for example, radio and IR positions and luminosities) in order to maintain and improve the overall celestial reference frame across all spectral wavelengths.

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*Bryan Dorland, Jean Souchay, Alexandre Andrei, E. Felicitas Arias,
Christophe Barache, Sébastien Bouquillon, Alan Fey,
Sébastien Lambert, François Taris, Norbert Zacharias*

3.5.5 ITRS Centre

This report summarizes the activities of the IERS ITRS Centre during the year 2016.

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 where added to the ITRF network and database.

ITRF2014 dedicated web site

A dedicated web site for the ITRF2014 was constructed: http://itrf.ign.fr/ITRF_solutions/2014/. It provides to the users all the detailed description of the ITRF2014 computation as well as all the necessary ITRF2014 products: stations positions and velocities in SINEX files, Earth Orientation parameters, and residual plots per techniques. In particular, the ITRF2014 web site provides to the users full description and equations of the Post-Seismic Deformation (PSD) parametric models used in the ITRF2014 generation, together with FORTRAN routines and some numerical examples to help the users on how to use the PSD models.

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 in 2018.

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 Website 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 website: http://itrf.ign.fr/local_surveys.php.

The operational entity of the ITRS Centre at the IGN Survey department has 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 is in its final stage and will be published in 2017 in a dedicated IERS Technical Note.

Other activities

- Participation in most meetings of the analysis working groups of the Technique Centres (in 2014: IDS, IGS, ILRS);
- Convening and organizing EGU and AGU sessions on reference frames and ITRF;
- Participation in the UN-GGIM related meetings, and contribution to the Roadmap on the Global Geodetic Reference Frame for Sustainable Development, following the UN GA resolution adopted February 26, 2015.

*Zuheir Altamimi, Bruno Garayt, Xavier Collilieux,
Paul Rebischung, Laurent Métivier*

3.5.6 Global Geophysical Fluids Centre

The Global Geophysical Fluid Center (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 with 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 reanalyses, 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 2016, the SBA updated all fields from AAM; the updates were performed by Dr. Y. Zhou of the Shanghai Astronomical Observatory, China.

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 Centre, 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 2016, the SBO website was maintained and products from the ECCO/JPL ocean model were updated. The ECCO/JPL ocean modeling team started assimilating newer versions of altimetry data into their model with the new solution being designated kf080h. The oceanic angular momentum, oceanic excitation functions, and oceanic center-of-mass from the entire kf080h solution was computed and uploaded to the SBO website. This update to the data assimilating ocean model did not affect the results of the simulation run kf079. 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 26 September 2016. 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://isdg.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://www.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://www.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 December 2016.

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/introduction.html>), J.-L. Chen, University of Texas at Austin, USA.
- Atmospheric (<http://gemini.gsfc.nasa.gov/aplo/>) and hydrological (<http://lacerta.gsfc.nasa.gov/hydlo/>) loading, D. MacMillan, NASA Goddard Space Flight Center (USA).
- Atmospheric, oceanic and hydrological loading, AM and time-variable gravity (<https://isdc.gfz-potsdam.de/esmdata/loading>), 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 2016, the DGFI-TUM ITRS Combination Centre (CC) focused its research activities on the evaluation, interpretation, and further analysis of the DTRF2014 global international terrestrial reference frame (ITRF) realization. Important topics have been the inter-comparison of the three ITRF solutions, the quality assessment of the DORIS contribution to the ITRF, and the geophysical interpretation of station coordinate velocity vectors.

Inter-comparison of the three ITRF solutions

For the most recent ITRS realization, the three IERS ITRS CCs computed three different realizations based on identical input data. The advantage of this redundant computation is, that errors or systematics caused by the combination approach, the analyst, or the software can be identified. Fig. 1 shows exemplarily the height differences between the ITRF solutions for selected SLR stations. Note that the differences outside the ITRF input data interval (after 2015.0) already reach the centimeter-level until 2017.0.

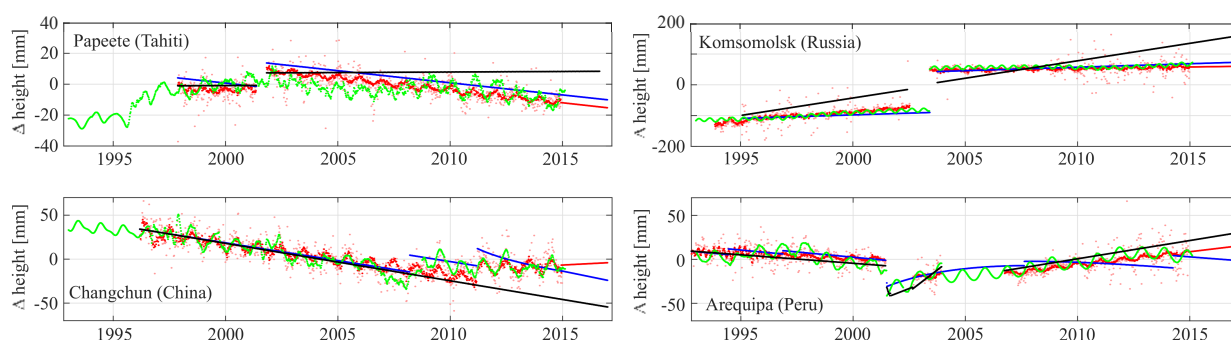


Fig. 1: Height time series (in mm: common mean subtracted) of the ILRS stations Papeete (Tahiti), Changchun (China), Komsomolsk (Russia), and Arequipa (Peru) between 1993.0 and 2015.0 (within ITRF data interval) and between 2015.0 and 2017.0 (extrapolated data interval) from four different ITRF realizations: most recent SLRF2008 (black), ITRF2014 (blue), DTRF2014+NTL (red), and JTRF2014 (green). In addition, the solution DTRF2014+Res+Ori+NTL (light red) is shown in the background. Note: no seasonal, annual, or semi-annual corrections are applied after 2015.0.

The main characteristics of each ITRS realization are summarized in Table 2. A special attention was drawn at DGFI-TUM on the investigation of the realized scales in the ITRF2014 and the DTRF2014 solution. Whereas the ITRF2014 comprises an SLR and a VLBI scale which differ by about 1.37 ppb (rate: 0.02 ppb/yr), the DTRF2014 realization

do not show such a large scale discrepancy. Details on this investigation are reported in Bloßfeld et al. (2017).

Solution	ITRF2014	DTRF2014	JTRF2014
Institute	IGN (Paris, France)	DGFI-TUM (Munich, Germany)	JPL (Pasadena, USA)
Software	CATREF	DOGS-CS	CATREF + KALMAN
Combination approach	Solution (parameter) level	Normal equation level	Solution (parameter) level
Station position	Position $X_{ITRF}(t_0)$ + velocity $\dot{X}_{ITRF}(t_0)$ + PSD model (for selected stations) + annual signals (on request)	Position $X_{DTRF}(t_0)$ + velocity $\dot{X}_{DTRF}(t_0)$ + NT-L models + SLR origin + residual station motions	Weekly positions $\tilde{X}_{JTRF}(t_i)$

Fig. 2: Characteristics of the ITRF2014, DTRF2014, and JTRF2014 solution.

Quality assessment of the IDS contribution to the ITRF2014

The quality of the IDS contribution to the ITRF2014 was assessed by Bloßfeld et al. (2016). The paper presents the analysis results of the most recent DORIS submission IDS-d09 and evaluates its quality w.r.t. the DTRF2008 (IDS-only) solution. In the most recent version of the analysis, we introduce in total 56 station discontinuities and reduce 15 stations due to a too short time span or too few observations. Time series of weekly IDS solutions are computed and validated w.r.t. DTRF2008. The transformation parameter time series and the station residuals are discussed in detail. Especially the scale parameter time series shows a significant improvement compared to the DTRF2008 input data. The scatter of the x- and y-translation is significantly reduced to 5.7 mm and 7.1 mm compared to 6.6 mm and 8.1 mm for the DTRF2008 (IDS-only) solution. The z-translation time series still shows a high correlation with solar activity. 10 % of all station residuals are significantly affected by spectral peaks at draconitic period harmonics of the altimetry satellites Jason and TOPEX/Poseidon and up to 48 % of all station residual time series contain significantly determined frequencies with a 14 day period. The multi-year IDS solution is validated w.r.t. DTRF2008 and the consistently estimated terrestrial pole coordinates are analyzed and compared to IERS 08 C04. The x-pole spectra comprises prominent peaks at various draconitic frequencies.

Geophysical interpretation

The velocity vectors of the DTRF2014 solution can be used to study geophysical phenomena. The left panel of Fig. 3 shows the plate tectonic motions of Greenland and the Scandinavian region. Note also Iceland which is located directly at the mid-Atlantic ridge and shows

different horizontal velocities for the east and the west coast. The right panel of Fig. 3 shows the vertical land motion of Greenland and the Scandinavian region. Both regions are significantly affected by post-glacial rebound motions of up to 14 mm per year.

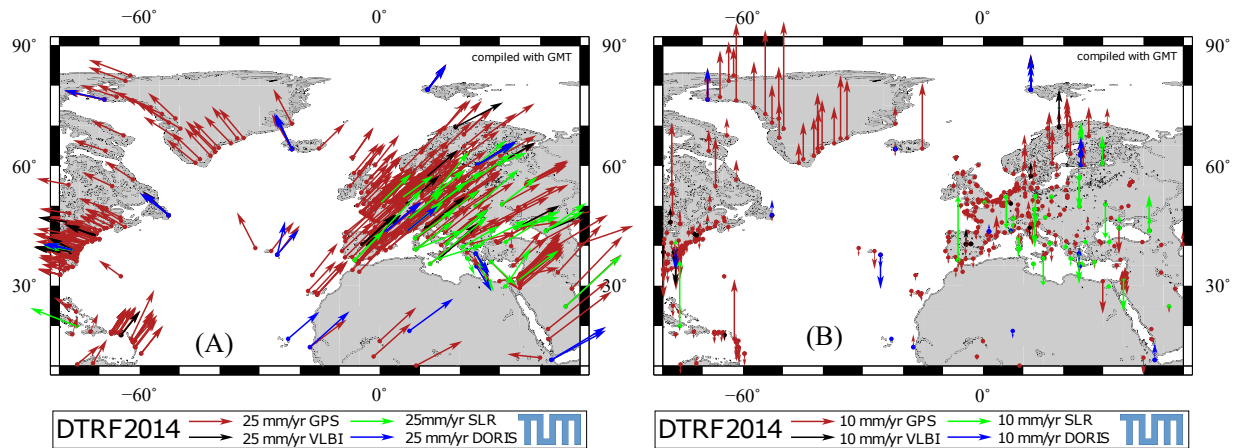


Fig. 3: Horizontal (A) and vertical (B) station velocities in Greenland (A) and Scandinavia (B) of the DTRF2014 solution.

Fig. 4 shows differences of the global horizontal station velocity field between the DTRF2008 and the DTRF2014 solution. The vector field clearly indicate the effect of the large Chile-Maule earthquake in Chile on February 27, 2010 and the Tohoku-Oki earthquake in Japan on March 11, 2011 on the station mean motions in the respective regions.

