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

# IERS
# Annual Report
# 2015

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IERS Annual Report 2015

Edited by Wolfgang R. Dick and Daniela Thaller

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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# Table of Contents

Appendices

# 1 Foreword

The release of the International Terrestrial Reference Frame 2014 (ITRF2014) is an important contribution to the operational and scientific communities. This new realization of the terrestrial reference frame (TRF) is a natural follow on to the ITRF2008, but incorporates two new features. First, annual and semiannual terms were determined for certain sites. Second, post-seismic deformation models were calculated for specific sites. These new features along with increased data, local ties, and improved modeling should provide an improved product for IERS users. Efforts to document the ITRF2014 will culminate in the release of an IERS Technical Note providing not only the descriptive and analytical details of the ITRF2014, but also comparisons with results from other ITRS Combination Centres.

The IERS announced and implemented the leap second that occurred on 30 June 2015. Software in the IERS Conventions was changed to account for the additional leap second.

The International Astronomical Union (IAU), International Association of Geodesy (IAG), and the IERS will be co-sponsoring the symposium "Geodesy, Astronomy, and Geophysics in Earth Rotation (GAGER2016)". The symposium will be held 18–23 July 2016 in Wuhan, Hubei, China. For more information, see http://main.sgg.whu.edu.cn/gager2016/.

A number of personnel changes in the IERS Directing Board occurred in 2015 (and into 2016):

- Christian Bizouard replaced the retiring Daniel Gambis as the Director of the Earth Orientation Centre.
- Jean-Paul Boy replaced Tonie van Dam as the Director of the Global Geophysical Fluids Center
- Bryan Dorland was named as USNO's permanent co-director of the ICRS Center.
- Nick Stamatakos replaced me as USNO's co-Director for the Conventions Center.
- Rolf Dach and Chuck Meertens were named the International GNSS Service (IGS) representatives, replacing Tim Springer and Steven Fisher.
- Ludwig Combrinck replaced Jürgen Müller as one of the International Laser Ranging Service (ILRS) representatives.
- Hugues Capdeville replaced Frank Lemoine as one of the International DORIS Service (IDS) representatives.
- Axel Nothnagel replaced Clark Wilson as the IAG/IUGG representative.

*Brian Luzum*
*Chair, IERS Directing Board, 2015*

# 2 The IERS
## 2.1 Structure

From 2015 to 2016, 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 2015 and beginning of 2017.

### 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*:
Bob E. Schutz † (until 6 June 2015),
Daniela Thaller (since 16 July 2015)

**International VLBI Service (IVS)**
*IVS Representatives to the IERS Directing Board*:
Chopo Ma, Rüdiger Haas
*IERS Representative to the IVS Directing Board*: Chopo Ma

**International DORIS Service (IDS)**
*IDS representatives to the IERS*:
Jérôme Saunier, Hugues Capdeville (since 1 January 2015)
*IERS Representative to the IDS Governing Board:*
Brian J. Luzum

### Product Centres

**Earth Orientation Centre**
*Primary scientist and representative to the IERS Directing Board*: Daniel Gambis (until 31 August 2015),
Christian Bizouard (since 1 September 2015)

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

**Conventions Centre**
*Primary scientists*: Brian J. Luzum (until 31 Dec. 2015),
Gérard Petit (until 31 Aug. 2016),
Nick Stamatakos (since 1 Jan. 2016),
Christian Bizouard (since 1 Sep. 2016)
*Representative to the IERS Directing Board*:
Brian J. Luzum (until 31 Dec. 2015), Gérard Petit (1 Jan. 2016 to 31 Aug. 2016), Christian Bizouard (since 1 Sep. 2016)

**ICRS Centre**
*Primary scientists*: Jean Souchay,
Bryan Dorland (since 14 Sep. 2015)
*Current representative to the IERS Directing Board*:
Bryan Dorland (14 Sep. 2015 to 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 1 January 2017*)

## 2.2 Directing Board

In 2015 to 2017, the IERS Directing Board had the following members (for addresses see Appendix 2):

| | |
|---|---|
| Chair | Brian J. Luzum |
| Analysis Coordinator | Thomas Herring |
| *Product Centres Representatives* | |
| Earth Orientation Centre | Daniel Gambis (until 31 August 2015),<br>Christian Bizouard (since 1 September 2015) |
| Rapid Service/Prediction Centre | Christine Hackman |
| Conventions Centre | Brian J. Luzum (until 31 Dec. 2015), Gérard Petit (1 Jan. 2016 to 31 Aug. 2016), Christian Bizouard (since 1 Sep. 2016) |
| ICRS Centre | Bryan Dorland (14 Sep. 2015 to 31 Dec. 2016),<br>Jean Souchay (since 1 Jan. 2017) |
| ITRS Centre | Zuheir Altamimi |
| Global Geophysical Fluids Centre | Tonie van Dam (until Feb. 2016),<br>Jean-Paul Boy (since Feb. 2016) |
| Central Bureau | Daniela Thaller |
| *Technique Centers Representatives* | |
| 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,<br>Rüdiger Haas |
| IDS | Jérôme Saunier,<br>Hugues Capdeville (since 1 January 2015) |
| *Union Representatives* | |
| IAU | Aleksander Brzezinski |
| IAG / IUGG | Clark R. Wilson (until June 2015),<br>Axel Nothnagel (since July 2015) |
| GGOS | Bernd Richter |

## 2.3 Associate Members

Abbondanza, Claudio
Angermann, Detlef
Arias, Elisa Felicitas
Behrend, Dirk
Bergstrand, Sten
Bianco, Giuseppe
Bloßfeld, Mathis
Boucher, Claude
Bruyninx, Carine
Capitaine, Nicole
Carter, William E.
Chao, Benjamin F.
Chen, Jianli
Chin, Mike
Collilieux, Xavier
Dawson, John
Dorland, Bryan
Fisher, Steven
Gambis, Daniel
Garayt, Bruno
Gaume, Ralph A.
Gipson, John
Gross, Richard S.
Heflin, Mike
Hugentobler, Urs
Johnston, Gary
Lambert , Sébastien
Lemoine, Frank
Lemoine, Jean-Michel
Lestrade, Jean-François
Luceri, Vincenza
McCarthy, Dennis D.
Métivier, Laurent
Moore, Angelyn W.
Müller, Jürgen
Neilan, Ruth E.
Noomen, Ron
Pearlman, Michael R.
Petit, Gérard
Ray, Jim
Rebischung, Paul
Reigber, Christoph
Richard, Jean-Yves
Rothacher, Markus
Salstein, David
Shelus, Peter J.
Seitz, Manuela
Soudarin, Laurent
Springer, Tim
Stamatakos, Nick
van Dam, Tonie
Veillet, Christian
Vondrák, Jan
Weber, Robert
Willis, Pascal
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
President of IAU Commission A3: Hohenkerk, Catherine Y.

(*Status as of 1 January 2017*)

# 3 Reports of IERS components

## 3.1 Directing Board

The IERS Directing Board (DB) met twice in the course of the year 2015. Summaries of these meetings are given below.

### Meeting No. 60

April 12, 2015, 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 #59 were distributed together with the agenda of DB Meeting #60.

**Re-election of AC**

Tom Herring was re-elected as IERS Analysis Coordinator for one additional term (4 years).

**Changes in IERS Terms of Reference**

The email voting on the IERS Terms of Reference (ToR) regarding the IERS Chair was successfully finished in March. The proposed change was accepted. The ToR on the website were updated accordingly.

The list of IERS Associate Members will be updated every year and distributed to the DB members for review/confirmation at the December DB meeting.

DB members may send one proxy, but the current ToR are not clear whether this person has the right to vote. A proposal for changing the ToR will be sent out after the DB meeting.

*New Action Item*:

#60.01 Set up voting for change in ToR regarding proxies.

**Reports from the Technique Centres**

***International DORIS Service (IDS)***

Jean-Michel summarized IDS activities:

- DORIS constellation status: SPOT-5 changed to lower orbit; future missions: Jason-3 launch postponed to July 2015, Sentinel-3A/-3B in 2015/2017; network evolution: new stations in Owenga (New Zealand) and Goldstone, reconnaissance at Wettzell (Germany).
- Analysis Update:
  - 6 active ACs (5 different software packages).
  - Contribution to ITRF2014: extension of DORIS data until September 6, 2014 (no more data for 2014 due to data and models latencies); combined solution delivered on February 27, 2015.

  - IDS ACs process the DORIS data in the RINEX format.
  - DORIS Special Issue (Adv. Space Research) in preparation.
- Scale offset increase w.r.t. ITRF2008 starting mid 2012 (will be investigated).
- Next meetings: IDS AWG May 28-29, 2015, Toulouse, IDS AWG in October 2015 probably in the US.

***International GNSS Service (IGS)***

Urs Hugentobler reported on IGS activities:

- New Governing Board chair is Gary Johnston, currently no ACC, probably no combination in the future, but AC solutions.
- Network of >120 stations, 6 ACs; transition to RINEX 3.
- ITRF2014 contribution:
  - Contributions from 7 operational ACs + 2 TIGA ACs; combined SINEX files delivered on February 27, 2015.
  - AC-specific features in station position residuals noticed.
  - Offsets and rates in the combined geocentre time series w.r.t. IGb08 found.
- Workshop on geodetic metadata planned for August this year.
- Next IGS Workshop in February 2016 in Sydney, Australia.

***International Laser Ranging Service (ILRS)***

Cinzia Luceri gave a report about the ILRS activities:

- Network: new Russian station Irkutsk validated; Mendeleevo 2 re-validated; new Wettzell SLR system will undergo validation soon. Still few stations in the southern hemisphere.
- Missions: 4$^{th}$ Indian GNSS s/c IRNSS-1D successfully launched on March 28, 2015.
- Space Debris study group has been established.
- Main LLR activities: IfE LLR solution for ITRF2013 submitted (for testing purposes only); Simulation of new LLR sites in progress; Studies on combined use of LLR, GRAIL and LRO data continue.
- Analysis: 8 operational AC/CCs; 8 ACs and 2 CCs contributed to ITRF2014; AC weighting factor peculiarities found (2 groups of factors); discontinuity in scale found around the year 2011.
- ILRSA v61 official ILRS contribution delivered in late February 2015 (another solution of the backup CC).
- Recent meetings: 19$^{th}$ Int. Laser Workshop and AWG meeting in Annapolis in October 2014.
- Future meetings:
  - Technical Workshop in Matera, Italy, October 25–30, 2015.
  - 20$^{th}$ Int. Workshop on Laser Ranging in 2016 in Potsdam, Germany.

- Next AWG meeting scheduled Saturday before the Matera Workshop week.

***International VLBI Service for Geodesy and Astrometry (IVS)***

Chopo Ma reported on the latest IVS activities:

- IVS ITRF2014 input: 11 ACs submitted a contribution, 9 ACs finally included in combined solution; Inconsistencies in variance factors found and corrected; Combined solution submitted in February 2015.
- VGOS (VLBI Global Observing System): small and agile telescopes with large bandwidth (2–14 GHz), allowing a denser sampling of the atmosphere.
- Network: multiple new stations with new receiver technology; new station Ishioka, Japan, RAEGE project: RAEGYEB in Yebes, Spain, already working and RAEGSMAR in Santa Maria, Azores, inauguration in May 2015. TIGO in Chile was closed in April and will be moved to Argentina, becoming AGGO.
- Next meetings: EVGA on the Azores in May 2015; Technical workshop in June in Robledo, Spain; 4$^{th}$ Int. VLBI Technology Workshop in November 2015 in Auckland, New Zealand.

**ITRS/ITRF**

***Report from ITRS Combination Center at DGFI***

Detlef Angermann presented the status of the DGFI CC.

- DGFI is now an institute of the TU Munich.
- ITRF2014:
  - First combined solution foreseen for IUGG in Prague; VLBI, SLR and DORIS input data analysed.
  - Very good agreement of SLR and VLBI TRF2014 solution w.r.t. DTRF2008.
  - DORIS scale: jump around 2011 found.
  - GNSS discontinuities still under investigation.

***Report from ITRS Combination Center at JPL***

Richard Gross reported on recent activities at the JPL CC:

- Quality comparisons for IVS, ILRS and IDS w.r.t. the ITRF2008 contributions.
- Discontinuity files: discontinuities were identified without station or service input. An inclusion of a discontinuity file by the Services with their data submissions is suggested.
- Solution will be weekly SINEX files for station positions.

***Report from ITRS Center***

Zuheir Altamimi reported on the activities of the ITRS Centre.

- New ITRF website to be ready by end of 2015.
- Local survey: 1$^{st}$ draft of a document for local survey guidelines; prepare an IERS Technical note; operational entity should be recognized by the IERS as a fundamental component of the ITRS Center (change the ToR?).

- Status of ITRF2014:
  - All TC contributions available; all SINEX files are archived at the IERS CB server; Work on local tie SINEX files in progress.
  - Origin and Scale: SLR: offset in TY and jump in scale starting in 2010; VLBI: large scale scatter due to changing networks from one session to another.
  - Post-seismic deformations: linear function vs. parametric model.
  - Seasonal signal vs applying NATML model? Proposal: remove periodic signals (at least annual and semiannual); do not apply NATML model.
  - Provide amplitude and relaxation time for stations with post seismic deformation.
  - Schedule: end June – beginning July: first ITRF2014P solution for evaluation by the TCs; final solution in September-October (evaluated by the four Techniques Centres within one month).

The United Nations GA adopted a resolution on a Global Geodetic Reference Frame. For the first time geodesy and the global geodetic reference frame are acknowledged at the UN level. A workshop on the roadmap will take place at UN in Vienna.