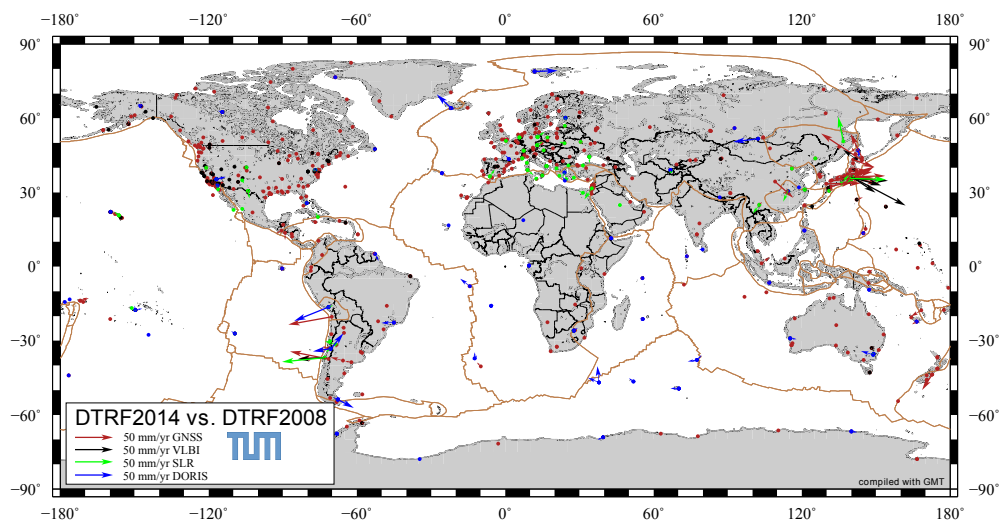


Fig. 4: Global horizontal velocity differences between the DTRF2014 and the DTRF2008 ITRF solution.

Publications

Bloßfeld M., Seitz M., Angermann D., Moreaux G.: Quality assessment of IDS contribution to ITRF2014 performed by DGFI-TUM. *Advances in Space Research*, 58(12), 2505-2519, DOI: 10.1016/j.asr.2015.12.016, 2016.

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Mathis Bloßfeld, Detlef Angermann, Michael Gerstl, Manuela Seitz

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 2016. These research activities are mainly related to the computation and publication of the ITRF2014.

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.

Finalization and publication of the ITRF2014

Specific new developments were achieved and validated for the ITRF2014 computation and analysis: CATREF software was enhanced and upgraded to include periodic terms of the station position time series, such as in particular annual, semi-annual terms for all techniques and draconitic signals for satellite techniques, especially GNSS. These new developments were applied to the technique solutions which were submitted to the ITRF2014.

The ITRF2014 involved two main modelling innovations to enhance the robustness of the frame, mainly (1) the estimation of the annual and semi-annual signals embedded in the time series of station coordinates provided by the four space geodesy techniques, and (2) the incorporation of Post-Seismic Deformation (PSD) models for sites subject to major earthquakes.

In summary, the ITRF2014 was the occasion to construct an ITRF solution with an improved accuracy and robustness, by adequately modelling nonlinear station motions: annual and semi-annual signals, as well as the post-seismic deformations for sites that were subject to major earthquakes.

We showed in Altamimi et al. (2016) that estimating the annual and semi-annual signals has statistically no impact on the horizontal station velocities, while the vertical station velocities may change by up to 1 mm/yr for sites with large seasonal signals, multiple number of discontinuities, or/and data gaps in their time series. Estimating these periodic terms helps the identification and detection of discontinuities in the times series and performs better than applying an atmospheric loading model, especially in the horizontal components.

Modelling the post-seismic deformations for sites impacted by major earthquakes allows the user to have access to the effective site trajectory during the relaxation period. The GNSS-derived parametric models were shown to precisely fit the time series of the co-located DORIS, SLR or VLBI instruments.

The full development, description and results of the ITRF2014 are published in an Open access article, freely available here: <http://onlinelibrary.wiley.com/doi/10.1002/2016JB013098/full>.

The full results and documentation of the ITRF2014 are available at its dedicated website: http://itrf.ign.fr/ITRF_solutions/2014/. In addition, the preparation for a dedicated IERS Technical Note on ITRF2014 analysis and results was initiated in 2016 to be published in 2017.

Publications

Altamimi, Z., P. Rebischung, L. Métivier, and X. Collilieux (2016), ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, *Journal of Geophysical Research: Solid Earth*, doi:10.1002/2016JB013098

Appleby, G., R. Rodriguez, and Z. Altamimi (2016), Assessment of the accuracy of global geodetic satellite laser ranging observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations 1993-2014, *Journal of Geodesy*, doi: 10.1007/s00190-016-0929-2

Rebischung, P., Z. Altamimi, J. Ray, and B. Garayt (2016), The IGS contribution to ITRF2014, *Journal of Geodesy*, doi:10.1007/s00190-016-0897-6

Zuheir Altamimi, Paul Rebischung, Laurent Métivier, Xavier Collilieux

3.6.3 Jet Propulsion Laboratory (JPL)

Introduction

The Jet Propulsion Laboratory is developing an approach to determining ITRF-like terrestrial reference frames based upon the use of a Kalman filter/smoothen (Wu et al., 2015). Kalman filters are commonly used for estimating 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 2016, besides continuing to analyze the JTRF2014 solution, JPL also started 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

JTRF2014 was submitted to the IERS and released to the community on March 8, 2016. Following its release, a journal article describing its determination and comparing it to ITRF2014 was prepared and has been accepted for publication by the Journal of Geophysical Research Solid Earth (Abbondanza et al., 2017). 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. The dynamic model of the station positions, used to predict the positions of the stations in the absence of observations, consists of a linear secular term and periodic terms at the annual and semi-annual frequencies. The stochastic model of the station positions consists of a random walk whose strength is given by the scatter evident in models of atmospheric, oceanic, and hydrologic loading. JTRF2014 is highly consistent with ITRF2014 with time derivatives of the Helmert transformation parameters between the two frames being at most 0.18 mm/yr and with wrms differences of the respective polar motion and polar motion rate values being at most 30 μ as and 17 μ as/day. JTRF2014's geocenter also agrees well with the geophysical inversion results of Wu and Heflin (2015) with differences in the amplitudes of the annual terms being only 0.5 to 0.8 mm.

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 2016, JPL started a project 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 and GRACE-FO measurements and 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 2016, 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. The resulting correlation maps clearly show patterns of regionally correlated deformation.

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 Earth Orientation Parameters (EOPs) that link the frames together,

consequently degrading their quality. During 2016, JPL started a project in which a joint and consistent determination of TRF/EOP/CRF will be achieved by extending the Kalman filter and smoother for reference frame (KALREF) software developed at JPL to include the processing of celestial pole offsets and source coordinates. In particular, the Kalman filter will be able to take into account proper motions of radio sources, which are not taken into account in current CRF solutions.

But before attempting a joint TRF/EOP/CRF solution, procedures must be developed to determine just the CRF using a Kalman filter/smoother. A Kalman filter and smoother to determine CRFs from VLBI-only observations has started to be 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/smoother 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).

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- Soja, B., R. 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.
- Wu, X., and M. B. Heflin (2015), A global assessment of accelerations in surface mass transport, *Geophys. Res. Lett.*, 42(16), 6716–6723, doi:10.1002/2015GL064941.

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.

*Richard Gross, Claudio Abbondanza, T. Mike Chin, Mike Heflin,
Jay Parker, Benedikt Soja, Xiaoping Wu*

3.7 IERS Working Groups

3.7.1 Working Group on Site Survey and Co-location

Automated monitoring with terrestrial instruments has been developed further, and a number of sites have been revisited and resurveyed. Evaluations indicate stable conditions in the majority of situations, and a general trend observed in several services is that current efforts are being directed towards systematic errors evaluations rather than site stability.

The SIB60 project of the European Metrology Research Program (EMRP) which included some VLBI and GNSS space geodetic stations was completed, and major project results were presented at dedicated sessions of the 3rd Joint International Symposium on Deformation Monitoring (JISDM). A new consortium involving several WG members was initiated to focus metrological efforts towards SLR in a follow-up proposal. Funding was not granted in the 2016 decision, but the consortium anticipates a resubmission on the next SI Broader scope theme in 2018. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Co-location status within the different services

International DORIS Service, IDS

The tie vectors originating from 1988 are being re-qualified, and a new file "DORIS_ext-ties.txt" are available on the IDS data centers. In an assessment of monument stability, 80% of the surveyed monuments were found to be stable within 1 mm, and monitoring of the stability is currently under consideration. A 4th generation beacon is under development and to be deployed in 2019, the antenna design will remain but cable lengths will increase. In September a new station was deployed at Wettzell.

International GNSS Service, IGS

A new observation pillar was installed at the co-located VLBI/GNSS Katherine observatory in Australia, which eliminates the need to remove the antenna when undertaking future surveys.

International Laser Ranging Service, ILRS

Local tie vectors and technique specific biases are being scrutinized and appears to reduce the offset at co-located sites. Presentations were given at IVS General Meeting, as well as a dedicated session at the 20th International Workshop on Laser ranging.

International VLBI Service, IVS

Terrestrial laser scanning were performed at the Onsala radio telescope and refinement of TLS deformation analysis to detect focal length

variations with respect to elevation and comparisons with local gain optimization parameters has been initiated. Presentations of preliminary SIB60 results were given at IVS GM 2016. IVS also hosted an international workshop on VLBI observations of near-field targets which included both ground and space co-locations.

Publications

2016 International Workshop on Laser Ranging, Potsdam, Germany, October 9–14, 2016, <https://cddis.nasa.gov/lw20/Program/index.html> (no hardcopies)

Behrend D., K. D. Baver, K. L. Armstrong (eds.) International VLBI Service for Geodesy and Astrometry 2016 General Meeting Proceedings, NASA/CP-2016-219016, <ftp://ivscc.gsfc.nasa.gov/pub/general-meeting/2016/IVS-2016-General-Meeting-Proceedings.pdf>

Lösler M., R. Haas, C. Eschelbach (2016) Terrestrial monitoring of a radio telescope reference point using comprehensive uncertainty budgeting. *J. of Geodesy*, Vol. 90, p. 467–486, DOI: 10.1007/s00190-016-0887-8

Saunier, J. (2016) Assessment of the DORIS network monumentation, *Advances in Space Research*, Vol. 58, Issue 12, p. 2725–2741. DOI: 10.1016/j.asr.2016.02.026

SIB60 consortium (2016), <https://www.ptb.de/emrp/sib60-home.html>

Nothnagel A. and F. Jaron (eds.), *Proceedings of the First International Workshop on VLBI Observations of Near-field Targets*, October 5 – 6, 2016, *Schriftenreihe des Instituts für Geodäsie und Geoinformation*, Vol. 54, ISSN 1864-1113, Bonn, <http://www3.mpifr-bonn.mpg.de/div/meetings/vonft/index.html>

Sten Bergstrand

3.7.2 Working Group on Combination at the Observation Level

Overview The Working Group on Combination at the Observation Level (WG COL) reviewed the interest in combining techniques at the observation level for EOP and reference frames. Its main goal was to bring together groups capable to do combinations on the observation level and to improve the homogeneity, precision and resolution of the products. After 5 years of activities, beginning the 22th October 2009 at the Centre for Space Research of Warsaw in Poland, the working group concluded its efforts during the last meeting on the 19th February 2016 at BKG, Frankfurt am Main, Germany. The WG COL activities has been transferred to the PLATO/IAG-GGOS group (Performance Simulations and Architectural Trade-Offs), organized by Daniela Thaller and Richard Gross, for further considerations on the combination technique.

Summary of combination presented during the 19th February 2016 meeting

The WG COL contributed to the ITRF2014 realization by combining geodetic techniques (DORIS, GNSS, SLR, and VLBI) at the Normal Equation level. Quasar coordinates, Earth Orientation Parameters solutions (EOP) and station positions have been produced at a weekly basis in SINEX format, spanning twelve years from January 4th, 2002 to December 28th, 2013 (625 weeks) and delivered to IGN for comparisons. The Normal Equations processed for each techniques are collected in Table 1 and parameters to estimate are presented in Table 2 with some added parameters for further analyses.

Table 1: *GRGS Normal Equations 2002–2013 processed and parameters for each technique*

GNSS: CNES-CLS Toulouse	DORIS: CNES-CLS Toulouse	SLR: IMCCE GRGS Paris	VLBI: OB LAB Bordeaux
4372 daily NEQ, January 1 st 2002 to December 30 th 2013 GPS week 1147 to 1773, GPS & Glonass constellations, between 23 and 55 GNSS satellites	Weekly NEQ per 3.5d arc length & per satellite: Doris using the Doppler signals: 288 Topex 2002-2004, 1077 Envisat 2002-2012 1071 Spot-2 2002-2009, 1228 Spot-4 2002-2013 1236 Spot-5 2002-2013, 386 Jason-1 2004-2008 573 Jason-2 2008-2013, 372 Cryosat2 2011-2013 234 Hy2a 2011-2013 Doris using the Laser reflectors: 284 Topex 2002-2004, 1072 Envisat 2002-2012, 382 Jason-1 2004-2008, 573 Jason-2 2008-2013, 371 Cryosat2 2011-2013, 234 Hy2a 2011-2013	Weekly NEQ arc length spanning 9d for the SLR satellites 628 LAGEOS-1 , 628 LAGEOS-2 , 628 ETALON-1 , 628 ETALON-2	Session R1 & R4, 621 NEQ R1 session 621 NEQ R4 session
Pole: PX, PY 1pt/d @12:00 Pole Rates: PXR, PYR 1pt/d @12:00 LOD 1pt/d @12:00 Stations coordinates SX, SY, SZ 1pt/d	Pole: PX, PY, UT1-TAI 4pt/d @ 00,06,12,18:00 Nutation NX, NY 2pt/d @ 00, 12:00 Stations SX, SY, SZ 1p/week @ 12:00 Tropospheric MZB (Zenith Tropospheric Delay) 12pt/d @ 02h MGE, MGN East & North Gradients 1pt/d *CDX,CDY,CDZ Center of mass correction on satellites 1/sat/week *Global station bias SXC, SXS, SXD, SXT, SXB 1pt/arc *Doppler frequency offset MFO @ 02h. *Orbital elements EX, EY, EZ, EXP, EYP, EZP 1pt /arc *Atmospheric drag and lift FD *Radiation Solar pressure FS 1pt/arc. *Orbit Biases BT, BN *Radiation forces, 1 to 8: -specular reflectivity of panel RRS -diffuse reflectivity of panel RRD *Emissivity of panel 1 à 8 per arc RE, RF *Gravity field coefficients normalized: GCN cosinus, GSN sinus 0 up to 40 degree	Pole : PX, PY 4pt/d @ 00,06,12,18h:00 UT1-TAI : PT 4pt/d @ 00,06,12,18:00 Nutation NX, NY 2pt/d @ 00:00, 12:00 Stations: SX, SY, SZ 1pt/week @12:00 Station range Bias MRB 1w/station *Orbital elements EX, EY, EZ, EXP, EYP, EZP 1pt /arc *Radiation Solar pressure 1pt/week/sat *Orbit Biases 1pt/week/sat *Gravity field coefficients normalized: GCN cosinus, GSN sinus degree 0 to 40 *Oceanic tides coefficients normalized OCN, OSN	Pole : PX, PY 4pt/d @ 00,06,12,18:00 UT1-TAI : PT 4pt/d @ 00,06,12,18:00 Nutation : NX, NY 4pt/d @ 00,06,12,18:00 Stations : SX,SY,SZ 1pt/week @12:00 Quasars : QRA, QDE 1pt/week Tropospheric zenithal delays MZB 12pt/d @ 02h (01,03,05,07,09,11,13,15,17,19,21,23) *Clock error MTB for VLBI stations @01:00h

One of the COL WG goals concerns the determination of the CRF, the TRF and the EOP parameters simultaneously and consistently by GNSS, DORIS, SLR and VLBI combination at the normal equation level. Concerning the quasar coordinate corrections versus ICRF-2 in right ascension (RS_RA) and declination (RS_DE) for all quasars estimated between 2002 and 2013, Fig. 1 shows a discrepancy of 722 μ as and 791 μ as respectively and rotation parameters R1, R2, R3 of the celestial network (w.r.t. ICRF-2) have the estimated values of 98 μ as, 20 μ as and 153 μ as respectively.

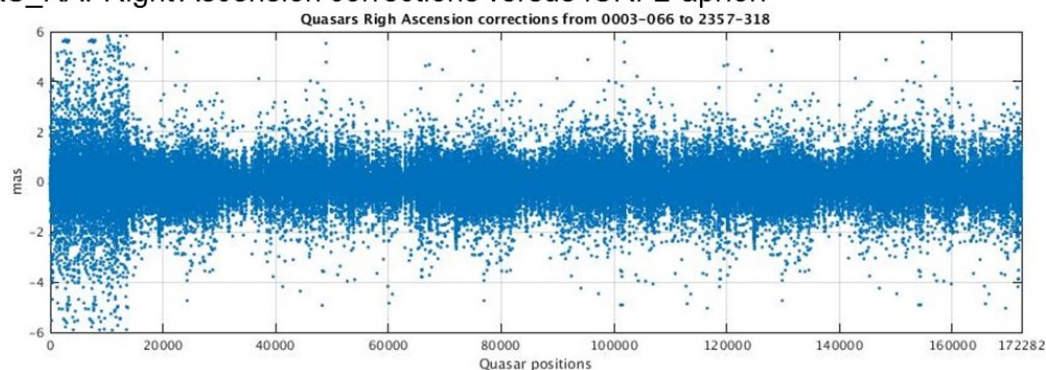
For the Earth rotation parameters, pole and UT1–UTC corrections w.r.t. IERS 08 C04 are plotted in Fig. 2 and exhibits an annual and semi-annual periodic signals in the polar motion (x, y) with a discrepancy of 51 μ as and 37 μ as respectively and 26 μ s for the UT1–UTC.

Concerning the nutation offsets issued only from VLBI observations, the quality of determination is not at the level of the IVS series. Estimations at 12h UTC are shown in Fig. 3 compared with the IERS 08 C04 series. The discrepancies in RMS are 367 μ as and 348 μ as for dX and dY respectively. Investments are in progress to complete the VLBI observations processing by GINS software used at GRGS.

Table 2: *Parameters to estimate for comparison with ITRF2014 and added parameters for further studies*

<i>Parameters</i>	<i>Estimated Parameters</i>	<i>Initial Values</i>
Pole, UT1-TAI	XPO, YPO, UT : PWL @ 12Hr (PX, PY into GINS)	IERS EOP 08-C04
Pole Rate	XPOR, YPOR 1pt/day @ 12Hr (PXR, PYR into GINS)	0.0
LOD	LOD 1pt/day @ 12Hr (PTR into GINS)	IERS EOP 08-C04
Precession/Nutation Corrections	NUT_X, NUT_Y : PWL @ 12Hr IAU2000A/2006 model corrections (dX,dY) (NX, NY dans GINS)	0.0
Station Coordinates	SX, SY, SZ 1 pt/week	ITRF2008
Radio sources Coordinates	RS_RA, RS_DE 1pt/week (QRA, QDE into GINS)	ICRF2
<i>Supplementary Parameters non used for ITRF2014 comparison</i>		
Zénithal Tropospheric Delay wet component & Horizontal Gradients	TROWET @ {01, 03, 05, ... 23} Hr: Estimation of wet component versus tropospheric model & TGETOT, TGNTOT 1 pt/d @ 00Hr	GPT2/GMF1 Model for radioelectric waves & Mendes-Pavlis for SLR/LLR + tropospheric gradient per station North & East directions

RS_RA: Right Ascension corrections versus ICRF2 apriori



RS_DE: Declination corrections versus ICRF2 apriori

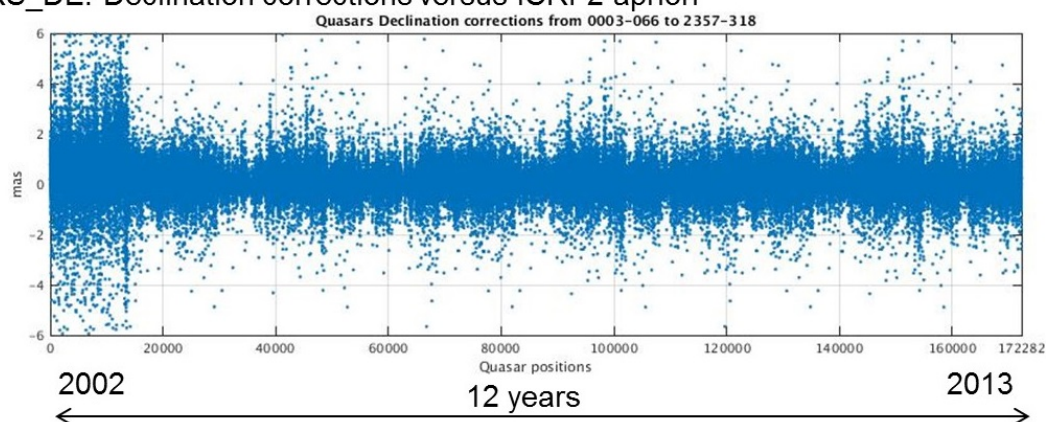


Fig. 1: Quasar coordinates corrections w.r.t. ICRF-2 from 2002 to 2013 – ~ 100 quasars estimated at a weekly basis

For the stations positions of all techniques determined at a weekly basis we apply preliminary averages set in Table 3.

Analyses of collocated stations obtained by this combination of four techniques are Ny-rAlesund site with the DORIS domes 10317S005, GPS domes 10317M005 and VLBI domes 10317S003, Wettzell (Bad Koetzing) site with GPS domes 14201M010, SLR domes 14201S018 and VLBI domes 14201S004 and Kokee Park site with DORIS domes 40424S009, GPS domes 40424M004 and VLBI domes 40424S007. These positions are estimated with their respective tropospheric bias parameters. Fig. 4, 5, 6 show the corrections w.r.t. Cartesian coordinates a-priori for Ny-Ålesund, Wettzell/Bad Koetzing and Kokee Park respectively with their differences, rates and the RMS3D estimated per techniques from the combination solutions over twelve years of observations. The differences calculated from the estimated positions are compatible with their respective local ties extracted from the SINEX files containing the co-location sites used in the ITRF2008 combination.