In the discussion, Zuheir Altamimi pointed out that only use IGS stations with more than 2.5 years of observations are used. DOMES numbers have currently been assigned by IGN. Time series may be provided to users upon request. Richard Gross requested that discontinuity files should come along with the technique solution, and Detlef Angermann proposed to compare discontinuities between the three Combinations Centres.

*New Action Items*:

#60.02 Provide full loading model to the ITRS Combination Centres.

#60.03 Provide routine for the model with amplitude and relaxation time.

#60.04 Prepare an IERS Technical Note on local survey guidelines.

**Unified Analysis Workshop (UAW) 2014**

Tom Herring presented the recommendations and the topics from the UAW concerning the IERS.

The recommendations cover many Services and Centres of the IERS, e.g. for the following issues:

- Resolving the VLBI/SLR/DORIS scale differences:
  - Re-assessment of the relativistic formulations for VLBI and satellite based systems → Conventions Centre.

- ○ Explore possible systematic height errors from radio telescope deformations → IVS.
- ○ Explore impact of range biases on SLR height estimates and of blue sky → ILRS.
- ○ Explore antenna phase centre model for satellite receiving antennas for DORIS → IDS.

- Geophysical Fluids: deficiencies in the model of the annual and semiannual EOP variations.
- Analysis methods: time variable gravity models; solid-Earth pole tide model; impact of ocean pole tide; monument stability: list of monument site issues from the operator

Monument stability: Develop a list of monument site issues from the operators → ITRS Combination Centres.

*Decision*: DB members representing the Services should take back the recommendations to the Services.

**ICRS/ICRF and IAU Working Group**

Bryan Dorland presented the ICRF-3 status:

- ICRF-3 goals: competitive in precision with Gaia and uniform precision for all sources; extend to higher frequencies, improve southern coverage. Complete ICRF-3 by 2018.
  - ○ Status: EGSG meeting in Dec. 2014; work underway to assess radio/optical tie issues; observing underway for 100–200 strong sources using southern CRF network @ S/X bands, weaker sources to be observed from 2015 to 2017.
  - ○ VLBA Cal Survey-II underway to re-observe VCS sources.
  - ○ K-band (24 GHz) southern hemisphere observations approved for 2015.
  - ○ Comparisons of VLBI frames from various analysis groups underway.

**Report on GGOS**

Brian Luzum reported on the IERS/GGOS Meeting:

- Meeting in San Francisco as an attempt to create a better working relationship between GGOS and IERS.
- Summary:
  - ○ Successful attempt to create a better working relationship between GGOS and IERS.
  - ○ No duplication or redundancy in the work of GGOS regarding IERS (and other services).
  - ○ Improve communication and coordination between these two entities.

  - ○ IERS representatives are asked to actively contribute to the revised structure of GGOS for better support, operation and promotion.

Discussion:

- Richard Gross: IERS does not feel any advantage/no value added in branding their products with the GGOS logo. A discussion with GGOS and all IERS contributing parties is needed.
- The “GGOS2020” book helped a lot to get funding.
- How to take advantage of the UN-GGIM resolution?
- IERS and GGOS are partners; but this relationship is not practiced at the moment.
- IERS is “coordinating” geometric services, GGOS should coordinate with gravity services.
- Would it help to co-organize sessions at meetings (EGU, AGU, etc.)?
- Richard Gross: UAW will be in future co-organized between IERS and GGOS (head of science panel).
- Open question: How can GGOS add some value to the already existing IERS products?

**Earth orientation products**

***Report from Earth Orientation Centre***

Daniel Gambis reported on the activities of the Earth Orientation Centre:

- Conventional Mean Pole:
  - ○ Need to adopt a mean pole for geodynamic applications.
  - ○ A conventional mean pole (CMP) model is provided by the IERS Conventions.
  - ○ Preparation of IERS Conventions 2013: list of mean pole values; modelling is an open question.
- IAU Working Group recommendations: 4 developments
  1. ASCII “Leap second file” available.
  2. EOP data available in XML format, ftp hpiers.obspm.fr.
  3. Leap second Web service.
  4. Secure protocol (via NTP) to give information on leap second announcements for server synchronization: Need of authoritative source for leap second announcement for NTP servers synchronization.

Inform (via IERS message) users about the existence of the file. Modify specificities of the NTP protocol to indicate that the file is available at the Earth Orientation Centre and no longer at NIST.

Daniel Gambis reported that he would retire in September 2015; Christian Bizouard will take over his position.

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

Christine Hackman reported:

- Products 2014: values downloaded to 18025 unique IP addresses.
- e-VLBI from KPGO unavailable since June 2014 → 40% accuracy reduction in one-day UT1–UTC prediction.
- Access issues to USNO EOP servers: http access mostly restored; ftp access restoration TBD. Long-term plan: migrate services to cloud.
- Test NTP UT1 service set up at NIST.

**IERS Conventions**

Brian Luzum summarized the activities on updating the IERS Conventions:

- Additional personnel: USNO Conventions personnel now include Nick Stamatakos, Maria Davis and Dennis McCarthy.
- Open topics: Chapter 7 (conventional mean pole), Chapter 9 (models for atmospheric propagation delays), Chapter 11 (general relativistic models for propagation).
- Leap second will occur on 30 June 2015.
- Need of feedback from the community.

**Reports from the Working Groups**

***IERS Working Group on on Site Survey and Co-location***

Sten Bergstrand reported on the current activities of the WG.

- Meetings: open meeting at REFAG, closed meeting at EGU.
- The WG's main focus will be on definitions.
- An IGN guideline document will be circulated for review in 2015.
- POCs have been established with IDS, ILRS, IVS and IGS + surveyors.
- How to support/implement UAW recommendations?
- How to get local tie numbers to be published?

He presented also examples for thermal deformations of telescopes. For this height measurements using invar rod and temperature sensors in the telescope's foundation were carried out.

***IERS Working Group on Combination at the Observation Level (COL)***

Richard Biancale reported on the COL activities.

- 6 years of COL activities.
- End the activities of COL and start a new WG COL 2 with new goals and participants.
- Proposal to focus combination efforts to satellite data only (DORIS, GNSS, SLR) and to check the impact of multi-technique platforms.
- Proposal to renew the COL-WG in preparation to new projects such as GRASP.
- A final WG meeting is expected after the ITRF2014 will be ready.

***IERS Working Group on SINEX Format***

Daniela Thaller reported on the activities of the WG on SINEX Format.

- VLBI: A. Nothnagel and Z. Malkin are working on a block to specify the quality of the radio source positions.
- Multi-GNSS: Galileo activities requested satellite antenna PCO with multi-frequencies, clearly defining the offsets.

***IERS Working Group on Time Series Format***

A splinter meeting will take place on Wednesday evening for discussing the next steps.

**Annual Reports**

Daniela Thaller gave an overview on the status of the Annual Report 2014. The deadline was end of March, as of now 6 contributions have been received.

**Next DB Meeting**

The next DB meeting will take place before the AGU meeting on Sunday, December 14, 2014 in San Francisco.

*New Action Item*:

#58.05 Prepare DB meeting #61.

## Meeting No. 61

December 13, 2015, Hotel Marriott Marquis, 780 Mission Street, San Francisco, USA

**Introduction and approval of agenda**

The agenda was accepted. Daniela Thaller welcomed the guests and the members of the IERS Directing Board and informed the IERS DB that Brian Luzum cannot participate in the meeting.

**Action Items of previous DB meetings**

59.01 The successor of R. Gaume as representative for the ICRS Centre is appointed: Bryan Dorland

59.03 Study S1/S2 issues: J.-P. Boy reported that studies are done; a report will come up soon.

60.01 Voting for changes in ToR has been done.

60.02 Full loading model for the ITRF2014 station list has been provided by T. van Dam to the ITRS Combination Centers.

60.03 Z. Altamimi has provided a routine for the model with amplitude and relaxation time for non-linear station motions.

60.06 Prepare DB meeting #61: done

**Changes in IERS Directing Board**

The new IAG/IUGG representative is Axel Nothnagel, replacing C. Wilson. The new IERS DB member representing the Earth Orientation Centre is Christian Bizouard, replacing D. Gambis. The new IERS DB member representing the ICRS Centre is Bryan Dorland, replacing R. Gaume.

**Associate Members**

A list of IERS Associate Members has been distributed by the CB in advance. The DB discussed the list of Associates and their rights regarding access to the minutes of IERS DB meetings.

*Decisions*:

More people working within IERS components should be added as IERS Associate Members. The minutes of each DB meeting first have to be approved by the IERS DB members before the IERS Associate Members will get access to them.

*New Action Item*:

61.01 Add persons from IERS components to list of IERS Associate Members

**Report on GGOS and GGOS Days**

Daniela Thaller gave the report prepared by Hansjörg Kutterer on the GGOS Days:

- The designation process for GGOS Consortium has been completed: IERS Representatives are T. Herring and D. Thaller.
- The GGOS Coordinating Office is still vacant; applications are possible until the end of January.

- GGOS Days were held in Frankfurt am Main on October 21–23 with a review of implementation plans and the initiation of an IAG position paper on GGRF (Global Geodetic Reference Frame).

The IERS DB discussed that with the new functionaries within GGOS, the relation between GGOS and the IERS seems to be weaker than before. Now, the gravity community is stronger involved in order to fulfill the GGOS goal to improve the connection with gravity.

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

Axel Nothnagel reported about the developments in the ICRF-3 Working Group:

- Patrick Charlot took over the working group chair in July 2015.
- The WG seems to be only an IAU activity at the moment.

The IERS DB discussed that it will be important to establish a connection between IAU and IAG/IERS in order to be sure that radio wavelengths are considered in ICRF-3. Axel Nothnagel will discuss with P. Charlot the possibility to establish a joint IAG/IAU working group (as in the past).

*New Action Item*:

61.02 Work for a joint IAG/IAU Working Group on ICRF-3

**ITRF2014 including update of EOP series**

***Report from ITRS Center***

Zuheir Altamimi presented the status:

- Main issue: implementation of PSD function for non-linear station motions; the PSD model was estimated from GNSS time series and then applied to co-located VLBI, SLR and DORIS sites; no PSD model for non-GNSS sites if no co-location.
- A minor but important impact is seen on polar motion (1–3 mm): requires a re-iteration of the solution.
- Estimating seasonal signals performs better than applying atmospheric loading (see discussion in Vienna 2015); but not estimated for most of VLBI/SLR sites due to sparse time series.
- Estimated seasonal signals can be provided to interested users (but only on request).
- Final solution will be ready by January 2016.

***Report from ITRS Combination Center at DGFI***

Mathis Blossfeld reported on the status of the ITRS CC at DGFI.

- First solution ready and distributed to Technique Centres for validation.
- Loading is corrected for atmosphere and hydrology (no oceans due to short time series).

- LOD is combined (different to the IGN approach where LOD is VLBI-only).
- A 13.65-day signal is visible in LOD when comparing to C04 (reason in C04 series?)
- The inter-comparison with the IGN solution is foreseen after publication of ITRF.

***Report from ITRS Combination Center at JPL***

Richard Gross gave an overview on the CC work at JPL:

- VLBI regional sessions are removed, as well as stations shorter than 2.5y.
- All local ties are used, but with different weighting.
- Combined scale is closer to VLBI than to SLR.
- Result: Time series of 1838 weekly SINEX files; backward prediction is included (based on linear + seasonal model).
- Few refinements are needed; final solution to be ready by end of January 2016.
- Operational updates are foreseen, depending on users' demand.

***Report from Earth Orientation Center on updating C04***

Christian Bizouard presented this report.

- Updates of C04 are available as soon as ITRF2014 is officially available.
  - Discussion: coordinate update with Bulletin A and Technique Centres.
- Nutation is now directly combined for dX / dY (not dEps / dPsi).
- Increase of formal uncertainties of Nutation and UT since 2005 visible.
  - Discussion: Are similar effects seen in IVS solutions?
- Question: Are dEps / dPsi still needed?
  - Discussion: Yes, they are needed (old flight missions; geophysical interpretation).

*Decisions*:

Two IERS Technical Notes have to be prepared:

- ITRF solutions (IGN, DGFI, JPL)
- Contributions and validations by the techniques (to be coordinated by the Technique Analysis Coordinators)

Nutation series dEps / dPsi should be maintained.

*New Action Items*:

61.03 Prepare two IERS Technical Notes on ITRF2014

61.04 Coordinate update of EOP series C04 and Bulletin A

**Reports from the Technique Centres**

***International DORIS Service (IDS)***

Hugues Capdeville presented the IDS report:

- Altogether 7 DORIS sites with post-seismic model in ITRF2014.
- Proposal to provide PSD corrections in XYZ and NEU.

***International GNSS Service (IGS)***

Paul Rebischung reported on IGS activities:

- Residuals for station positions increased in recent years due to antenna phase centers of new GNSS satellites.
- JPL and GFZ were the only ACs answering the request of validating the preliminary ITRF2014 solution; none of both ACs saw any major problems.

***International Laser Ranging Service (ILRS)***

Erricos Pavlis presented the ILRS report:

- A technical workshop was held in Matera, Italy in October 2015.
- Intensive discussions at the Matera workshop on the preliminary ITRF2014 solution; several issues were discovered and a re-iteration for the discontinuities had to be done.
- Arequipa does not fit well from the ITRF2014 series with the ILRS series, but better than ITRF2008.
- The evaluation of ITRF is still going on, with a 2009–2014 re-analysis by all ACs.
- Next AWG meeting is scheduled during the EGU 2016 week.