The systematic effects absorbed by Helmert parameters added for each technique have been weekly estimated. Fig. 7 shows the translations and scale for the satellite techniques and scale for VLBI over twelve

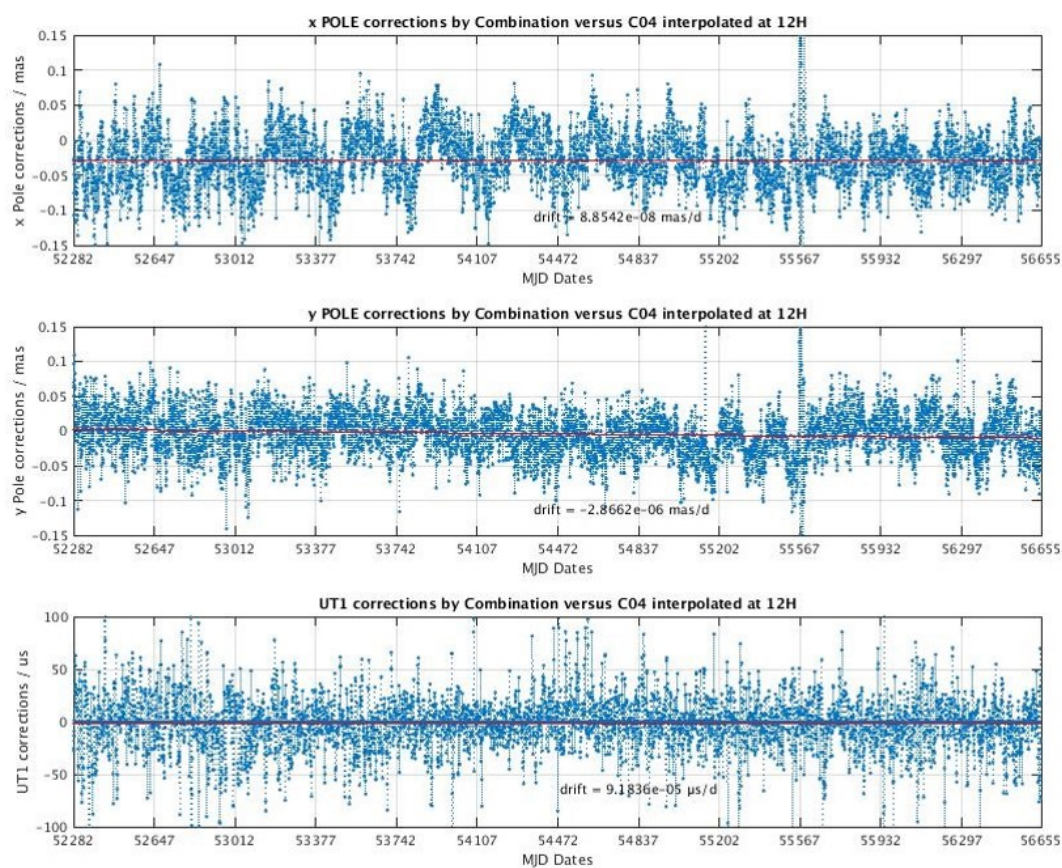


Fig. 2: x and y Pole coordinates corrections and UT1-UTC corrections w.r.t. IERS 08 CO4 series interpolated at 12h UTC – 4370 samples over 2002–2013 with 1pt/day at 12h UTC

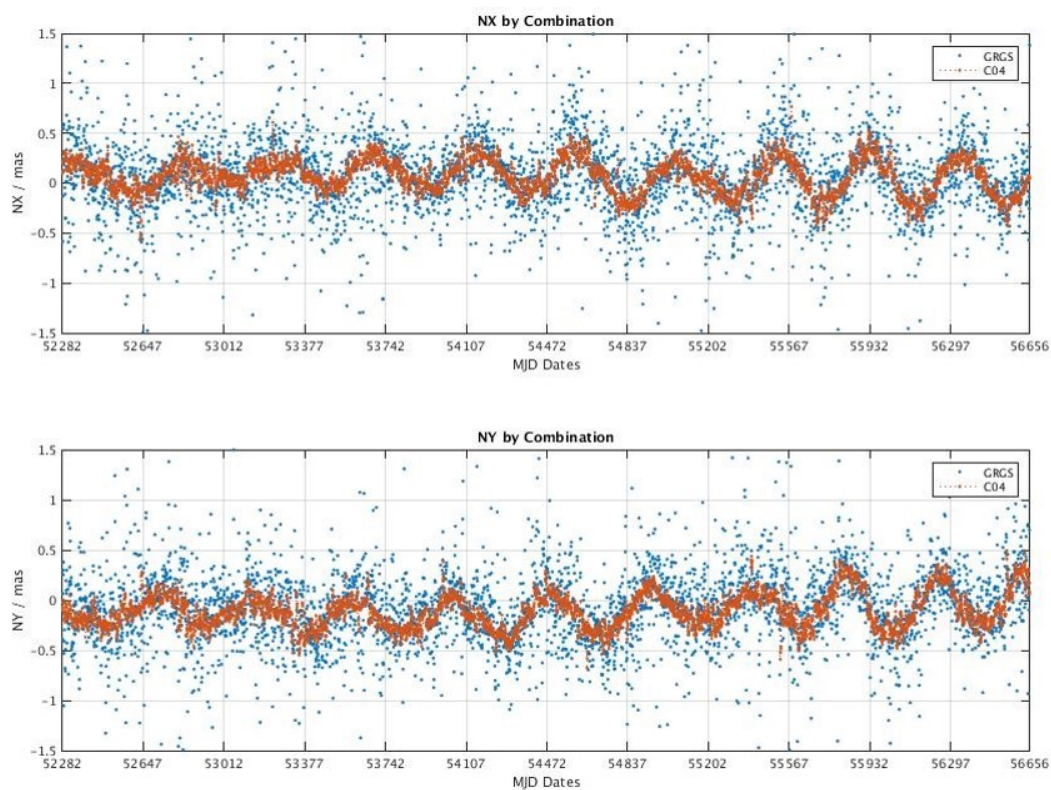


Fig. 3: Nutation offset corrections w.r.t. IERS 08 CO4 series interpolated at 12h UTC – 4370 samples over 2002–2013 with 1pt/day at 12h UTC

Table 3: Doris, GPS, SLR, VLBI Stations considered and pre-processing applied

	DORIS	GNSS	SLR	VLBI	Total
Number of Station	50	204	26	14	294
Observation frequency	Weekly	Daily	Weekly	Per session R1 R4, each week	~900 parameters per week
Processing		Weekly average	SLR stations measured by DORIS satellites are separated to SLR stations measured by SLR satellites	Weekly average	Systematic effects per technique (17) & 7 minimal constraints per techniques (35)

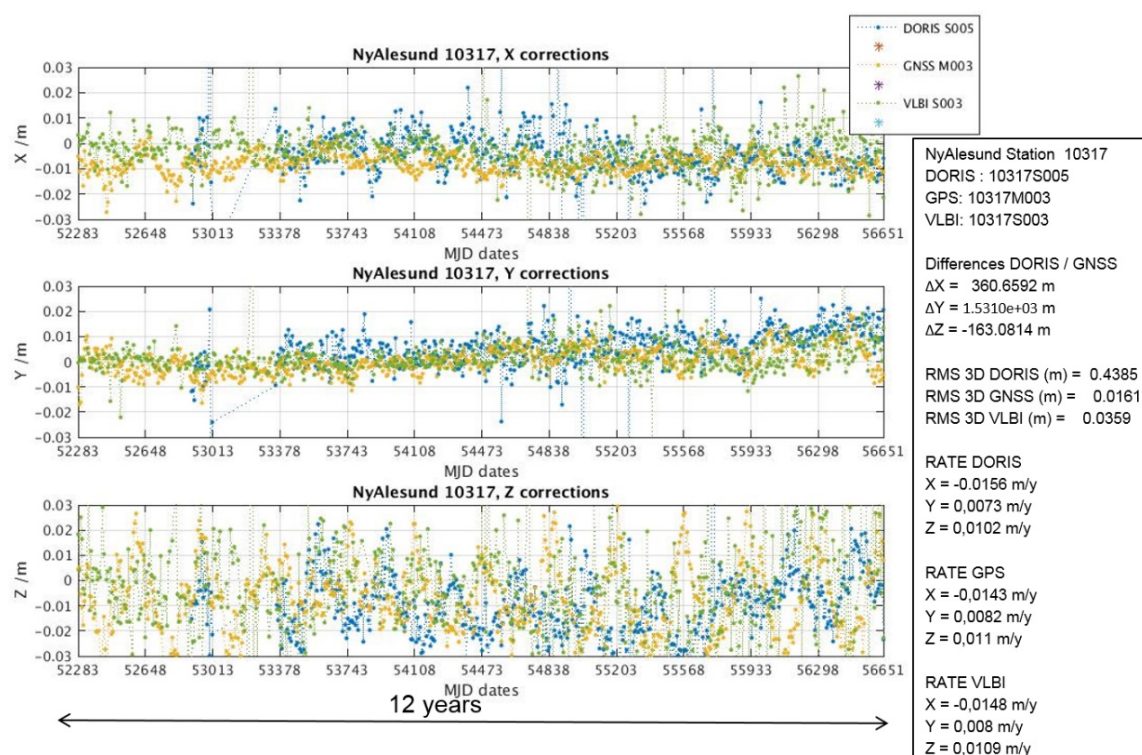


Fig. 4: Ny-Ålesund Cartesian coordinate corrections w.r.t. ITRF2008 for DORIS, GPS & VLBI collocated stations

years of observations. Table 4 shows the mean and standard deviation for each Helmert parameters in mm. We note that no bias is observed for the SLR origin either from the Doris satellites using Laser reflectors nor SLR satellites. The origin for all Doris satellites (with or without Laser reflectors) has -2 mm of bias over x and z components compatible with the null bias considering the associated discrepancies estimated to more than 1.2 cm.

Concerning the application of minimal constraints, the seven transformation parameters – 3 translations, 1 scale factor, 3 rotations – for each technique applied to their respective reference networks have been plotted in Fig. 8, and Table 5 collects the mean and standard deviation for the DORIS, GPS, SLR and VLBI techniques.

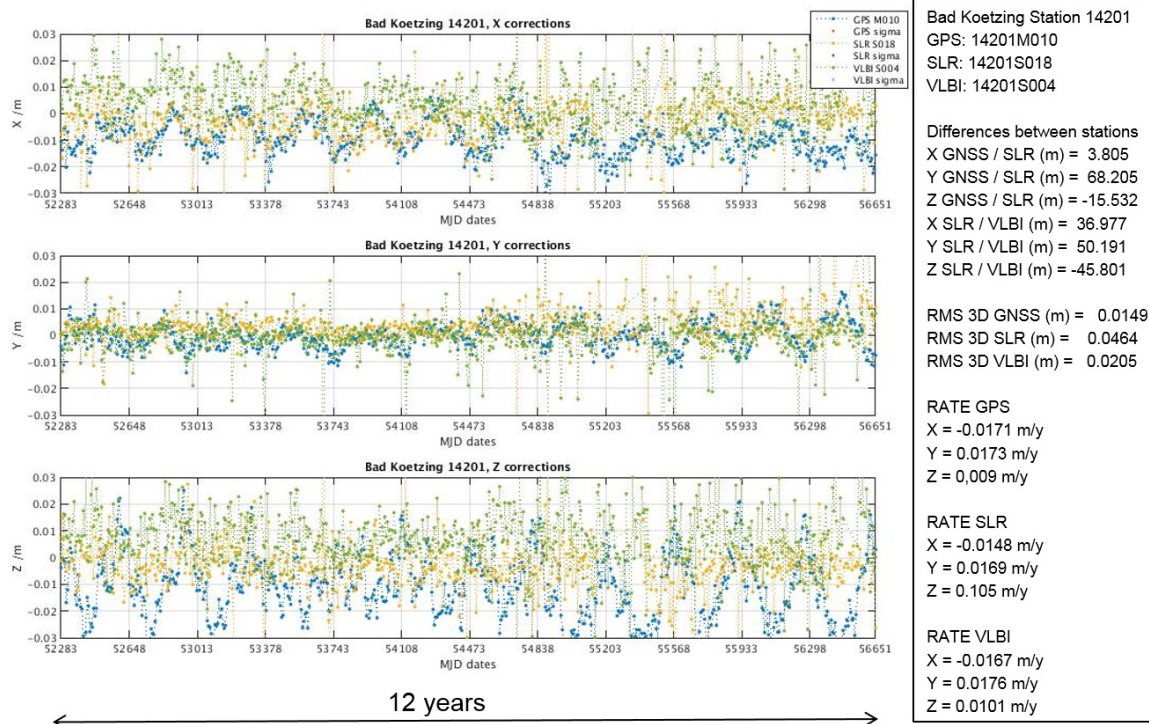


Fig. 5: Wettzell (Bad Koetzing) Cartesian coordinate corrections w.r.t. ITRF2008 for GPS, SLR & VLBI collocated stations

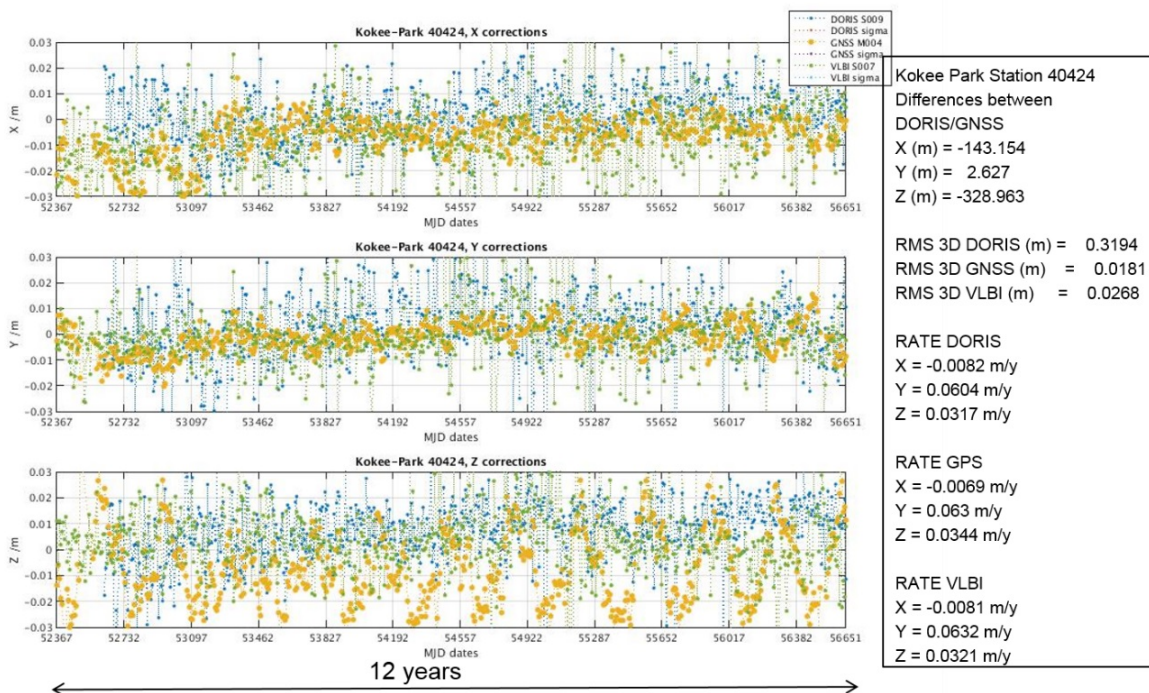


Fig. 6: Kokee Park Cartesian coordinate corrections w.r.t. ITRF2008 for GPS, SLR & VLBI collocate stations

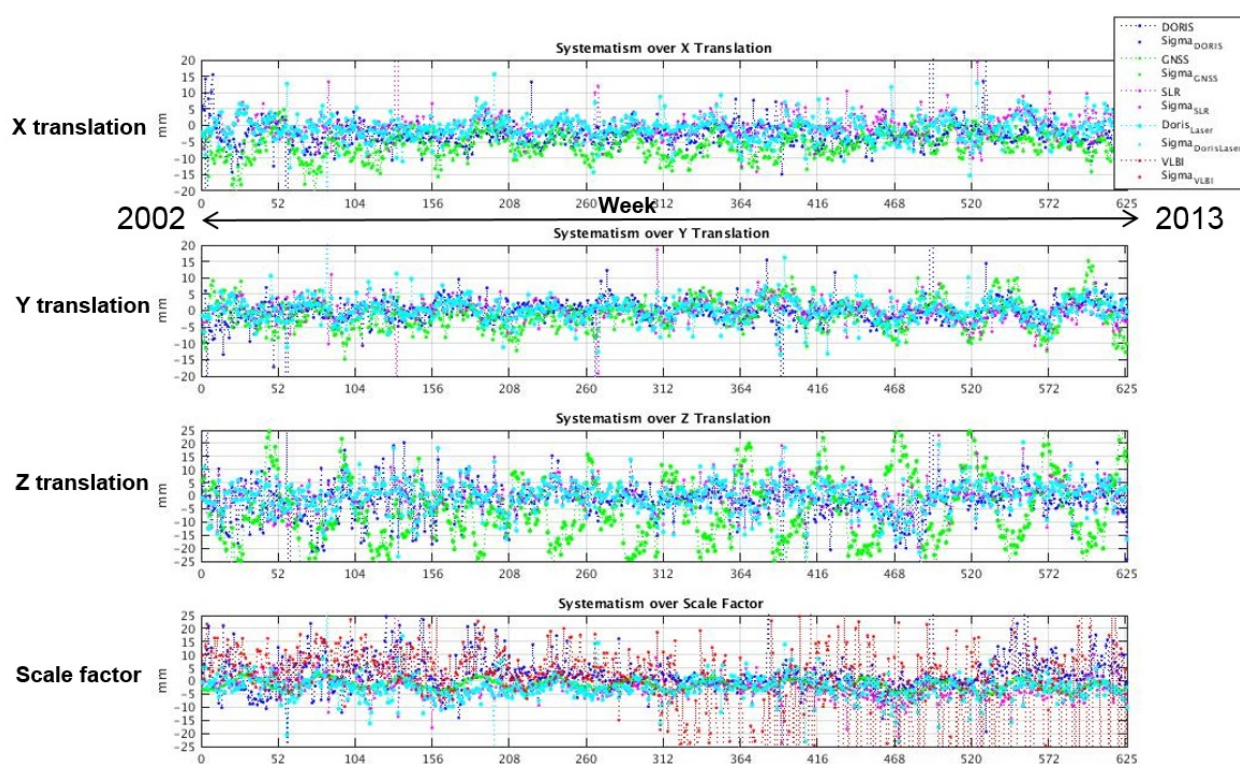


Fig. 7: Systematic effects on station networks for DORIS, GPS, SLR and VLBI

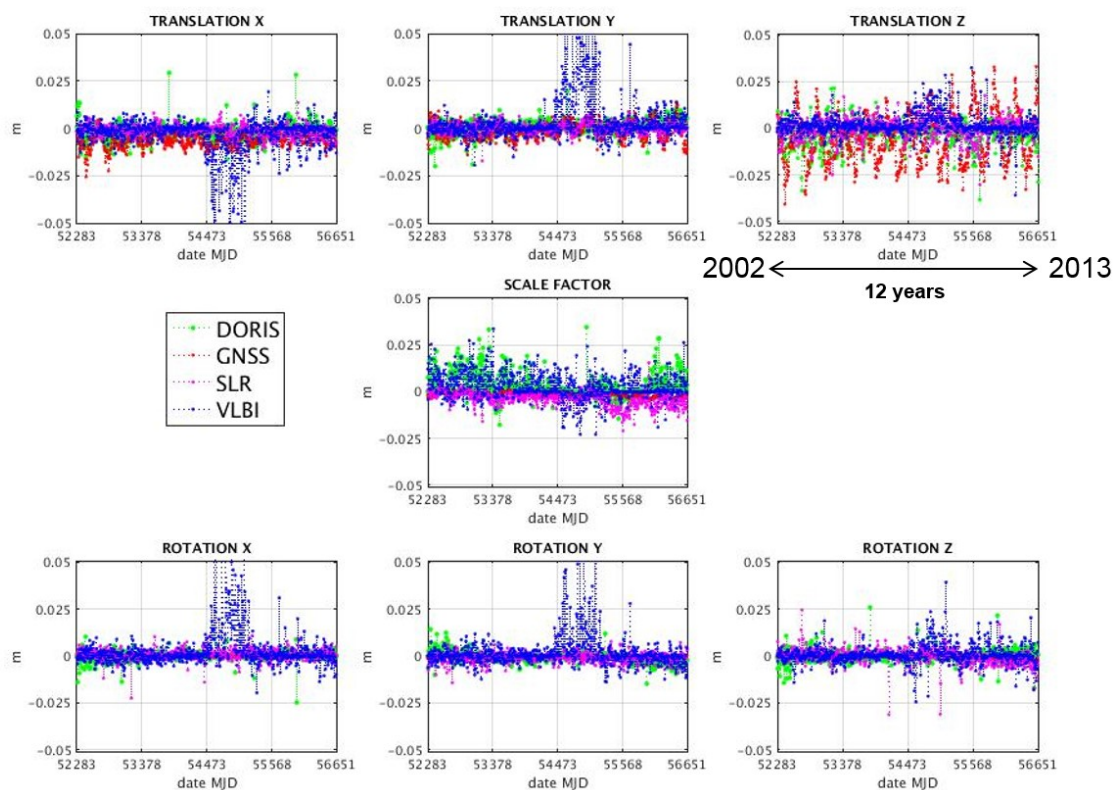


Fig. 8: Transformation parameters – 3 translations, 1 scale factor, 3 rotations – for DORIS, GPS, SLR and VLBI techniques over 2002–2013 period

Table 4: Mean and standard deviation for the Systematic effects estimated for each technique over the 2002–2013 period

Networks	DORIS		SLR by DORIS satellites		GNSS		SLR by SLR satellites		VLBI	
	Mean	Rms	Mean	Rms	Mean	Rms	Mean	Rms	Mean	Rms
TX (mm)	-2,8	16,0	0,0	3,9	-6,1	7,3	0,0	7,6		
TY (mm)	0,0	16,5	0,0	3,9	-1,2	4,8	0,0	3,6		
TZ (mm)	-1,9	12,4	0,0	6,1	-5,7	14,3	0,0	5,9		
Scale (mm)	2,5	17,0	-2,4	5,4	-1,6	2,5	-2,5	13,0	-5,3	25,8

Table 5: *Mean and standard deviation of transformation parameters weekly estimated for DORIS, GPS, SLR and VLBI techniques*

	TX mm	TY mm	TZ mm	Sc mm	RX μ as	RY μ as	RZ μ as
DORIS	-2,0 $\pm$ 4,6	0,0 $\pm$ 3,7	-2,8 $\pm$ 7,2	-3,2 $\pm$ 7,1	0,2 $\pm$ 2,4	-1,0 $\pm$ 3,0	0,0 $\pm$ 3,1
GNSS	-6,3 $\pm$ 7,4	-1,1 $\pm$ 4,6	-5,5 $\pm$ 14,5	-1,7 $\pm$ 2,1	-0,07 $\pm$ 0,3	-0,4 $\pm$ 0,6	-0,2 $\pm$ 0,9
SLR	-1,1 $\pm$ 3,3	0,2 $\pm$ 2,7	-0,2 $\pm$ 5,5	4,0 $\pm$ 5,6	0,7 $\pm$ 2,8	-0,9 $\pm$ 2,8	-0,3 $\pm$ 4,2
VLBI	-4,0 $\pm$ 11,7	3,8 $\pm$ 12,2	1,6 $\pm$ 5,9	3,1 $\pm$ 7,8	2,8 $\pm$ 10,5	1,7 $\pm$ 8,6	0,8 $\pm$ 5,4

Conclusion

The method developed to combine normal equations from astro-geodetic techniques by the COL WG has proved its capability to perform consistently CRF-EOP-TRF solutions at a weekly basis. During the campaign of generation the new terrestrial reference frame ITRF2014, the COL WG has generated weekly solutions and delivered files in SINEX format over 12 years, 2002–2013.