***International VLBI Service for Geodesy and Astrometry (IVS)***

Chopo Ma reported on the latest IVS activities:

- 4 groups submitted validations for ITRF2014P (GFZ, Uni Bonn, GSFC, SHAO).
- ITRF2014P does not exhibit any significant errors relative to ITRF2008.
- The new PSD model generally shows good agreement with VLBI position time series.
- There are EOP rate differences between solutions applying ITRF2014P and ITRF2008 that need further work to understand.

**Optimal strategy for TRF**

Tom Herring presented some thoughts on non-linear modelling of station positions:

- Exponential function will approach linear model within few years, but logarithmic function will take several 100 years to approach linear model.
- Sites in regions of earthquakes do not all have parameterizations in ITRF2014P – something to be careful of as sites are added.

- Remaining issues with annual terms not provided with ITRF2014: they are propagating into EOPs (as seen from DGFI presentation, approx. 10 micro-arcsec).

*Decision*: Keep annual signals only “on request”.

**IERS Annual Reports**

Daniela Thaller informed about the status of IERS Annual Report 2014: The IGS contribution is still missing, all other have been received.

*Decision*: Publish IERS AR 2014 after DB meeting, independent of availability of IGS contribution.

**IAG Service Assessment**

Daniela Thaller reported that IAG sent back comments on the IERS spreadsheet. It is not clear how the IERS should continue.

Due to a lack of time, the discussion was postponed to the next IERS DB meeting in Vienna. The CB will distribute the assessment summary to all DB members.

*New Action Item*:

61.05 Distribute summary of IAG Service Assessment to DB

**UN-GGIM GGRF resolution (Global Geodetic Reference Frame)**

Zuheir Altamimi reported on the UN-GGIM Resolution on the Global Geodetic Reference Frame (GGRF):

- Key points are development and sustainability of the GGRF, enhancement of global cooperation, sharing of geodetic data, standards and conventions, outreach programs, and commitments to improve and maintain national geodetic infrastructure.
- A roadmap is currently developed.
- The GGRF contains not only the terrestrial reference frame (like ITRF) but also the geodetic networks, data holdings, analysis / combination centres, gravimetric products, height systems, the ICRF and EOPs.

*Discussion*: The IERS with its products are highly involved by the GGRF. Therefore, the roadmap should be distributed as soon as it is finalized.

*New Action Item*:

61.06 Distribute GGRF Roadmap within IERS DB

**Symposium on Earth Rotation 2016**

Richard Gross provided information on the joint IAU / IAG / IERS Symposium:

- July 18 – 23, 2016 in Wuhan / China
- A website is available: <http://main.sgg.whu.edu.cn/gager2016/>
- Abstract deadline is April 30, 2016

Richard Gross also proposed to held a special conference for the centennial anniversary of IAU and IAU Commission A2 (Rotation of the Earth) on July 28, 2019. The IERS DB agrees with this proposal.

**Other reports**

***GGFC***

Jean-Paul Boy reported that a half-day meeting of the GGFC was held in Vienna during EGU 2015. After this meeting, all models became “official”.

***IERS Working Group on Combination at the Observation Level***

Daniela Thaller reported on behalf of Richard Biancale the idea that the COL working group (enlarged with other persons) should prepare a proposal for ESA’s call on Earth Explorer 9 missions, with a European GRASP-like mission. The Letter of Intent need to be submitted by February 1st, 2016, the proposal in June 2016.

The IERS DB underlines the importance of having a GRASP-like mission.

*Decision*: The WG COL should work for proposing a European GRASP mission.

**Next IERS DB Meeting**

The next DB meeting will be an all-day meeting and will take place on Sunday, April 17, 2016 before the EGU meeting.

*New Action Item*:

#61.07 Prepare next DB meeting 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. 60, April 12, 2015, at Technical University of Vienna, Austria, and No. 61, December 13, 2015, 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: European Geosciences Union General Assembly 2015, ISO TC211 Meeting, IUGG XXVI General Assembly, XXIXth IAU General Assembly, ILRS Technical Workshop, GGOS Days, and AGU 2015 Fall Meeting. For the GGOS Geodetic Metadata Workshop a presentation on metadata of IERS products was prepared together with Allison Craddock, who presented it.

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 2015 the web site was continually updated, several new pages and documents were added. New pages include a compilation of IERS' relations to other organizations and a text on “The Foundation Phase and Establishment of the International Latitude Service at the end of the 19th Century”, written by a historian of science for IERS. 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.

IERS Annual Report 2013 was printed and distributed. The IERS Annual Report 2014 was edited and published online in December 2015. Along with the reports of the IERS components, provided by them, the annual reports contain general information on the IERS compiled by the CB. For both reports, the CB provided also summaries of DB meetings and its own reports.

Reports about the activities of the IERS in the period from 2011/12 to 2015 were compiled for IAG and IAU in cooperation with members of the DB.

During the year 2015, 23 IERS Messages (Nos. 264–286) 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 2500 users in 2015 with valid addresses who subscribed to IERS publications for e-mail and regular mail distribution. The development of a new system of address management was finished.

Questions from IERS users concerning IERS publications and products as well as Earth rotation and reference frames in general were answered or forwarded to other specialists. The major activity with regard to public relations was related to the leap second of June 30, 2015. A large number of interviews on leap second questions were given for newspapers as well as radio and TV stations during the first half of the year.

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. 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, and is a member of the ISO project 19161 “Geodetic references”.

## 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 2015 further developments of the IERS DIS concentrated on the new system for address management and the development and improvement of interactive tools.

The development of a new system of address management in cooperation with a software company was finished in 2015 after a test phase at the end of 2014 and beginning of 2015. This system, which is related to the Content Management System used for the IERS web site, allows easier maintenance and gives access for users to register as well as to check and update their data through the IERS web pages. It allows also to send email messages and newsletters to groups of users. Address data for IERS personnel from the database is also used in dynamic IERS web pages. In February 2015, all users were informed about the new possibility to log in, to check their data and to subscribe or unsubscribe to/from distribution lists of IERS bulletins and publications. Many of them used this to update their data.

Due to new releases of the Content Management System “Government Site Builder” used for the IERS web site and the end of support for the old release, it became necessary to move to a new release in 2014. For the migrated web site and the new address management a number of improvements were introduced by CB personnel in 2015.

Several tools for visualization and analysis of IERS data and products, developed in the framework of the German research unit

“Earth Rotation and Global Dynamic Processes”, were improved and added to the IERS website. These are: Plot tool; Interactive data analysis tool; EOP of today; Timescales; EOP reader.

Further improvements of the IERS DIS included the following:

- For IERS products metadata according to ISO 19115 „Geographic Information – Metadata“ were made available at the IERS ftp server.
- A monitoring procedure for the retrieval of IERS products from external servers was created.
- The search possibility at the IERS web site was optimized.
- The newsletter function of the address management system was improved.
- For the data management system an XML schema validation was introduced and the administration interface was improved.

It became apparent that the internal processes of the data management component of the IERS DIS are in need of improvements. The requirements were formulated and a bidding procedure was initiated in December 2015.

## Staff in 2014

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

## Publications

Dick, Wolfgang; Ma, Chopo: Report of the IERS to IAU Commission 19 (2009–2012). In: Thierry Montmerle (ed.), Proceedings of the Twenty Eighth General Assembly, Beijing, China, 2012. (Transactions of the International Astronomical Union; Vol. XXVIIIB). Cambridge: Cambridge University Press, 2015, p. 99

Thaller, Daniela, Bachmann, Sabine: The IERS Retreat: How to improve Earth Rotation products? N. Capitaine (ed.), Proceedings of the Journées 2013 “Systèmes de Référence Spatio-Temporels”. Paris: Observatoire de Paris, 2015, pp. 175–180, online: http://syrte.obspm.fr/jsr/journees2013/pdf/Thaller.pdf

*Wolfgang R. Dick, Daniela Thaller, Sonja Geist*

# 3.3 Analysis Coordinator

## 1. Introduction

In this report we outline the activities of the Analysis Coordinator during 2015. The main activities were analysis of the ITRF2014 extended model presentation of post-seismic deformation after large earthquakes and a comparison of recent diurnal and semi-diurnal EOP models with the IERS Conventions (2010).

## 2. Analysis of ITRF2014 post-seismic parameterization

The ITRF2014 reference frame, as generated by IGN, contains parametric fits to earthquake post seismic motions as an alternative to the piece-wise linear functions that had been used in earlier ITRFs. Two parametric forms are used:

$$p(t) = A\left(1 - e^{-\frac{t}{T_e}}\right) \quad \text{Exponential}$$

$$p(t) = A\ln(1 + \frac{t}{T_l}) \quad \text{Logarithmic}$$

where $P(t)$ is a position evolution with time in topocentric North, East, Up direction, $T_e$ is an exponential decay time, and $T_l$ is a logarithmic decay time. One earthquake can have different combinations of exponential and logarithmic terms with different time constants and different numbers of terms between each of the topocentric components at a site. In this report we examine the long term implications of these types of models applied in ITRF2014.

We start by looking at two metrics of these models. The exponential model decays to a steady state such that after a finite duration the total residual motion remaining can be calculated. We denote $t_{1mm}$ at the duration after an earthquake until the total remaining postseismic deformation is less than 1 mm:

$$t_{1mm} = -T_e \ln(\frac{1\text{mm}}{A})$$

where the exponent amplitude is in units of mm. For the logarithmic function there is no corresponding limit (i.e., log will go to infinity as time goes to infinity) and for log decay we use the time until instantaneous velocity due to the log is less than specified amount. The log velocity is given by

$$\frac{dp(t)}{dt} = \frac{A}{\left(1 + \frac{t}{T_l}\right) T_l} \approx A/t$$

In the figures below, we show the time until the log velocity is less than 0.1 mm/yr. Our general interest is in exploring the duration of data that would need to be deleted if the post-seismic curvature terms were ignored and the earthquake was modeled as simply an offset and data processing resumed only after the post-seismic terms had “decayed” away. For many of the earthquakes that have effected GPS stations, waiting for postseismic signals to “decay away” is not a viable option.

In Figures 1 and 2 we give examples of the impact of the post-seismic motions of two GPS sites affected by large earthquakes. We see here how large these effects can be with the response at Tsukuba being large enough that the postseismic motions for all sites in this region could extend for many hundreds of years.

A large number of GPS stations in ITRF2014 are effected by post-seismic motion i.e., site with an exponential or logarithmic terms in model parameterization in ITRF2014. In all, 17% of IGS sites in ITRF2014 have at least one post-seismic term in their co-ordinate evolution. Figure 3 shows the time history of the number of GPS sites effected by earthquakes. In general, there are a few sites per year with the peak number being the Mw 9.1 Tohuko

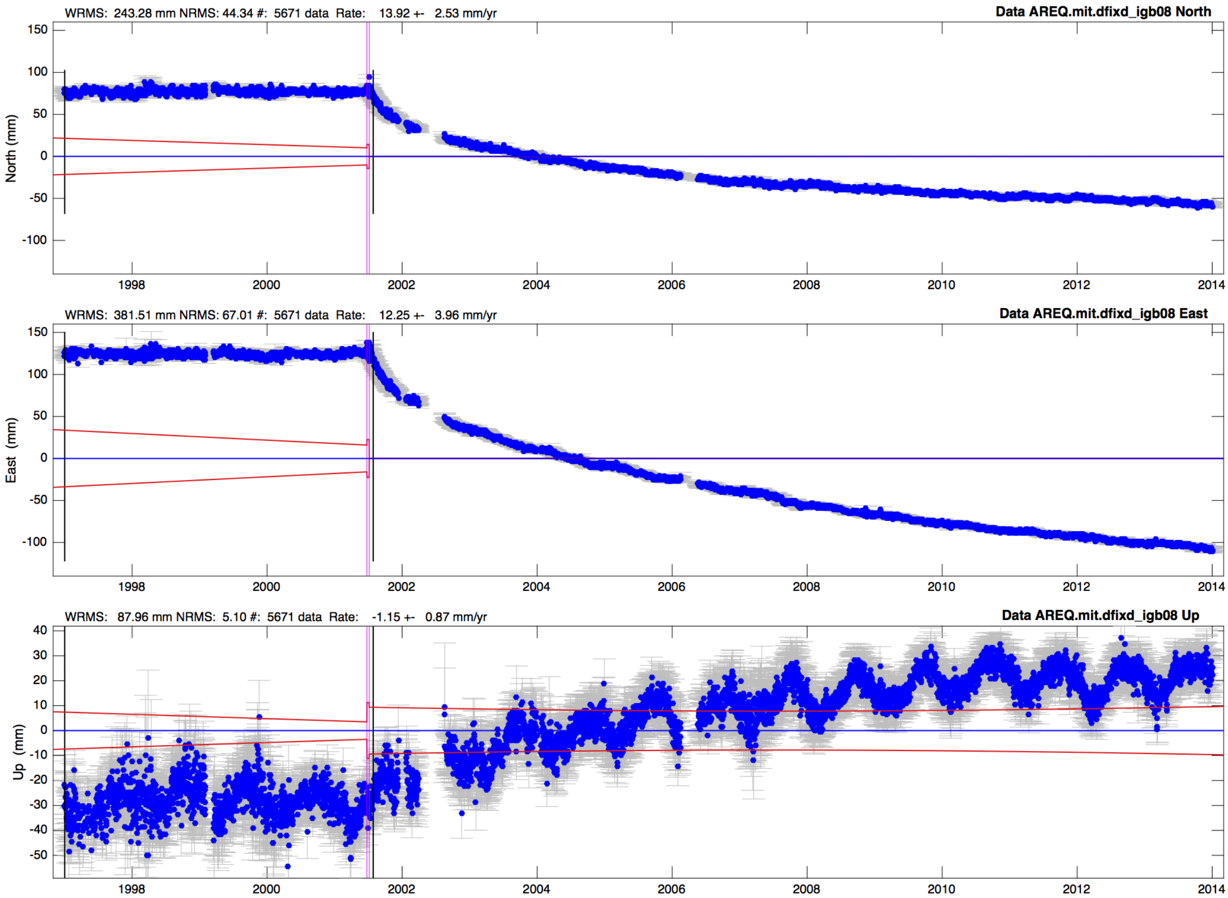



*Fig. 1: Residuals to North (top), East (middle) and Up (bottom) position estimates for AREQ (Arequipa, Peru) after removing a linear trend based on data prior to the June 23, 2001 earthquake and the coseismic offset. The post seismic motion from the June 23 and July 7 earthquakes are modeled with exponential decay terms with time constants up to 3162 days. Even a decade after the events the effects of post-seismic motion is still evident.*

earthquake in 2011 that generated postseismic motions at 17 GPS sites in the region around Japan (see Figure 5 as well).