The results for Quasar positions simultaneously estimated with station coordinates at a weekly basis show a discrepancy of about 700 μ as versus ICRF2, for the Pole coordinates compared to IERS 08 C04: rms(xp_corr) = 51 μ as, rms(yp_corr) = 37 μ as shows an annual periodic term, for UT versus C04: rms(UT_corr) = 26 μ s & LOD is comparable to C04, for Nutation offset issue only from VLBI technique shows a large discrepancy versus C04 due to the processing on the VLBI observables not suitable for this combination (improvement is in progress for using VLBI NEQ from GINS software in order to combine them with other techniques). For the station coordinates we show an annual effect w.r.t. ITRF2008 a-priori probably due to the atmospheric loading not included in the model of station displacements, with discrepancies at the cm level. The systematic effects exhibit an annual oscillation for all techniques at 1.5 cm level for DORIS, 5 mm level for SLR by DORIS satellites, 1.4 cm for Z components of GNSS, 1 cm level for SLR by SLR satellites and 2.6 cm for scale factor of VLBI network. The transformation parameters show a large discrepancy for VLBI on translations and rotations at 5 cm level during the 2008-2010 period probably due to the VLBI network containing seismic stations, annual oscillation on translations for GNSS network at 6 mm level for TX and TZ, 1 mm for TY, scale factor for SLR is at a level of 4 mm with 6 mm of discrepancy.

Further investigations have to consider to take benefits of this COL WG efforts on doing this combination procedure. First concern the comparison of EOP and station solutions with ITRF2014, the analysis on mutualisation of tropospheric parameters and on mutualisation of orbital parameters for multi-techniques satellites.

Jean-Yves Richard

3.7.3 Working Group on SINEX Format

General activities

The IERS Working Group (WG) on SINEX Format was established in early 2011. The Charter of the Working Group is available on the website dedicated to the working group and maintained at the IERS Central Bureau: <http://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>

Sinex Format Description - Sinex Block Generator

☐ Insert into "Sinex Format Description" (final document)

Block title:

Block Description:

Table title:

Content row 1:

Field:

Description:

Format:

Content row 2:

Fig. 1: Web interface developed for automatized generation of SINEX block description.

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 2016 there was no special meeting of the working group. All discussions on possible format revisions and additions have been done via email or personal communication.

As the maintenance of the format description becomes difficult due to the pure ascii format with tables symbolized by special characters only, a web-based tool has been developed where the content descriptions of the individual SINEX blocks can be added and changed more conveniently. The text filled in via the web-interface is then transformed internally to a LaTeX document which allows a subsequent generation of a pdf. An example of this web-interface is shown in Figure 1. At the moment, this tool is only available at the IERS Central Bureau internally, but might be provided to outside users in the future.

This tool for a generalized creation of the SINEX format description is the basis for the foreseen changes and additions to the SINEX format, especially due to the new type of representation of non-linear station motions as part of the ITRF2014, and other extensions coming up in the framework of the next Unified Analysis Workshop (UAW) to be held in 2017.

Daniela Thaller on behalf of the SINEX WG

3.7.4 Working Group on Site Coordinate Time Series Format

No report for 2016 submitted.

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 cooperate 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

Appendix 2: Contact addresses of the IERS Directing Board

Chair Brian Luzum
U.S. Naval Observatory
Scientific Director
3450 Massachusetts Avenue, NW
Washington, DC 20392-5420
USA
phone: +1-202-762-1513
fax: +1-202-762-1461
e-mail: brian.luzum@navy.mil

Analysis Coordinator Thomas Herring
Massachusetts Institute of Technology
77 Massachusetts Avenue
Building 54-322
Cambridge, MA 02139
USA
phone: +1-617-253-5941
fax: +1-617-253-6385
e-mail: tah@mit.edu

Product Centres Representatives

**Earth Orientation Centre
Representative** Christian Bizouard
Observatoire de Paris
61, avenue de l'Observatoire
75014 Paris
France
phone: +33-1-4051-2335
e-mail: christian.bizouard@obspm.fr

**Rapid Service/Prediction
Centre Representative** Christine Hackman
U.S. Naval Observatory
Earth Orientation Department
3450 Massachusetts Avenue, NW
Washington, DC 20392-5420
USA
phone: +1-202-762-1444
fax: +1-202-762-1563
e-mail: christine.hackman@navy.mil

**Conventions Centre
Representative** Christian Bizouard
(address see above)

**ICRS Centre
Representative** Jean Souchay
Observatoire de Paris
SYRTE
61, Avenue de l'Observatoire
75014 Paris
France
phone: +33-1-4051-2322
e-mail: jean.souchay@obspm.fr

**ITRS Centre
Representative** Zuheir Altamimi
Institut National de l'Information
Géographique et Forestière (IGN)
Laboratoire de Recherche en Géodésie (LAREG)
Bâtiment Larmarck A
5, rue Thomas Mann, Case courrier 7011
75205 Paris Cedex 13, France
phone: +33 1 57 27 53 28
fax: +33 1 57 27 84 82
e-mail: zuheir.altamimi@ign.fr

**Global Geophysical Fluids
Centre Representative** Jean-Paul Boy
École et Observatoire des Science de la Terre (EOST)
Institut de Physique du Globe de Strasbourg (IPGS)
5 rue René Descartes
1511 Luxembourg, Luxembourg
phone: +33.3.68.85.01.09
fax: +33.3.68.85.01.25
e-mail: jeanpaul.boy@unistra.fr

**Central Bureau
Representative** Daniela Thaller
Bundesamt für Kartographie und Geodäsie
Richard-Strauss-Allee 11
60598 Frankfurt am Main
Germany
phone: +49-69-6333-273
fax: +49-69-6333-425
e-mail: daniela.thaller@bkg.bund.de

Technique Centers Representatives

IGS Representatives

Rolf Dach
Universität Bern
Astronomisches Institut
Sidlerstrasse 5
3012 Bern
Switzerland
phone: +41 31 631-8593
e-mail: rolf.dach@aiub.unibe.ch

Chuck Meertens
UNAVCO
6350 Nautilus Drive
Boulder, CO 80301-5394
USA
phone: +1-303-381-7465
fax: +1-303-381-7501
e-mail: chuckm@unavco.org

ILRS Representatives

Ludwig Combrinck
Hartebeesthoek Radio Astronomy Observatory
P.O. Box 443
Krugersdorp, 1740
South Africa
phone: +27-12-301-3100
fax: +27-12-301-3300
e-mail: ludwig@hartrao.ac.za

Erricos C. Pavlis
Joint Center for Earth Systems Technology (JCET/UMBC)
University of Maryland, Baltimore County & NASA GSFC
1000 Hilltop Circle, TRC #182
Baltimore, MD 21250
USA
phone: +1-410-455-5832
fax: +1-410-455-5868
e-mail: epavlis@umbc.edu

IVS Representatives

Rüdiger Haas
Chalmers University of Technology
Onsala Space Observatory
439 92 Onsala
Sweden
phone: +46 31 772 55 30
fax: +46 31 772 55 90
e-mail: rudiger.haas@chalmers.se

Guangli Wang
Center for Astrogeodynamics Research
Shanghai Astronomical Observatory, CAS
80 Nandan Road
Shanghai 200030
China
phone: +86 13916381811
fax: +86 021-64384618
e-mail: wgl@shao.ac.cn

IDS Representatives

Hugues Capdeville
CLS
8-10 rue Hermes, Parc Technologique du Canal
31520 Ramonville Saint-Agne
France
phone: +33 5 61 39 37 06
fax: +33 5 61 75 10 14
e-mail: ids.analysis.coordination@ids-doris.org

Jérôme Saunier
Réseaux et Services Internationaux
Service de Géodésie et Nivellement
Institut National de l'Information Géographique et Forestière
2, avenue Pasteur, 94165 Saint Mande Cedex
France
phone: +33 1 43 988 363
fax: +33 1 43 988 450
e-mail: jerome.saunier@ign.fr

Union Representatives

IAU Representative	Aleksander Brzezinski Space Research Centre Polish Academy of Sciences Bartycka 18a 00-716 Warsaw Poland phone: +48-22-381 6287 fax: +48-22-840 3131 e-mail: alek@cbk.waw.pl
IAG / IUGG Representative	Axel Nothnagel Institut für Geodäsie und Geoinformation (IGG) Universität Bonn Nußallee 17 53115 Bonn Germany phone: +49-228-73-3574 fax: +49-228-73-2988 e-mail: nothnagel@uni-bonn.de
GGOS Representative	Richard S. Gross Jet Propulsion Laboratory (JPL) Mail Stop 238-600 4800 Oak Grove Drive Pasadena, CA 91109-8099 USA phone: +1-818-354-4010 fax: +1-818-393-4965 e-mail: Richard.Gross@jpl.nasa.gov

(Status as of December 2017)

Appendix 3: Contact addresses of the IERS components

Analysis Coordinator Thomas Herring
 Massachusetts Institute of Technology
 77 Massachusetts Avenue
 Building 54-322
 Cambridge, MA 02139
 USA
 phone: +1-617-253-5941
 fax: +1-617-258-6385
 e-mail: tah@mit.edu

Central Bureau IERS Central Bureau
 Bundesamt für Kartographie und Geodäsie
 Richard-Strauss-Allee 11
 60598 Frankfurt am Main
 Germany
 phone: +49-69-6333-273/261/314/250
 fax: +49-69-6333-425
 e-mail: central_bureau@iers.org
Director: Daniela Thaller
Scientific Assistant: Wolfgang R. Dick

Technique Centres

International GNSS Service (IGS) International GNSS Service (IGS)
 IGS Central Bureau
 Jet Propulsion Laboratory (JPL)
 M/S 238-540, 4800 Oak Grove Drive
 Pasadena, CA 91109
 USA
 phone: +1-818-354-8330
 fax: +1-818-393-6686
 e-mail: cb@igs.org
IGS Representatives to the IERS Directing Board:
 Rolf Dach, Chuck Meertens
IERS Representative to the IGS Governing Board:
 Richard S. Gross

International Laser Ranging Service (ILRS)	International Laser Ranging Service (ILRS) ILRS Central Bureau (c/o Carey Noll) NASA Goddard Space Flight Center (GSFC) Code 61A Greenbelt, MD 20771 USA phone: +1-301-614-6542 fax: +1-301-614-5970 e-mail: ilrs-cb@lists.nasa.gov <i>ILRS Representatives to the IERS Directing Board:</i> Ludwig Combrinck, Erricos C. Pavlis <i>IERS Representative to the ILRS Directing Board:</i> Daniela Thaller
International VLBI Service for Geodesy and Astrometry (IVS)	International VLBI Service for Geodesy and Astrometry (IVS) IVS Coordinating Center NASA's Goddard Space Flight Center (GSFC) Code 61A.1 Greenbelt, MD 20771 USA phone: +1-301-614-5939 fax: +1-301-614-6099 e-mail: ivscc@lists.nasa.gov <i>IVS Representatives to the IERS Directing Board:</i> Rüdiger Haas, Guangli Wang <i>IERS Representative to the IVS Directing Board:</i> Rüdiger Haas
International DORIS Service (IDS)	International DORIS Service (IDS) IDS Central Bureau Collecte Localisation Satellites (CLS) 8-10, rue Hermes, Parc Technologique du Canal 31526 Ramonville Saint-Agne France phone: +33 5 61 39 48 49 / 5 61 39 47 50 fax: +33 5 61 39 48 06 e-mail: ids.central.bureau@ids-doris.org <i>IDS representatives to the IERS:</i> Hugues Capdeville, Jérôme Saunier <i>IERS Representative to the IDS Governing Board:</i> Brian Luzum