We can summarize the effects of the postseismic terms in ITRF2014 by examining the histogram of the duration of time needed for the postseismic terms to becoming negligible. Figure 4 shows these durations based on the ITRF2014 model fits. For the exponential decay we use the time until the remaining post-seismic motion is less than 1.0 mm and for the logarithmic terms, until the instantaneous velocity contribution is less than 0.1 mm/yr (see equations above). For the exponential decay model, the duration times can reach 50 years while for the logarithmic terms the duration is much longer and can reach 2500 years (if the logarithmic is correct).

The global impact of the postseismic terms can be been in Figure 5 where the GPS network is shown (red dots) with those sites that

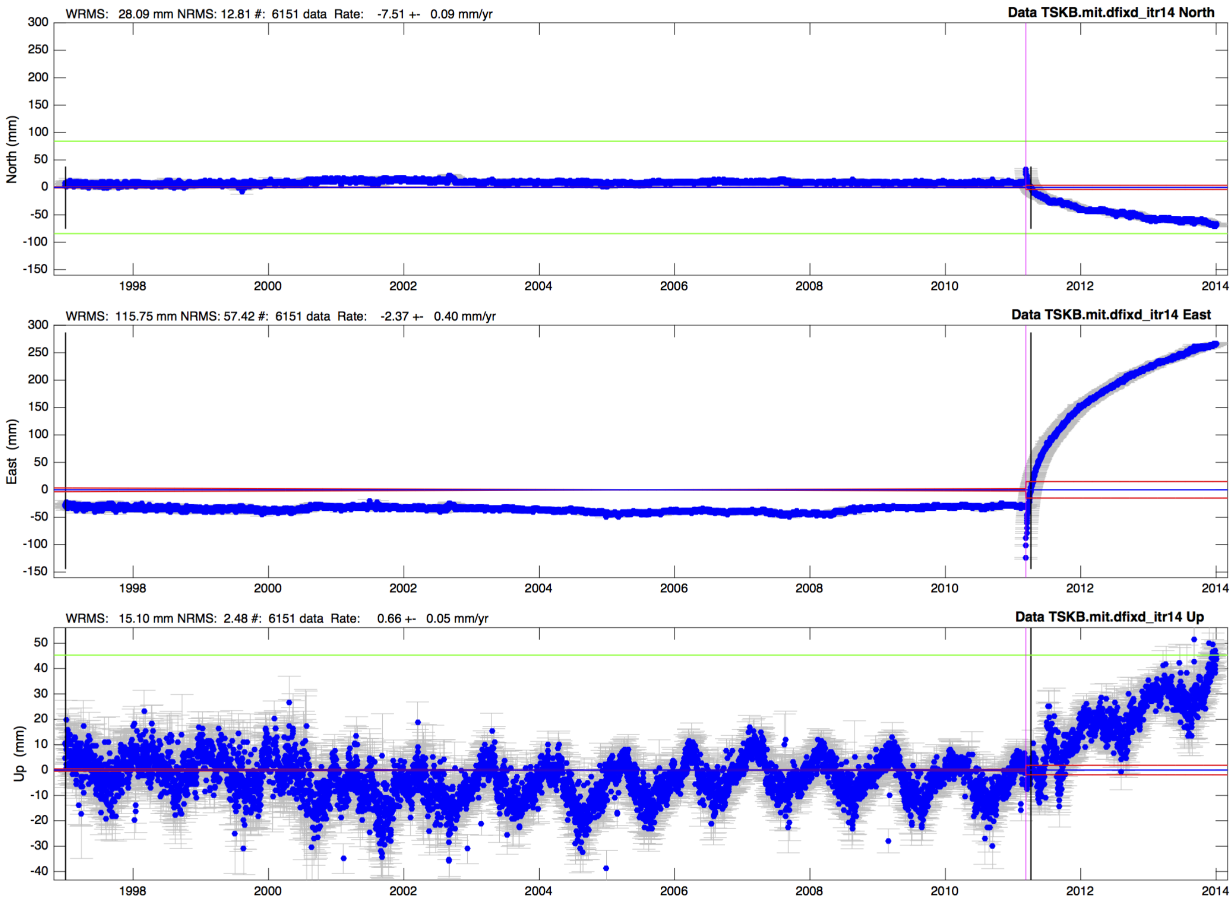



*Fig. 2: Residuals to North (top), East (middle) and Up (bottom) position estimates for TSKB (Tsukuba, Japan) after removing a linear trend based on data prior to the March 11, 2011 earthquake and the coseismic offset. The postseismic motion for this earthquake is modeled as combination of log and exponential terms. The amplitude of the log term in the estimates is such that it will be over 500 years before the east velocity returns to its pre-event rate if the log model is correct.*

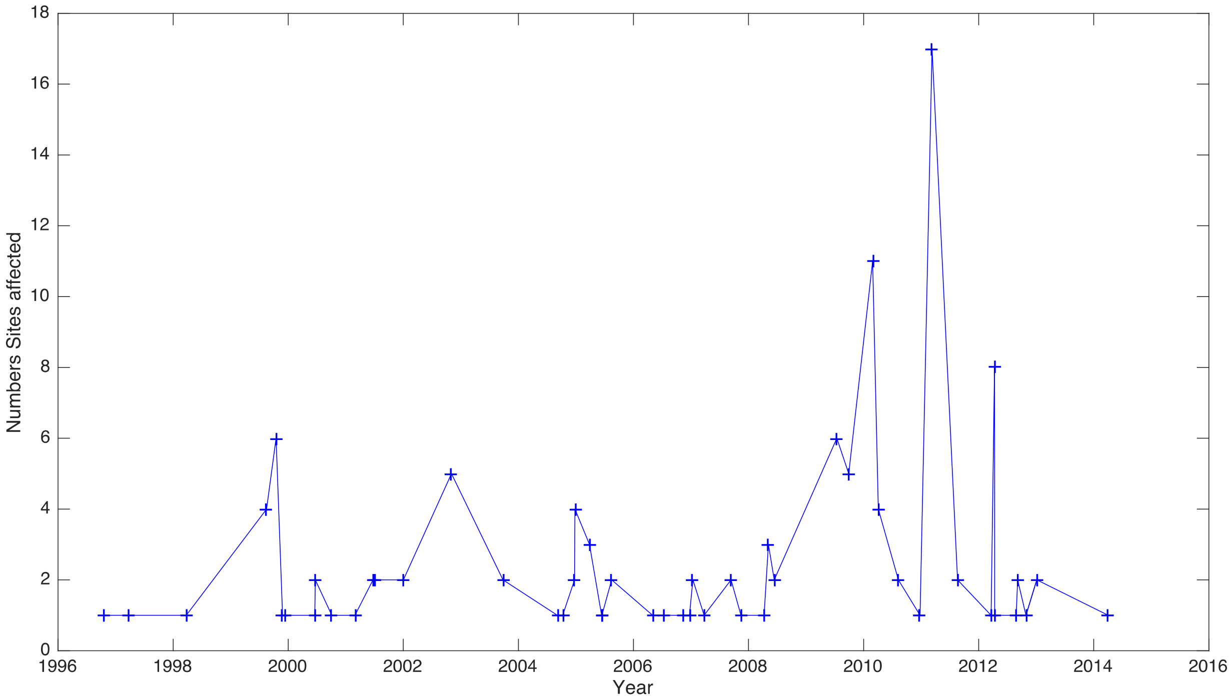



*Fig. 3: Count of the number of GPS stations with postseismic terms as a function of time. The largest event is the March 11, 2011 Tohoku magnitude 9.1 earthquake.*

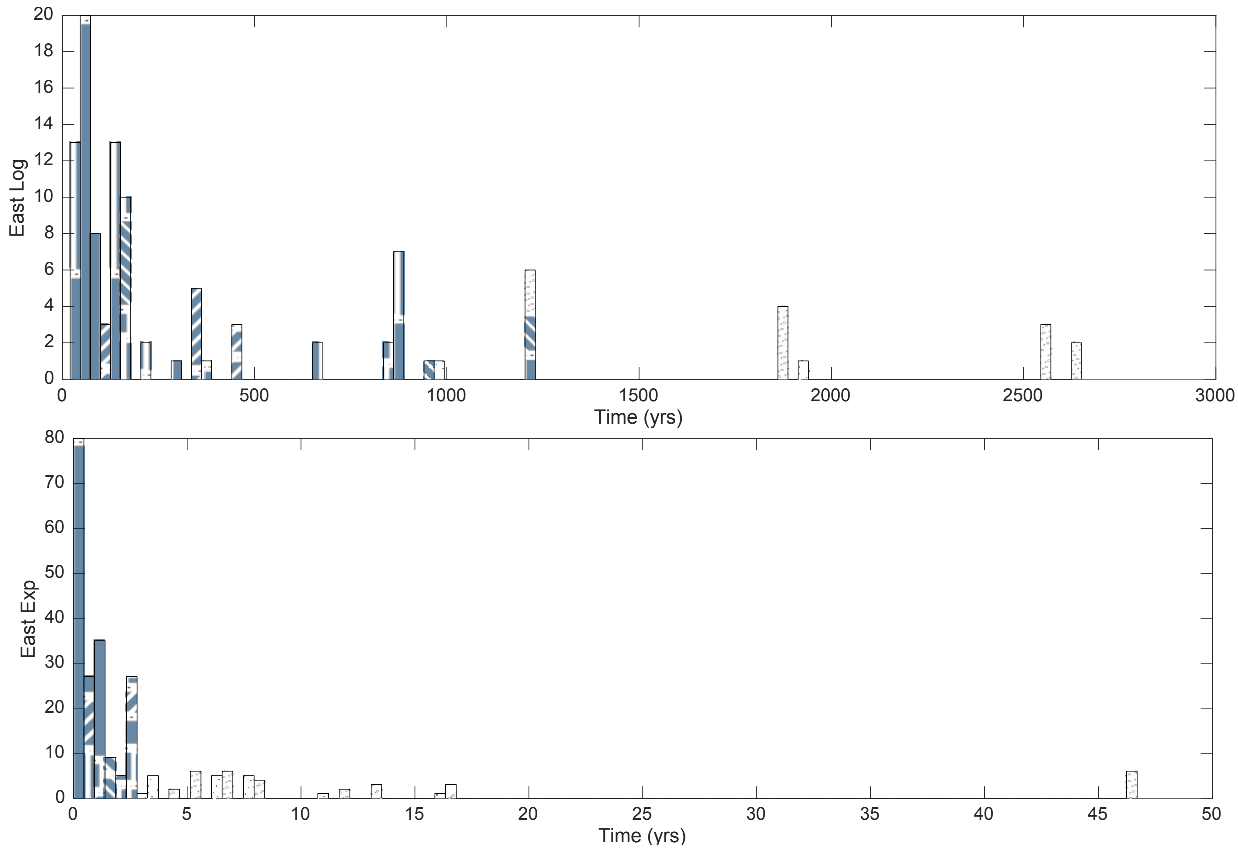



*Fig. 4: Histograms of the time intervals needed for postseismic signals to reach negligible levels (0.1 mm/yr for logarithmic and 1 mm for exponential models). The top plot is log terms in ITRF2014 and the bottom plot for exponential terms. See text for discussion.*

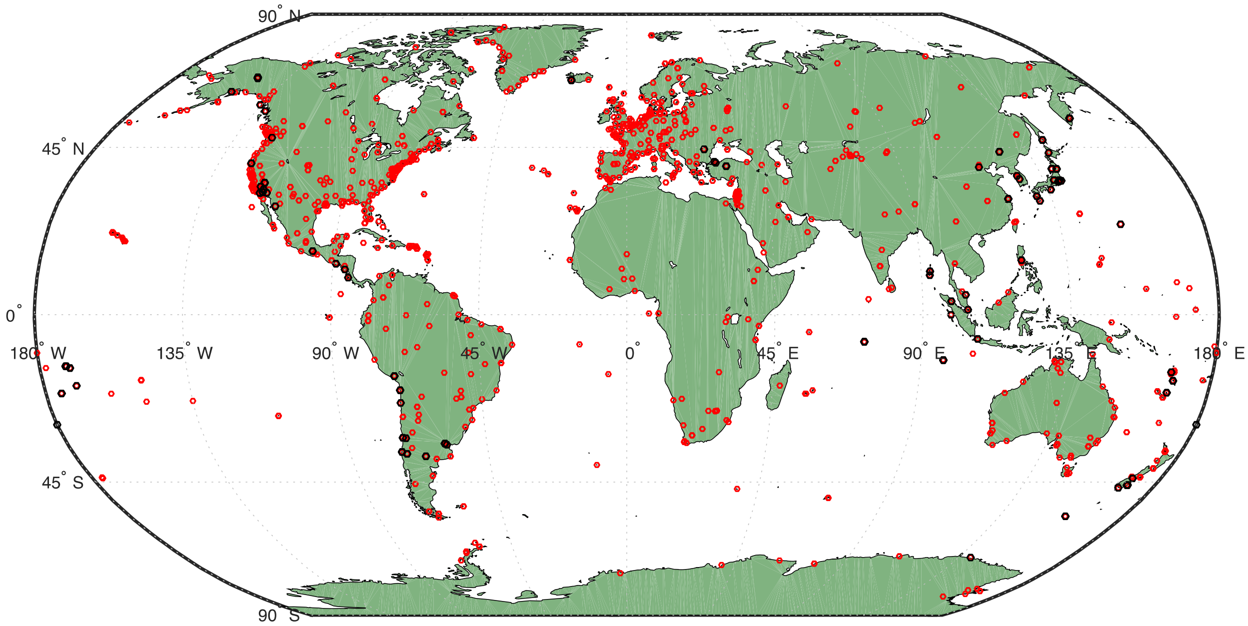



*Fig. 5: Distribution of GPS sites in ITRF2014. Red dots are GPS sites and black dots are those stations with post-seismic parameterizations. Approximately 17% of the global network needs postseismic terms.*

have post-seismic parametrizations (black). Approximately 17% of sites are affected by postseismic phenomena although this number is probably underestimated. As can be seen in the figure, there are regions of the world where red (un-affected) and black (affected) are interspersed. This occurs because red sites in these regions have no data after the earthquake(s) that results in postseismic deformation at the nearby sites. In the future, this might introduce problems if GPS sites are re-established in these regions because these sites might be undergoing significant post-seismic motions but this will not be apparent because there was no data from the site in the interval immediately after the earthquake.

## 3. Analysis of diurnal and semidiurnal EOP models

We compared several different up-to-date sub-daily EOP models with the IERS standard model (IERS 2010). The models compared are (the roman numbers are used to refer to the models below).

(i) the diurnal and semidiurnal EOP model determined based on ~35 years VLBI observation by John Gipson.

(ii) the predicted diurnal and semidiurnal EOP variation based on the GOT4.7 ocean tide model, which is the new version of Richard Ray's tide models and has been derived from TOPEX/Poseidon, Jason-1, ERS and GFO altimetry satellites [*Egbert and Erofeeva*, 2002].

(iii) the predicted diurnal and semidiurnal EOP model based on the TPXO.7.1 model, which is computed based on inverse theory using tide gauge and TOPEX/Poseidon data.

(iv) the sub-daily EOP model determined by combining 13-year (1994~2007) GPS and VLBI observations [*Artz et al.*, 2012].

Details about the altimeter satellite tidal models can be found at <https://www.esr.org/polar_tide_models/Model_TPXO71.html>.

We compute the sub-daily EOP for the interval between 1994 and 2015 based on these models. Following tables summarizes the statistics of the differences between these optional models and the current IERS standard model and between the models. Table 1 gives the RMS differences between the four models above and the IERS 2010 model. Table 2 compared the models with each other.

*Table 1: Statistics of the differences between the alternative sub-daily EOP models and the IERS standard model during 1994/1/1 – 2014/12/31. The sampling rate of the model is 1 sample per 3 hours, i.e. 8 samples per day. The models are I Gipson; II GOT4.7; III TPXO.71.; IV Artz et al. [2012]. Values in red are the smallest values.*

| Component | Model I | Model II | Model III | Model IV |
|---|---|---|---|---|
| Δx [mas] | 0.037 | 0.053 | 0.043 | 0.030 |
| Δy [mas] | 0.042 | 0.050 | 0.045 | 0.031 |
| Δut1 [μs] | 2.544 | 4.700 | 1.872 | 2.782 |

*Table 2: Statistics of the differences among the four sub-daily EOP models during 1994/1/1 – 2014/12/31. The sampling rate of the model is 1 sample per 3 hours, i.e. 8 samples per day. See Table 1 for model names.*

| Δx [mas] | Model I | Model II | Model III | Model IV |
|---|---|---|---|---|
| Model I | 0 | 0.0470 | 0.0285 | 0.0255 |
| Model II | 0.0470 | 0 | 0.0369 | 0.0480 |
| Model III | 0.0285 | 0.0369 | 0 | 0.0348 |
| Model IV | 0.0255 | 0.0480 | 0.0348 | 0 |

| Δy [mas] | Model I | Model II | Model III | Model IV |
|---|---|---|---|---|
| Model I | 0 | 0.0425 | 0.0313 | 0.0291 |
| Model II | 0.0425 | 0 | 0.0330 | 0.0432 |
| Model III | 0.0313 | 0.0330 | 0 | 0.0332 |
| Model IV | 0.0291 | 0.0432 | 0.0332 | 0 |

| Δut1 [μs] | Model I | Model II | Model III | Model IV |
|---|---|---|---|---|
| Model I | 0 | 4.7850 | 2.1873 | 2.3333 |
| Model II | 4.7850 | 0 | 4.4478 | 5.0760 |
| Model III | 2.1873 | 4.4478 | 0 | 3.1448 |
| Model IV | 2.3333 | 5.0760 | 3.1448 | 0 |

The discrepancies between these models and current IERS standard model reflect either model improvement or mis-modeling in sub-daily EOP variations. The differences between the newer models are similar in magnitude to the difference to the IERS conventions model and it is not clear which if any would provide an improvement over the IERS model. Models I and IV, both based on geodetic estimates, with Model I being pure VLBI while Model IV combines both VLBI and GPS match the best in polar motion but not in UT1.

## References

Artz, T., L. Bernhard, A. Nothnagel, P. Steigenberger and S. Tesmer, Methodology for the combination of sub-daily earth rotation from GPS and VLBI observations. *Journal of Geodesy 86*, 221–239, 2012.

Egbert, G. D. and Erofeeva, L. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology 19*, 183–204, 2002.

*Thomas Herring*

# 3.4 Technique Centres

## 3.4.1 International GNSS Service (IGS)

### International Global Navigation Satellite Service 2015

The International Global Navigation Satellite System Service (IGS) was established in 1994 with a mission to provide the highest quality Global Navigation Satellite System (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 2015 that are of interest to IERS are summarized within this report. The information herein was compiled from the 2015 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 2015. It is available for download from the publications section of the IGS website <www.IGS.org>.

### Summary of 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 1 TB (15 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 700 IGS final, rapid, and ultra-rapid product files (GPS and GLONASS), as well as 140 ionosphere files, are made available weekly; additionally, daily troposphere files 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 150 000 file (25 Gb) 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 491 select GNSS tracking stations that operate according to the IGS guidelines, 127 of them are providing an extended set of observations in the frame of the IGS MGEX project. Approximately 118 IGS stations provide real-time data streams so support the IGS Real Time Pilot Project activities. Currently 36 stations have the status of a proposed site.

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.

## Analysis and Core Product Generation

The IGS core products have continued to be routinely combined and delivered to users in a timely manner through 2015. 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.

An important activity for the ACC in the second half of the year 2015 was the preparation of the transition of the coordination activities from NGS to GA+MIT. This is related to a move of the software components, and in order to simplify the technical aspect for the future, the combination software was installed on Amazon cloud computers. At this point, we thank NGS for taking on the task of the ACC over two terms (a total of 8 years).

*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.*

| | | Sampling Interval | Accuracy | Latency | Submission | Target Availability |
|---|---|---|---|---|---|---|
| **GPS Satellite Ephemerides / Satellite & Station Clocks** | | | | | | |
| Broadcast (for comparison) | Orbits | 1 s | ~100cm | real time | continuous | 99.99% |
| | Sat. clocks | | ~5 ns RMS<br>~2.5 ns SDev | | | |
| Ultra-Rapid (predicted half) | Orbits | 15 min | ~5 cm | predicted | 4x daily at 03, 09, 15, 21 UTC | 95% |
| | Sat. clocks | | ~3 ns RMS<br>~1.5 ns SDev | | | |
| Ultra-Rapid (observed half) | Orbits | 15 min | ~3 cm | 3-9 hours | 4x daily at 03, 09, 15, 21 UTC | 95% |
| | Sat. clocks | | ~150 ps RMS<br>~50 ps SDev | | | |
| Rapid | Orbits | 15 min | ~2.5 cm | 17 - 41 hours | at 17 UTC daily | 95% |
| | Sat. & stn. clocks | 5 min<br>17 - 41 hours | ~75 ps RMS<br>~25 ps SDev | | | |
| Final | Orbits | 15 min | ~2.5 cm | 12 - 18 days | weekly, every Thursday | 99% |
| | Sat. & stn. clocks | sat: 30s;<br>stn: 5 min | ~75 ps RMS<br>~20 ps SDev | | | |
| Real-time | Orbits | 5-60 s | ~5 cm | 25 seconds | continuous | 95% |
| | Sat. clocks | 5 s | 300 ps RMS;<br>120 ps SDev | | | |
| **GLONASS Satellite Ephemerides** | | | | | | |
| Final | Orbits | 15 min | ~3 cm | 12 - 18 days | weekly, every Thursday | 99% |
| **Geocentric Coordinates of IGS Tracking Stations** | | | | | | |
| Positions of real-time stations | Horizontal | daily | 3 mm | 1-2 hours | daily | 99% |
| | Vertical | | 6 mm | | | |
| Final positions | Horizontal | daily | 3 mm | 11-17 days | weekly, every Wednesday | 99% |
| | Vertical | | 6 mm | | | |
| Final velocities | Horizontal | daily | 2 mm/yr | 11-17 days | weekly, every Wednesday | 99% |
| | Vertical | | 3 mm/yr | | | |
| **Earth Rotation** | | | | | | |
| Ultra-Rapid (predicted half) | Polar motion | daily integra-tions at 00, 06, 12, 18 UTC | ~200 µas | predicted | 4x daily at 03, 09, 15, 21 UTC | 99% |
| | Polar motion rate | | ~300 µas/day | | | |
| | Length of day | | ~50 µs | | | |
| Ultra-Rapid (observed half) | Polar motion | daily integra-tions at 00, 06, 12, 18 UTC | ~50 µas | 3-9 hours | 4x daily at 03, 09, 15, 21 UTC | 99% |
| | Polar motion rate | | ~250 µas/day | | | |
| | Length of day | | ~10 µs | | | |
| Rapid | Polar motion | daily integra-tions at 12 UTC | ~40 µas | 17 - 41 hours | at 17 UTC daily | 99% |
| | Polar motion rate | | ~200 µas/day | | | |
| | Length of day | | ~10 µs | | | |
| Final | Polar motion | daily integra-tions at 12 UTC | ~30 µas | 12 - 18 days | weekly, every Thursday | 99% |
| | Polar motion rate | | ~150 µas/day | | | |
| | Length of day | | ~10 µs | | | |
| **Atmospheric parameters** | | | | | | |
| Final tropospheric zenith path delay with N, E gradients | | 5 minutes | 4 mm (ZPD) | < 4 weeks | daily | 99% |
| Final ionospheric TEC grid | | hourly;<br>5 deg (lon) x 2.5 deg (lat) | 2-8 TECU | ~11 days | weekly | 99% |
| Rapid ionospheric TEC grid | | hourly;<br>5 deg (lon) x 2.5 deg (lat) | 2-9 TECU | < 24 hours | daily | 99% |

## Second Reprocessing Campaign (IG2)

The second reprocessing campaign (IG2) has mainly been carried out by the ACs during the year 2014. The processing follows the minimum analysis standards (see items delineated in black on the IG2 web page at <http://acc.igs.org/reprocess2.html>).

In February 2015, the results were submitted by the ACs to the CDDIS product server. To ensure a timely contribution to the ITRF2014, the reference frame working group chair gave priority for the combination to the daily SINEX files containing station coordinates and Earth orientation parameters. The combined SINEX files from the 2$^{nd}$ reprocessing initiative have been made available to the IERS after an intensive quality evaluation, in order to allow the relevant groups to generate the ITRF2014 candidate solutions.

The combination of the orbit and clock products from the 2$^{nd}$ reprocessing is planned to be done outside the operational structures of the IGS.

## Multi-GNSS Experiment

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. The focus of this cornerstone experiment is the data flow, the understanding of observables, the characterization of tracking equipment, and the generation of products.

During the last few years the dataflow has been successfully established. The transition to RINEX3 files with an extended set of observations into the operational structures of the IGS was prepared at the IGS 2014 workshop in Pasadena, California, USA. This activity is coordinated by the infrastructure committee and involves all relevant components of the IGS (station manager, data and analysis centers, and several working groups).

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 <http://mgex.igs.org/>. This page also contains some comparisons demonstrating the current performance of the different contributions. The very successful Workshop on GNSS Biases, held in Bern, Switzerland on 5 and 6 November 2015 addressed very significant issues related to the implementation of multi-GNSS within IGS. One important result is the agreement to an exchange format for GNSS biases.

The launch of a Multi-GNSS Pilot Project is targeted in 2016.

## 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. 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 <http://rts.igs.org>.