Product Centres

- Earth Orientation Centre** Earth Orientation Centre
Observatoire de Paris
61, Avenue de l'Observatoire
75014 Paris
France
phone: +33-1-4051-2335
e-mail: services.iers@obspm.fr, christian.bizouard@obspm.fr
Primary scientist and representative to the IERS Directing Board:
Christian Bizouard
- Rapid Service/Prediction Centre** Rapid Service/Prediction Centre
U.S. Naval Observatory, Earth Orientation Department
3450 Massachusetts Avenue, NW
Washington, DC 20392-5420
USA
phone: +1-202-762-1444
fax: +1-202-762-1563
e-mail: christine.hackman@navy.mil
secondary email: nick.stamatakos@navy.mil
Primary scientist and representative to the IERS Directing Board:
Christine Hackman
Production director and lead project scientist: Nick Stamatakos
- Conventions Centre** Conventions Centre
U.S. Naval Observatory, Earth Orientation Department
3450 Massachusetts Avenue, NW
Washington, DC 20392-5420
USA
phone: +1-202-762-1518
fax: +1-202-762-1563
e-mail: nick.stamatakos@navy.mil
- Observatoire de Paris
61, Avenue de l'Observatoire
75014 Paris
France
phone: +33-1-4051-2335
e-mail: christian.bizouard@obspm.fr
- Primary scientists:*
Nick Stamatakos (USNO), Christian Bizouard (Obs. Paris)
Current representative to the IERS Directing Board:
Christian Bizouard

ICRS Centre ICRS Centre
 U.S. Naval Observatory, Astrometry Department
 3450 Massachusetts Avenue, NW
 Washington, DC
 USA
 phone: +1-202-762-0134
 fax: +1-202-762-1516
 e-mail: bryan.dorland@navy.mil

Observatoire de Paris, SYRTE
 61, Avenue de l'Observatoire
 75014 Paris
 France
 phone: +33-1-4051-2322
 e-mail: Jean.Souchay@obspm.fr

Primary scientists:

Bryan Dorland (USNO), Jean Souchay (Obs. Paris)

Current representative to the IERS Directing Board:

Jean Souchay

ITRS Centre ITRS Centre
 Institut National de l'Information Géographique et Forestière (IGN)
 Laboratoire de Recherche en Géodésie (LAREG)
 Bâtiment Larmarck A
 5, rue Thomas Mann, Case courrier 7011
 75205 Paris Cedex 13
 France
 phone: +33 1 57 27 53 28
 fax: +33 1 57 27 84 82
 e-mail: itrfr@ign.fr
Primary scientist and representative to the IERS Directing Board:
 Zuheir Altamimi

**Global Geophysical Fluids
Centre**

Global Geophysical Fluids Centre
 Jean-Paul Boy
 École et Observatoire des Science de la Terre (EOST)
 Institut de Physique du Globe de Strasbourg (IPGS)
 5 rue René Descartes
 67084 Strasbourg Cedex
 France
 phone: +33.3.68.85.01.09
 fax: +33.3.68.85.01.25
 e-mail: jeanpaul.boy@unistra.fr
Primary scientist and representative to the IERS Directing Board:
 Jean-Paul Boy
Co-Chair: Tonie van Dam

**Special Bureau for the
Oceans**

Special Bureau for the Oceans
 Richard S. Gross
 Jet Propulsion Laboratory (JPL)
 Mail Stop 238-600
 4800 Oak Grove Drive
 Pasadena, CA 91109-8099
 USA
 phone: +1-818-354-4010
 fax: +1-818-393-4965
 e-mail: Richard.Gross@jpl.nasa.gov

**Special Bureau for
Hydrology**

Special Bureau for Hydrology
 Jianli Chen
 Center for Space Research
 University of Texas at Austin
 Austin, TX 78712
 USA
 phone: +1-512-232-6218
 fax: +1-512-471-3570
 e-mail: chen@csr.utexas.edu

**Special Bureau for the
Atmosphere**

Special Bureau for the Atmosphere
 David A. Salstein
 Atmospheric and Environmental Research, Inc.
 131 Hartwell Avenue
 Lexington, MA 02421-3126
 USA
 phone: +1-781-761-2288
 fax: +1-781-761-2299
 e-mail: salstein@aer.com

***Special Bureau for
Combination***

Special Bureau for Combination
 Tonie van Dam
 Faculté des Sciences, de la Technologie et de la Communication
 University of Luxembourg
 162a, avenue de la Faïencerie
 1511 Luxembourg
 Luxembourg
 phone: +352-46-66-44-6261
 fax: +352-46-66-44-6567
 e-mail: tonie.vandam@uni.lu

**ITRS Combination
Centres****Deutsches Geodätisches
Forschungsinstitut der TU
München (DGFI-TUM)**

Deutsches Geodätisches Forschungsinstitut der TU München
 (DGFI-TUM)
 Manuela Seitz
 Deutsches Geodätisches Forschungsinstitut der TU München
 Arcisstraße 21
 80333 München
 Germany
 phone: +49-89-23031-1294
 fax: +49-89-2303-1240
 e-mail: manuela.seitz@tum.de

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

Institut National de l'Information Géographique et Forestière (IGN)
 Zuheir Altamimi
 Institut National de l'Information Géographique et Forestière (IGN)
 Laboratoire de Recherche en Géodésie (LAREG)
 Bâtiment Larmarck A
 5, rue Thomas Mann, Case courrier 7011
 75205 Paris Cedex 13
 France
 phone: +33 1 57 27 53 28
 fax: +33 1 57 27 84 82
 e-mail: zuheir.altamimi@ign.fr

Jet Propulsion Laboratory (JPL) Jet Propulsion Laboratory (JPL)
Richard S. Gross
Jet Propulsion Laboratory
Mail Stop 238-600
4800 Oak Grove Drive
Pasadena, CA 91109-8099
USA
phone: +1-818-354-4010
fax: +1-818-393-4965
e-mail: Richard.Gross@jpl.nasa.gov

Working Groups

Working Group on Site Survey and Co-location Sten Bergstrand
SP Technical Research Institute of Sweden
Measurement Technology
Box 857
SE-501 15 Borås
Sweden
phone: +46 10 516 50 00, direct: +46 10 516 57 73
fax: +46 10 516 56 20
e-mail: sten.bergstrand@sp.se

Working Group on SINEX Format Daniela Thaller
Bundesamt für Kartographie und Geodäsie
Richard-Strauss-Allee 11
60598 Frankfurt am Main
Germany
phone: +49-69-6333-273
fax: +49-69-6333-425
e-mail: daniela.thaller@bkg.bund.de

Working Group on Site Coordinate Time Series Format Laurent Soudarin
Collecte Localisation Satellites (CLS)
8-10 rue Hermès
Parc Technologique du Canal
31520 Ramonville Saint-Agne
France
phone: +33-5-61-39-48-49
fax: +33-5-61-39-48-06
e-mail: laurent.soudarin@cls.fr

(Status as of December 2017)

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/itrffield>

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://itrfield.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: <http://www.aer.com/scienceResearch/diag/sb.html>***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>.

2MASS	Two Micron All Sky Survey	C/P	Combination and Prediction
AAC	Associated Analysis Centre	CA	California, USA
AAM	Atmospheric Angular Momentum	CATREF	Combination and Analysis of Terrestrial Reference Frames
AC	Analysis Centre	CB	Central Bureau
AC	Analysis Coordinator	CC	Combination Centre
ACC	[IGS] Analysis Center Coordinator	CDB	USNO's Celestial Reference Frame Database
ACES	Atomic Clock Ensemble in Space	CDDIS	NASA Crustal Dynamics Data Information System
ADC	[Gaia] Affiliated Data Center	CERGA	Centre d'Etudes et de Recherches Géodynamiques et Astronomiques
AGU	American Geophysical Union	CfA	Harvard-Smithsonian Center for Astrophysics
AJ	Astronomical Journal	CfP	Call for Participation/Proposals
AM	angular momentum	CIO	Conventional International Origin
AOV	Asia-Oceania VLBI Group for Geodesy and Astrometry	CIP	Celestial Intermediate Pole
APOLLO	Apache Point Observatory Lunar Laser-ranging Operation	CLS	Collecte, Localisation, Satellites
APSG	Asia-Pacific Space Geodynamics	CLM	Conventional Mean Pole
AR	Annual Report	CNES	Centre National d'Etudes Spatiales
AR	autoregressive	CNSA	China National Space Administration
ASC	Analysis Standing Committee	CODE	Centre for Orbit Determination in Europe
ASI	Agenzia Spaziale Italiana	COL	combination at/on the observation level
AWG	Analysis Working Group	CoM	centre of mass
BIPM	Bureau International des Poids et Mesures	CoP	centre of phase
BKG	Bundesamt für Kartographie und Geodäsie	COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
BOSS	Baryon Oscillation Spectroscopic Survey		
c	century		

CPC	Climate Prediction Center	DOR-O-T	DORIS Online Tools
CRF	Celestial Reference Frame	DPAC	Data Processing and Analysis Consortium
CSR	Center for Space Research, University of Texas	DPOD	DORIS extension of the ITRF for Precise Orbit Determination
CSTG	Commission on International Coordination of Space Techniques for Geodesy and Geodynamics	DTRF	ITRS realization by DGFI
CTIO	Cerro Tololo Inter-American Observatory	DUT1	= UT1-UTC
DB	Directing Board	E	East [position/coordinate/direction]
DC	Data Center	EAM	Effective Angular Momentum
DC	District of Columbia, USA	ECCO	Estimating the Circulation and Climate of the Ocean
DE	JPL Development Ephemeris	ECMWF	European Centre for Medium-Range Weather Forecasts
DE	declination	EGU	European Geosciences Union
Dec	declination	ELP	Éphéméride Lunaire Parisienne
DEC	declination	ELPN	Éphéméride Lunaire Parisienne Numérique
deg	degree	EMRP	European Metrology Research Program[me]
DGFI	Deutsches Geodätisches Forschungsinstitut	ENVISAT	Environmental Satellite
DiFX	Distributed FX	EO	Earth orientation
DIODE	Détermination Immédiate d'Orbite par Doris Embarqué	EOC	Earth Orientation Centre
DIS	IERS Data and Information System	EOP	Earth Orientation Parameters
DOGS	DGFI Orbit & Geodetic Parameter Estimation Software	EOST	École et Observatoire des Science de la Terre
DOI	Digital Object Identifier	EPOS-OC	Earth Parameter and Orbit System - Orbit Computation [software]
doi	Digital Object Identifier	Eratosthenes	European Reference Antenna of Space Geodetic Techniques Enhancing Earth Science
DOMES	Directory Of MERIT Sites (originally; now of more general use)	ESA	European Space Agency
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)	ESAC	European Space Astronomy Centre

ESOC	European Space Operations Center, ESA	GHz	gigahertz
ET	Epheremis Time	GINs	Geodesy by Simultaneous Digital Integration [software]
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites	GIOVE	Galileo In-Orbit Validation Element
EURAMET	European Association of National Metrology Institutes	GPSY/OASIS	GNSS-Inferred Positioning System and Orbit Analysis Simulation Software
EVGA	European VLBI [Group] for Geodesy and Astrometry	GIQC	Gaia Initial Quasar Catalog[ue]
eVLBI	Electronic transfer VLBI	GLDAS	NASA's Global Land Data Assimilation System
e-VLBI	Electronic transfer VLBI	GLONASS	GLObal'naya NAVigatsionnay Sputnikovaya Sistema [Global Orbiting Navigation Satellite System, Russia]
FL	Florida, USA	GLOUP	GLObal Undersea Pressure
FNMOc	[US Navy] Fleet Numerical Meteorology and Oceanography Center	GM	General Meeting
FTP	File Transfer Protocol	GMF	Global Mapping Function
ftp	File Transfer Protocol	GNSS	Global Navigation Satellite System
GA	General Assembly	GPS	Global Positioning System
GA	Geoscience Australia	GPT	Global Pressure and Temperature
GB	Governing Board	GRACE	Gravity Recovery and Climate Experiment
Gb	gigabyte	GRASP	Geodetic Reference Antenna in Space
GCRF	Gaia Celestial Reference Frame	GRGS	Groupe de Recherches de Géodésie Spatiale
GDR	Geophysical Data Record	GSFC	Goddard Space Flight Center
GDR1	Gaia Data Release 1	GSI	Geospatial Information Authority of Japan (formerly: Geographical Survey Institute)
GEO	Group on Earth Observations	HartRAO	Hartebeesthoek Radio Astronomy Observatory
GEODVEL	GEODetic VELocity [model]	HEO	High Earth Orbiter
GFZ	GeoForschungsZentrum Potsdam	hr	hour, hours
GGFC	Global Geophysical Fluids Centre		
GGIM	= UN GGIM		
GGOS	Global Geodetic Observing System		
GGRF	Global Geodetic Reference Frame		

HRAO	Hartebeesthoek Radio Astronomy Observatory	IGMAS	International GNSS Monitoring and Assessment System
HVAC	Heating, Ventilation and Air Conditioning	IGN	Institut National de l'Information Géographique et Forestière (formerly: Institut Géographique National)
HY	HaiYan / Haiyang / Hai Yang [satellite]	IGS	International GNSS Service (formerly: International GPS Service)
IAA	Institute of Applied Astronomy, St. Petersburg	IIUL	integrated IGS Ultra LODs
IAG	International Association of Geodesy	ILRS	International Laser Ranging Service
IASPEI	International Association of Seismology and Physics of the Earth's Interior	ILRSA	ILRS official solution
IAU	International Astronomical Union	INASAN	(Institute of Astronomy of the Russian Academy of Sciences)
ICESat	Ice, Cloud, and land Elevation Satellite	INFN	Istituto Nazionale di Fisica Nucleare [National Institute for Nuclear Physics]
ICG	International Committee on Global Navigation Satellite Systems	Int.	International
ICRF	International Celestial Reference Frame	IP	Internet Protocol
ICRS	International Celestial Reference System	IPGP	Institut de Physique du Globe de Paris
ICSU	International Council for Science	IPGS	Institut de Physique du Globe de Strasbourg
ID	Identification/Identifier	IR	infrared
IDS	International DORIS Service	IRIS	International Radio Interferometric Surveying
IERS	International Earth Rotation and Reference Systems Service (formerly: International Earth Rotation Service)	IRNSS	Indian Regional Navigation Satellite System
IfE	Institut für Erdmessung [Institute of Geodesy], University of Hannover	ISA	IAG Service Assessment
IGG	Institute of Geodesy and Geoinformation of the University of Bonn (formerly: GIUB)	ISBN	International Standard Book Number
IGGB	Institute of Geodesy and Geoinformation of the University of Bonn (formerly: GIUB)	ISO	International Organization for Standardization
		IT	Information Technology
		ITRF	International Terrestrial Reference Frame

ITRS	International Terrestrial Reference System	lon	longitude
IUGG	International Union of Geodesy and Geophysics	LQAC	Large Quasar Astrometric Catalog[ue]
IVS	International VLBI Service for Geodesy and Astrometry	LS	least-squares
Jason-CS	Jason Continuity of Service [mission]	LSST	Large Synoptic Survey Telescope
JCET	Joint Center for Earth Systems Technology, GSFC	MA	Massachusetts, USA
JISDM	Joint International Symposium on Deformation Monitoring	MA	moving average
JMA	Japan Meteorological Agency	mas	milliarcsecond(s)
JPL	Jet Propulsion Laboratory	masec	milliarcseconds
JTRF	ITRS realization by JPL	MCC	Russian Mission Control Centre
JWG	Joint Working Group	MD	Maryland, USA
KALREF	Kalman filter for Reference frames	MeO	Métrieologie Optique [Grasse SLR/LLR system]
kHz	kilohertz	MGEX	Multi-GNSS [Global] Experiment, Multi-GNSS Extension
LAGEOS	Laser Geodynamics Satellite	MIRAGN	mid-IR AGNs
LAREG	Laboratoire de Recherches en Géodésie	MIT	Massachusetts Institute of Technology
LARES	Laser Relativity Satellite	MJD	Modified Julian Day
LARGE	Laser Ranging to GNSS s/c Experiment	MLRO	Matera Laser Ranging Observatory
lat	latitude	MLRS	McDonald Observatory Laser Ranging Station
LBO	Long Baseline Observatory	MORVEL	mid-ocean ridge velocities [model]
LDAS	Land Data Assimilation System	MPIfR	Max-Planck-Institut für Radioastronomie / Max Planck Institute for Radio Astronomy
LEO	Low Earth Orbit(er)	msec	milliseconds
LFOA	Leopold-Figl-Observatorium für Astrophysik	N	number
LLR	Lunar Laser Ranging	N	North [position/coordinate/direction]
LoD	Length of Day	NAPEOS	NAvigation Package for Earth Orbiting Satellites
LOD	Length of Day	NASA	U.S. National Aeronautics and Space Administration

NAVGEN	[U.S.] Navy Global Environmental Model	O–C	observed – calculated
NCAR	U.S. National Center for Atmospheric Research	OCA	Observatoire de la Côte d’Azur
NCEP	U.S. National Centers for Environmental Prediction	OCARS	Optical Characteristics of Astrometric Radio Sources
ND	neutral density	OHIG	O’Higgins [station]
NEQ	normal equation	OP	Observatoire de Paris
NGS	U.S. National Geodetic Survey	OPA	Observatoire de Paris
NISAR	NASA-ISRO Synthetic Aperture Radar [satellite]	OPAR	Paris Observatory IVS Analysis Center
NIST	[U.S.] National Institute of Standards and Technology	PANDOR	Pré traitement et ANalyse des mesures DORis
NMA	Norwegian Mapping Authority [Statens kartverk / Kartverket]	Pan-STARRS	Panoramic Survey Telescope And Rapid Response System
NNR	No-net-rotation, No Net Rotation	PC	Product Centre
NNT	No-net-translation, No Net Translation	PLATO	Performance Simulations & Architectural Trade-Offs
No.	Number, Numbers	PM	Polar Motion
Nos.	Number, Numbers	POD	Precise [or Precision] Orbit Determination
NOAA	U.S. National Oceanic and Atmospheric Administration	POLAC	Paris Observatory Lunar Analysis Center
NP	SLR normal point(s)	ppb	parts per billion (10 ⁻⁹)
NRAO	U.S. National Radio Astronomy Observatory	PPP	Precise Point Positioning
ns	nanosecond(s)	PSD	post-seismic deformation
NSOAS	National Satellite Ocean Application Service	QC	quality control
NTP	Network Time Protocol	QCB	Quality Control Board
OAM	Oceanic Angular Momentum	QSO	Quasi-Stellar Object [quasar]
Obs.	Observatory, Observatoire, Observatório	RA	right ascension
OC	Organizing Committee	RAEGE	Red Atlantica de Estaciones Geodinamicas y Espaciales
		RF	Reference Frame
		RINEX	Receiver INdependent EXchange format
		rms	Root Mean Square
		RMS	Root Mean Square

RMS3D	RMS in three dimensions	SME	Standard-Model Extension
RT	real-time	SNAP	SuperNova Acceleration Probe
RT-AC	RT Analysis Center	SOFA	Standards Of Fundamental Astronomy
RT-CC	RT Combination Center	SOKENDAI	Graduate University for Advanced Studies
RTCM	Radio Technical Commission for Maritime Services	SP	SP Technical Research Institute of Sweden [SP Sveriges Tekniska Forskningsinstitut; formerly Statens Provningsanstalt]
RTS	IGS Real-Time Service	SPOT	Satellite Pour l'Observation de la Terre
SAA	South Atlantic Anomaly	SSALTO	Segment Sol multi-mission d'ALTimétrie, d'Orbitographie et de localisation précise
SARAL	Satellite with ARGOS and ALTIKA	SSEM	Station Systematic Error Monitoring
Sat.	satellite	SVN	Apache Subversion [repository]
SB	Special Bureau	SWOT	Surface Water Ocean Topography [mission]
SBA	Special Bureau for the Atmosphere	SyrTE	Systèmes de Référence Temps-Espace [department]
SBCP	Special Bureau for Combined Products / Special Bureau for the Combination Products	SYRTE	Systèmes de Référence Temps-Espace [department]
SBH	Special Bureau for Hydrology	T2L2	Time Transfer by Laser Link
SBO	Special Bureau for the Oceans	TAI	Temps Atomique International (International Atomic Time)
SDev	standard deviation	TAROT	Télescopes à $\frac{1}{2}$ Action Rapide pour les Objets Transitoires
SDSS	Sloan Digital Sky Survey	Tb	terabyte
sec	second(s) [of time]	TC	Technique Centre
SERC	STEM [Science, Technology, Engineering and Mathematics] Education Research Centre, University of Canberra	TEC	Total Electron Content (Total Electron Count), total electron content
SGP	Space Geodesy Project	TECU	TEC Unit
SGSLR	Space Geodesy SLR [system]	TGAS	Tycho Gaia Astrometric Solution
SI	Système International (International System of Units)		
SIC	Satellite Identification Code		
SINEX	Solution (Software/technique) INdependent EXchange Format		
SLR	Satellite Laser Ranging		

TIGO	Transportable Integrated Geodetic Observatory	USNO	United States Naval Observatory
TIO	terrestrial intermediate origin	USO	Ultra Stable Oscillator
TJO	Telescopi Joan Oró	UT	University of Texas
TLS	terrestrial laser scanning	UT	Universal Time
TN	IERS Technical Note	UT0	Universal Time
ToR	Terms of Reference	UT1	Universal Time
TRF	Terrestrial Reference Frame	UTAAM	NCEP [or NOAA] AAM analysis and forecast data
TT	Terrestrial Time	UTC	Coordinated Universal Time
TU	Technical University	UTGPS	Universal Time-like quantity using Global Position System
TUM	Technische Universität München (Technical University of Munich)	VCS	VLBA Calibrator Survey
TWS	terrestrial water storage	VGOS	VLBI Global Observing System
TX	Texas, USA	VLBA	Very Long Baseline Array, NRAO
U	Up [position/coordinate/direction]	VLBI	Very Long Baseline Interferometry
UAW	GGOS Unified Analysis Workshop	VM	virtual machine
UBAD	USNO Bright-Star Astrometric Database	VTs	[Gaia] Validation Test Specification
UCL	University College London	VTs	Visualization Tool for Space Data
UK	United Kingdom	w.r.t.	with respect to
UKMO	U.K. Meteorological Office	WDS	ICSU World Data System
UMBC	University of Maryland, Baltimore County	WG	working group
UN	United Nations	WISE	Wide-field Infrared Survey Explorer
UNAVCO	University Navstar Consortium	WRMS	Weighted Root Mean Square
UNB	University of New Brunswick	wrms	Weighted Root Mean Square
UPC	URAT Parallax Catalog	XML	eXtensible Markup Language
URAT	USNO Robotic Astrometric Telescope	yr	year
URL	Uniform Resource Locator	ZA	South Africa
US	United States	ZPD	zenith path delay