## Formats and Standards

The joint IGS/RTCM RINEX Working Group is responsible for maintenance of the RINEX format. The latest adapted version is RINEX3.03. 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 RINEX3 format within the IGS. This first step involves the station manager, the data centers and analysis centers and shall be realized during the year 2016. In the next step, the formats for result and exchange files shall also support the new longer station IDs, as foreseen in the RINEX3 format description. Thanks to the alternative file naming convention for RINEX3 data, both versions can coexist in one and the same directory in the IGS data centers.

## Governance

At the beginning of 2015 Gary Johnston became the chair of the IGS Governing Board, replacing outgoing chair Urs Hugentobler. Other members of the governing board have been replaced as well. 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 2015: first on 12 April, for a business meeting during the EGU General Assembly in Vienna, Austria; a second business meeting on 23 June, during the 26th IUGG General Assembly in Prague, Czech Republic; and finally on 13 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 Urs Hugentobler, Gary Johnston , Chuck Meertens, Ruth Neilan, Chris Rizos, Tim Springer and with regular participation of Steve Fisher and of WG Chairs as required – met several times in 2015 by teleconference.

## Strategic Planning

The current IGS Strategic Plan covers the period 2013–2016. During the year 2015, two 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 2014 Workshop was hosted by the NASA Jet Propulsion Laboratory at the campus of California Institute of Technology (Caltech) in Pasadena, California, United States. More than 200 participants from more than 25 countries attended the workshop. The main theme "Celebrating 20 Years of Service" was well reflected in the scientific program that did review the history and also provided an outlook into the future of the IGS: A short workshop summary may be found in IGSMAIL #6635. The workshop presentations, posters and recommendations can be found on the IGS website at <http://www.igs.org/workshop/>.

No workshops were held in 2015. The IGS 2016 Workshop was hosted by Geoscience Australia, Land Information New Zealand, and the University of New South Wales in Sydney, Australia. A full summary of the Sydney workshop will be included in the 2016 report.

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).

## 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 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 2015. 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 2015.

## Network

The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2015 the network further expanded with the addition of several new sites, most of them 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 at the 10 mm level, with a significant number of 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 while the tracking of targets increased by ~10% and the number of tracking sites decreased by ~10%, the

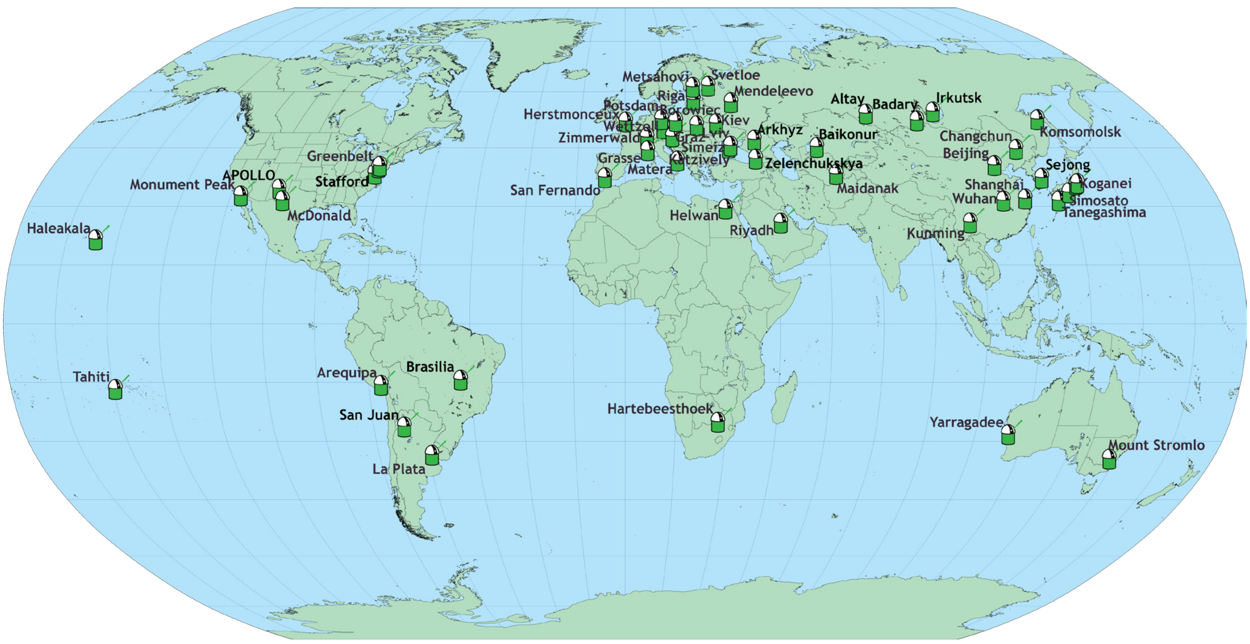



*Fig. 1: The global network of SLR stations (status early 2016).*

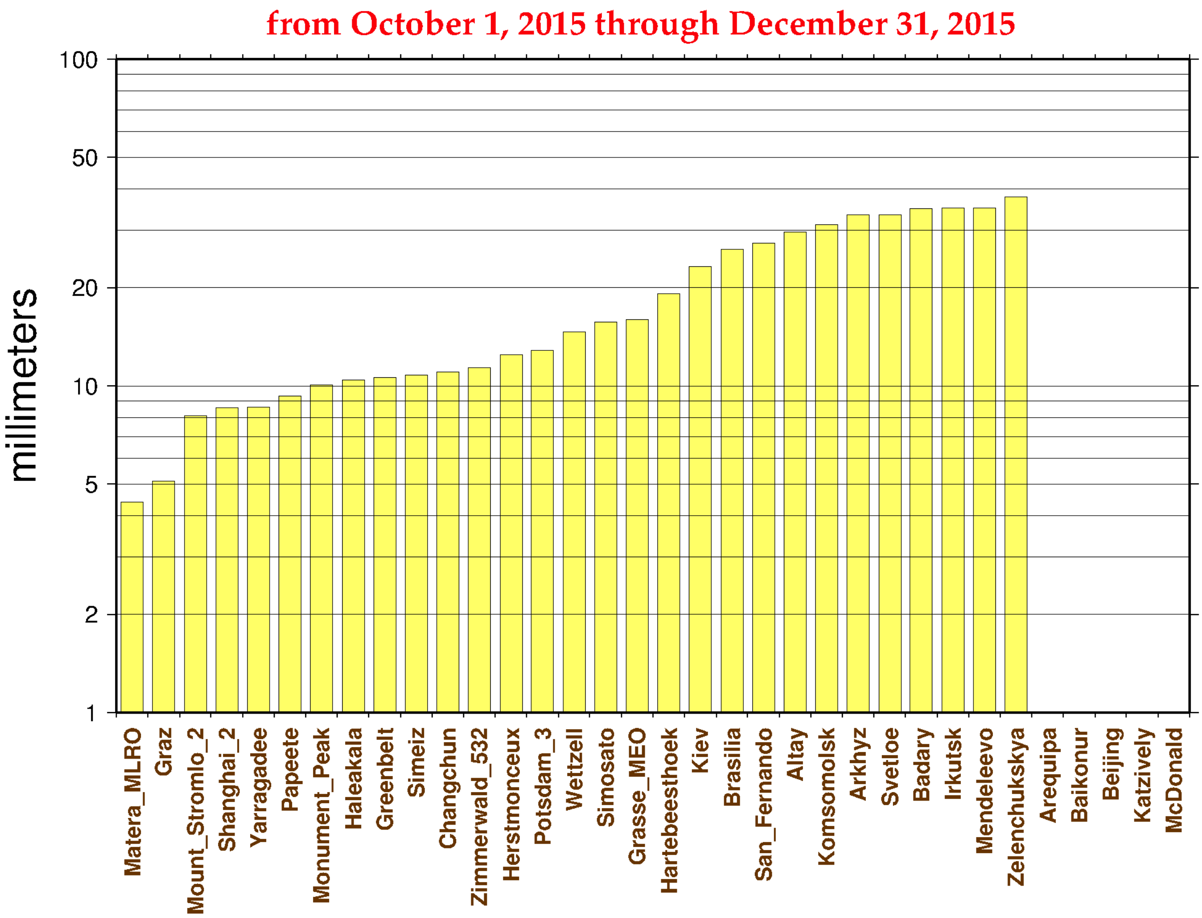



*Fig. 2: Performance of the global network of SLR stations on LAGEOS (last quarter of 2015).*

annual data yield of the network is nearly identical to that of the prior year (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. 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- and GNSS-, VLBI-implied frames.

Statistics of the SLR data collected as pass segments during the calendar year 2015 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.

Of all the active ILRS observatories (~36), very few are technically equipped to track retro-reflector arrays on the surface of the

3.4.2 International Laser Ranging Service (ILRS)

*Table 1: ILRS Network Tracking Statistics for 2015.*

| Site Name | Station | Number of Pass Segments | | | |
|---|---|---|---|---|---|
| | | **Low** | **LAGEOS** | **High** | **Grand** |
| Altay | 1879 | 244 | 323 | 1,974 | 2,541 |
| Apache Point | 7045 | 0 | 0 | 190 | 190 |
| Arequipa | 7403 | 2,250 | 332 | 0 | 2,582 |
| Arkhyz | 1886 | 331 | 309 | 1,317 | 1,957 |
| Badary | 1890 | 2,762 | 571 | 427 | 3,760 |
| Baikonur | 1887 | 23 | 193 | 343 | 559 |
| Beijing | 7249 | 640 | 224 | 648 | 1,512 |
| Brasilia | 7407 | 8 | 292 | 906 | 1,206 |
| Changchun | 7237 | 9,260 | 2,180 | 7,386 | 18,826 |
| Grasse | 7845 | 360 | 308 | 178 | 846 |
| Graz | 7839 | 3,689 | 1,146 | 3,420 | 8,255 |
| Greenbelt | 7105 | 6,069 | 1,847 | 1,990 | 9,906 |
| Haleakala | 7119 | 1,178 | 596 | 0 | 1,774 |
| Hartebeesthoek | 7501 | 2,374 | 1,000 | 790 | 4,164 |
| Herstmonceux | 7840 | 3,330 | 1,242 | 3,143 | 7,715 |
| Irkutsk | 1891 | 83 | 289 | 670 | 1,042 |
| Katzively | 1893 | 1,346 | 290 | 0 | 1,636 |
| Kiev | 1824 | 783 | 215 | 4 | 1,002 |
| Komsomolsk | 1868 | 73 | 216 | 1,586 | 1,875 |
| Matera | 7941 | 3,068 | 2,128 | 3,568 | 8,764 |
| McDonald | 7080 | 400 | 203 | 145 | 748 |
| Mendeleevo | 1874 | 84 | 102 | 312 | 498 |
| Monument Peak | 7110 | 5,545 | 1,423 | 1,449 | 8,417 |
| Mount Stromlo | 7825 | 6,666 | 2,018 | 3,069 | 11,753 |
| Potsdam | 7841 | 2,786 | 711 | 366 | 3,863 |
| San Fernando | 7824 | 2,579 | 308 | 54 | 2,941 |
| Shanghai | 7821 | 1,414 | 405 | 1,631 | 3,450 |
| Simeiz | 1873 | 1,188 | 364 | 131 | 1,683 |
| Simosato | 7838 | 961 | 398 | 24 | 1,383 |
| Svetloe | 1888 | 1,006 | 685 | 537 | 2,228 |
| Tahiti | 7124 | 741 | 337 | 542 | 1,620 |
| Wettzell | 7827 | 134 | 57 | 172 | 363 |
| Wettzell | 8834 | 2,484 | 541 | 2,416 | 5,441 |
| Yarragadee | 7090 | 18,534 | 4,526 | 8,651 | 31,711 |
| Zelenchukskaya | 1889 | 544 | 301 | 690 | 1,535 |
| Zimmerwald | 7810 | 4,038 | 1,211 | 2,866 | 8,115 |
| **Totals:** | 36 stations | 86,975 | 27,291 | 51,595 | 165,861 |

Moon or spacecraft orbiting around the Moon. In 2015, three Lunar Laser Ranging (LLR) sites regularly collected ranging data to the Moon: The Observatoire de la Côte d' Azur, France (249 normal points, NP), the APOLLO site in New Mexico, USA (236 NP) and the Matera Laser Ranging station in Italy (22 NP). Additionally in 2015, the McDonald Observatory in Texas, USA, returned with (only) 2 successful lunar tracks after one year without any lunar measurements. One has to await the further development of LLR capabilities at McDonald in the near future. These numbers still do not contain quite new measurements carried out in infrared at the French site. And also not all APOLLO data might be available in the archive, yet.

The measurement statistics of 2015 (Figure 3) shows that about one half of all LLR data have been collected at the French MeO site near Grasse and almost one half at APOLLO. Figure 4 illustrates the statistics for the observed retro-reflectors, where a much better coverage of all reflectors could be achieved in the past years. Nevertheless, most of the data have been obtained

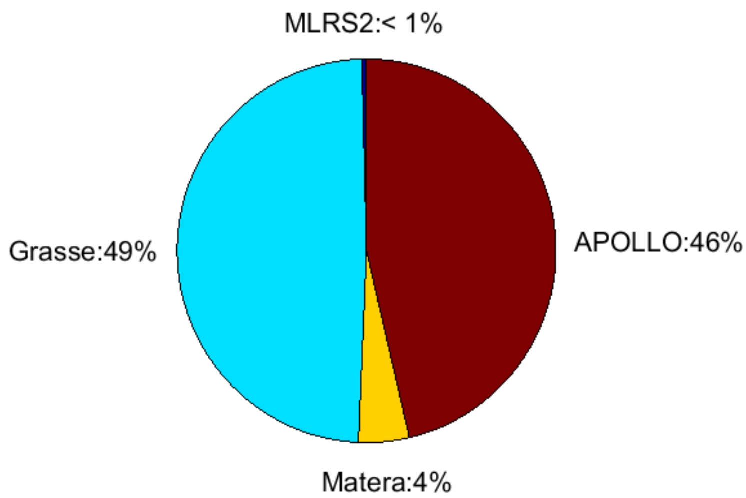



*Fig. 3: Observatory statistics in 2015*

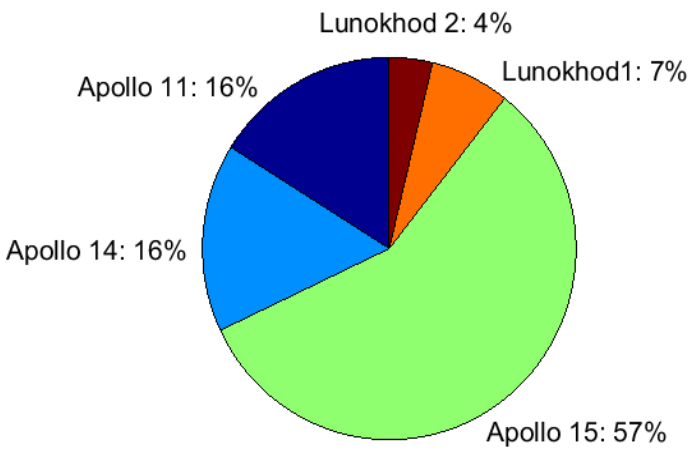



*Fig. 4: Retro-reflector statistics in 2015*

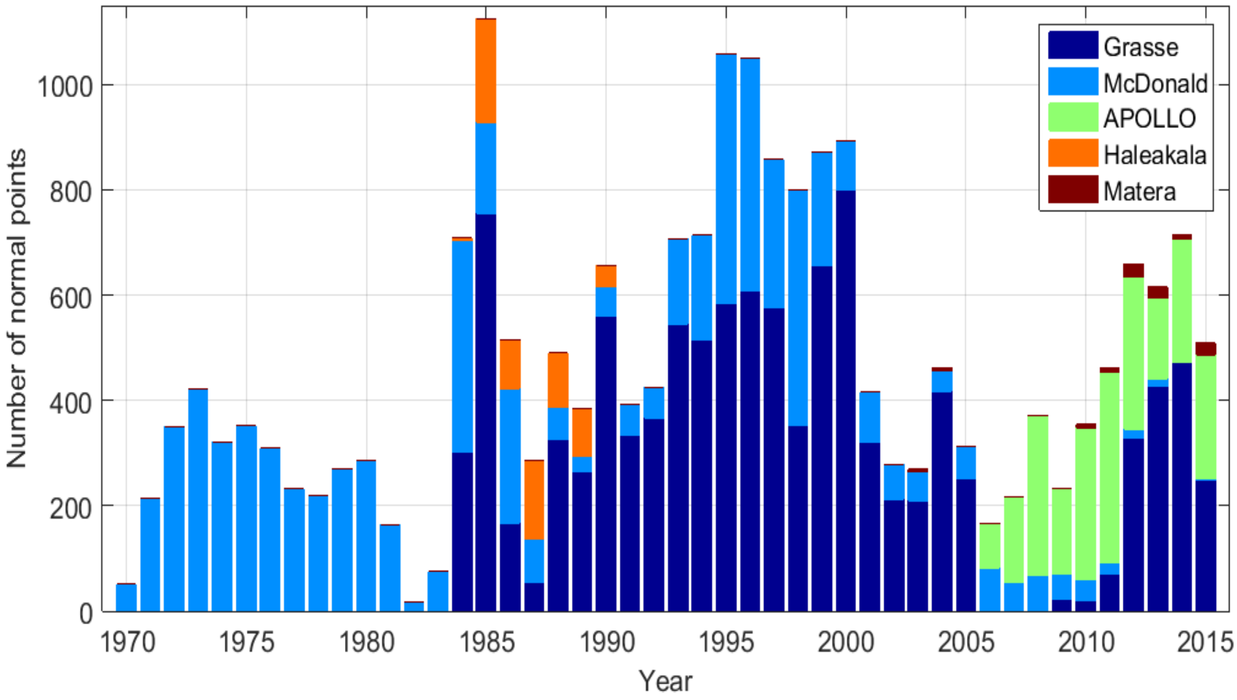



*Fig. 5: Data yield of the global LLR network of stations (up to 2015). Note the increasingly significant contribution of Grasse's MeO system upon its return to operations in 2011.*

by tracking the big Apollo 15 reflector (57%). Figure 5 shows the entire LLR data set from 1970 to 2015 indicating the amount of data collected by each of the active LLR sites in each year. It is more than 21,000 normal points in total. After several years with less LLR NP, one has reached quite a good level of more than 600 NP per year in the previous years, but a little bit less, about 500 NP, in 2015.

LLR data analysis is carried out by 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; Institute of Geodesy (IfE), University of Hannover, Germany. In the last years, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Japan, increased their activities to analyze LLR data.

One general objective of LLR analysis is to achieve mm level of accuracy; today it is still at the cm level (see Figure 6). The various analysis centers are eager to improve their various algorithmic codes, which is a difficult task. Recent activities also comprise simulations to show the potential benefit of improved tracking from further observatories and/or to new reflectors. These activities are aiming for a better science output, 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.

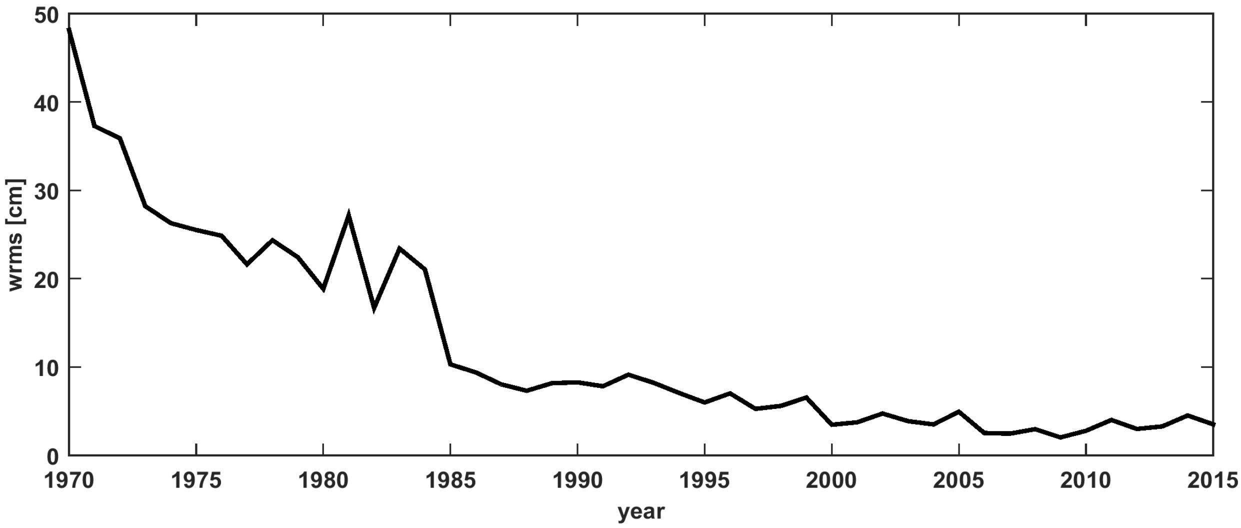



*Fig. 6: LLR residuals, annual WRMS.*

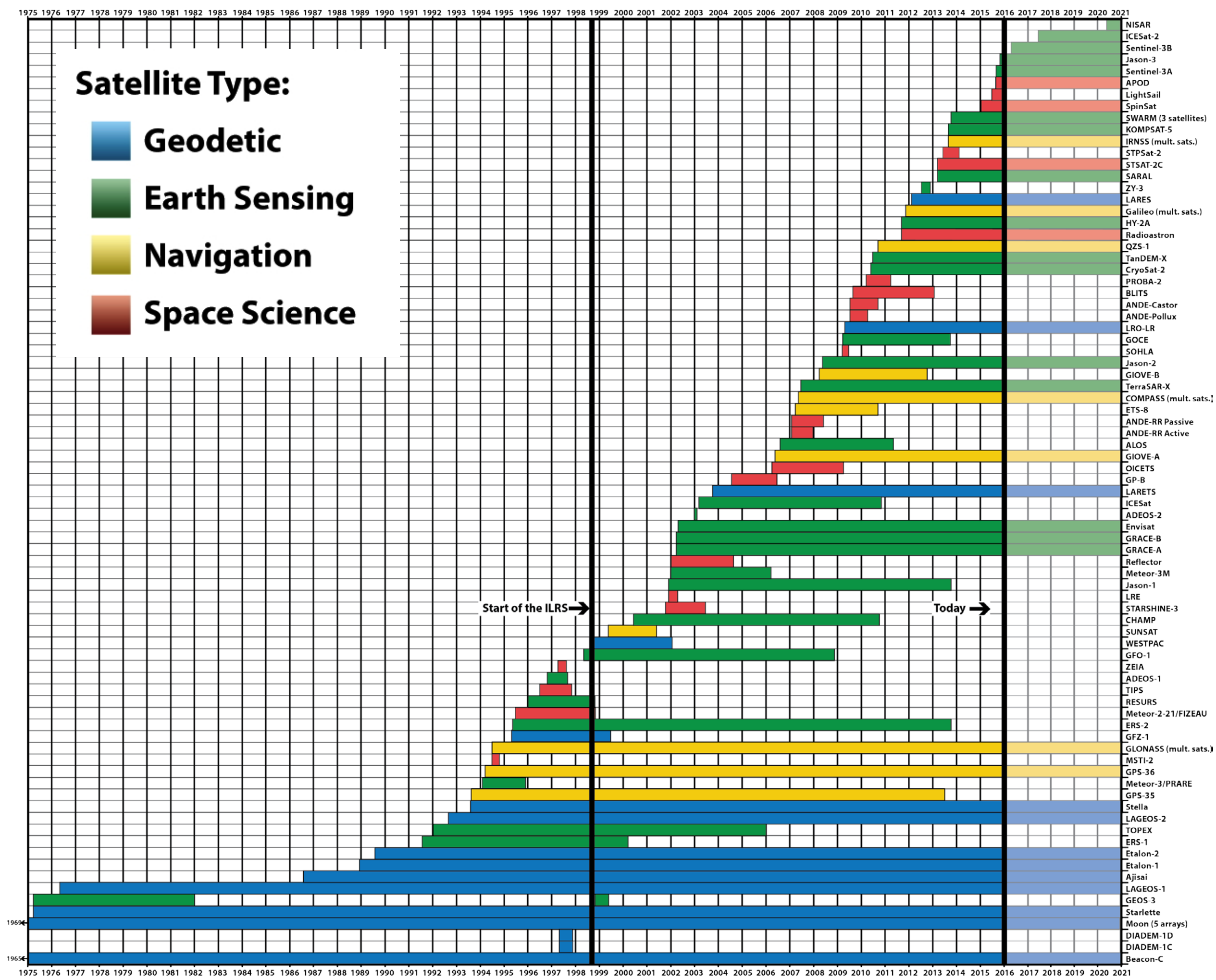



*Fig. 7: The currently tracked SLR missions (status as of late 2015).*

## 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.

During 2015 the new missions that were launched are shown in Table 2. They were almost exclusively spacecraft of GNSS Constellations. PN-1 is an experimental mission that includes four spacecraft (1A through 1D) that form the APOD mission (Atmospheric density Detection and Precise Orbit Determination), an initiative of China's Beijing Aerospace Control Center (BACC) aiming at precise orbit determination and thermosphere density detection, designed and manufactured by DFH satellite Co. Ltd. APOD consists of one nano-satellite (PN-1A) with a mass of 15 kg and three identical pico-satellites (PN-1B, -1C,-1D) with a mass of 5 kg. There was one additional launch of an experimental mission in late May, 2015: LightSail-A (<http://ilrs.gsfc.nasa.gov/missions/satellite_missions/past_missions/lita_general.html>), which however had a very short lifetime due to its very low altitude that resulted in not being tracked by the network. A more advanced version of this spacecraft is scheduled for launch in late 2016.

*Table 2: ILRS Supported Missions Launched or Initiating Tracking in 2015.*

| Satellite Name | Satellite ID | SIC Code | Satellite Catalog Number* | NP Indicator | Bin Size (sec) | Altitude (Km) | Inclination (deg) | First Data Date |
|---|---|---|---|---|---|---|---|---|
| Galileo-202 | 1405002 | 7202 | 40129 | 9 | 300 | 17,000-26,210 | ~ 50 | 2015-Mar-17 |
| Galileo-203 | 1501701 | 7203 | 40544 | 9 | 300 | 23,220 | 56 ± 2 | 2015-Mar-27 |
| Galileo-204 | 1501702 | 7204 | 40545 | 9 | 300 | 23,220 | 56 ± 2 | 2015-Mar-27 |
| IRNSS-1D | 1501801 | 3304 | 40547 | 9 | 300 | 42,293 | 30.5 | 2015-Apr-24 |
| COMPASS-MS1 | 1503702 | 2007 | 40749 | 9 | 300 | 21,528 | 55 | 2015-Jul-25 |
| COMPASS-MS2 | 1503701 | 2008 | 40748 | 9 | 300 | 21,528 | 55 | 2015-Jul-25 |
| COMPASS-IS1 | 1501901 | 2006 | 40549 | 9 | 300 | 35,786 | 55.5 | 2015-Sep-08 |
| Galileo-205 | 1504501 | 7205 | 40889 | 9 | 300 | 23,220 | 56 ± 2 | 2015-Sep-11 |
| Galileo-206 | 1504502 | 7206 | 40890 | 9 | 300 | 23,220 | 56 ± 2 | 2015-Sep-11 |
| COMPASS-IS2 | 1505301 | 2010 | 40938 | 9 | 300 | 35,786 | 55.5 | 2015-Sep-29 |
| PN-1 | 1504905 | 2203 | 40903 | 1 | 5 | 450-120 | 94.47 | 2015-Nov-11 |
| Galileo-208 | 1507902 | 7208 | 41175 | 9 | 300 | 23,220 | 56 ± 2 | 2015-Dec-17 |
| Galileo-209 | 1507901 | 7209 | 41174 | 9 | 300 | 23,220 | 56 ± 2 | 2015-Dec-17 |

** Formerly known as the NORAD Number.*

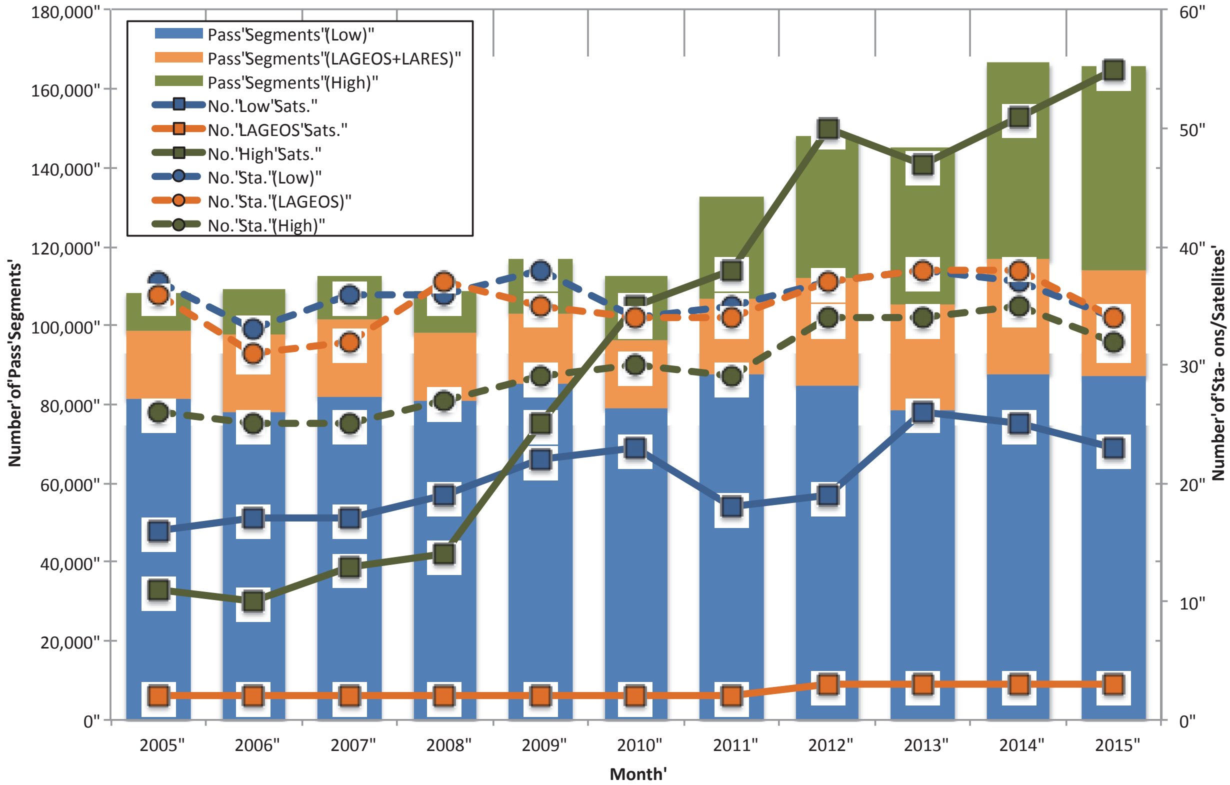



*Fig. 8: ILRS network data yield by target type since 2005 (by end of 2015).*

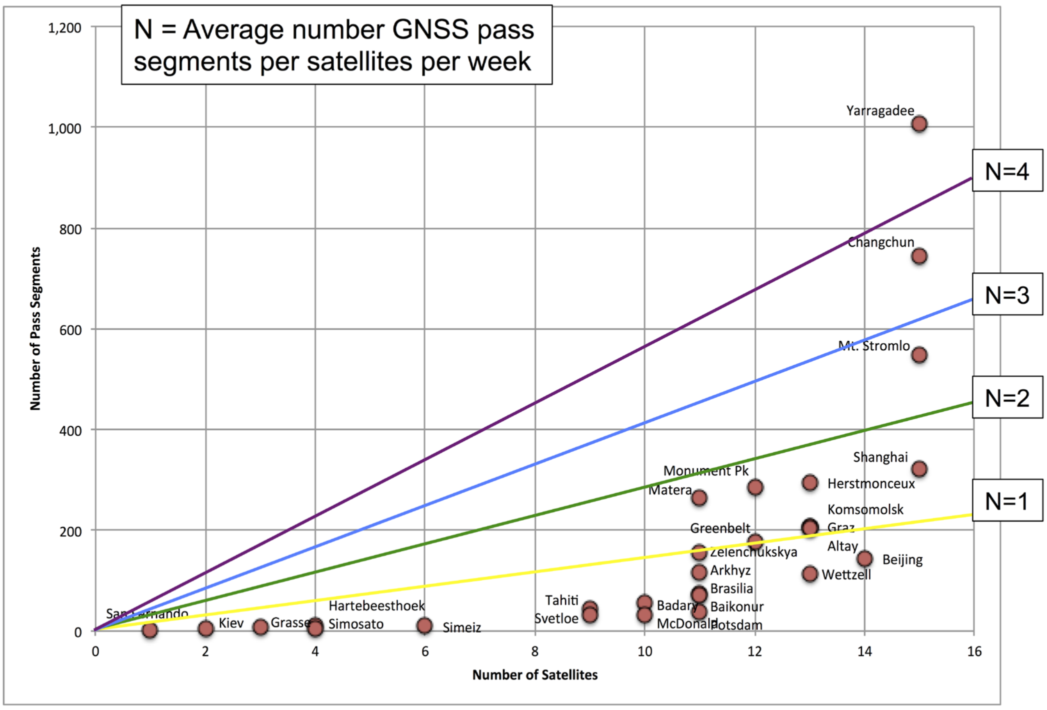
Despite the small decrease in active stations in 2015 and comparable increase in tracked targets, the ILRS network has increased its productivity tremendously to maintain the data yield (Figure 8). A major contributor in the recent years' data yield increase is the fact that several stations now track all GNSS satellites. The results of the second and third GNSS target tracking campaigns organized by the LARGE Working Group (November 2014 through October 2015) indicated that only a few sites were able to track significant number of passes on multiple targets during the second campaign and things improved dramatically during the third campaign (Fig. 9).

## Analysis and science

The Analysis Working Group (AWG) delivered the final version of the ILRS contribution to ITRF2014 prior to the European Geosciences Union meeting in April 2015 (Figure 10). When the ITRS Center's preliminary result was released in the summer of 2015, the ILRS ACs evaluated the proposed ITRF2014P model and based on several ACs tests, a positive recommendation was submitted to the ITRS Center, in late October 2015, following the ILRS Technical Workshop in Matera, Italy. The new model shows significant improvements to the outdated ITRF2008, especially

## Campaign 2

**November 22, 2014 – February 28, 2015 (3 months/14 weeks/99 days)**




## Campaign 3

**August 20 – October 16, 2015 (2 months/8 weeks/58 days)**

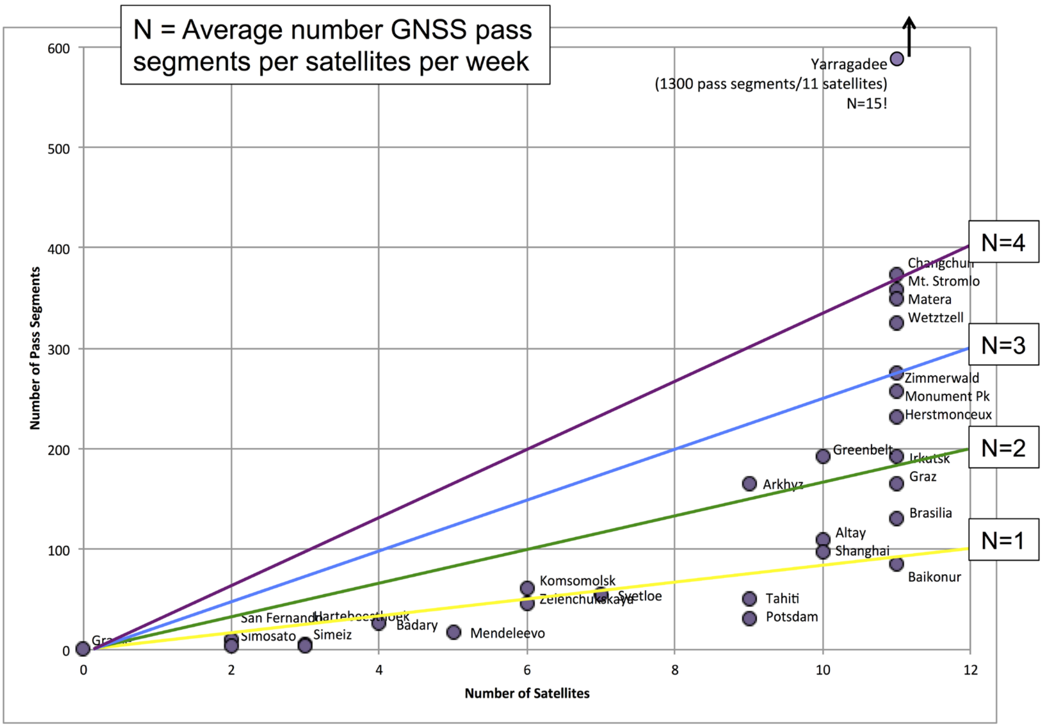



*Fig. 9: Tracking data distribution statistics for the second (top) and third (bottom) GNSS target tracking campaigns (2015).*

for a large number of newly established SLR sites. There are still some inter-technique issues with most prominent the scale inconsistency between SLR and VLBI. There are ongoing efforts now looking into this inconsistency from various points of view and it is hoped that a thorough review of both techniques in the coming year will lead to a resolution.

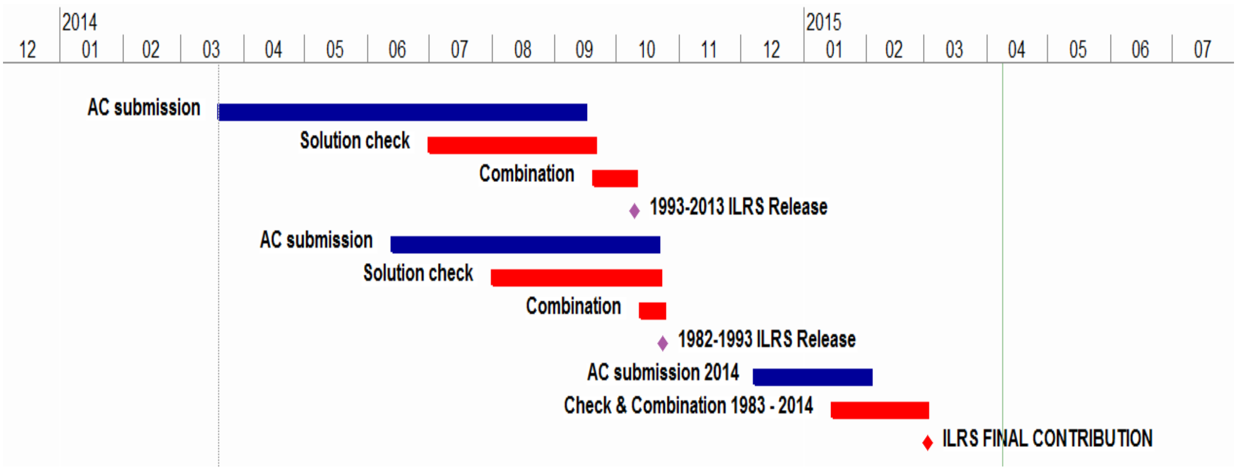



*Fig. 10: The timeline of the official ILRS Analysis and Combination process for the development of the ILRS contribution to ITRF2014 based on the input of the ILRS ACs.*

The final ITRF2014 model exhibits a very good quality in the definition of the origin (Fig. 11) and the scale of the SLR-only TRF, which were already described in presentations by the ILRS Analysis Working Group chairs (Luceri, V. et al., 2015, Pavlis, E. C. et al., 2015).

## Meetings

In 2015 the ILRS Technical Workshop was held at the Casa Cava in Matera, Italy, October 26 – 30, co-sponsored by the Italian Space Agency (ASI) and the ILRS, to address:

1. Network performance on GNSS and present and future user expectations,
2. Present performance and future expectations for time transfer, and
3. Present performance and future expectations for space debris tracking.

The workshop was very well attended with over 100 participants and 50 oral presentations and over 15 posters. The AWG held two meetings in 2015, one during the EGU General Assembly, on April 16, and one prior to the Matera Workshop, on October 24 (<http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/>). The ILRS Governing Board met once in 2015, prior to the Matera workshop

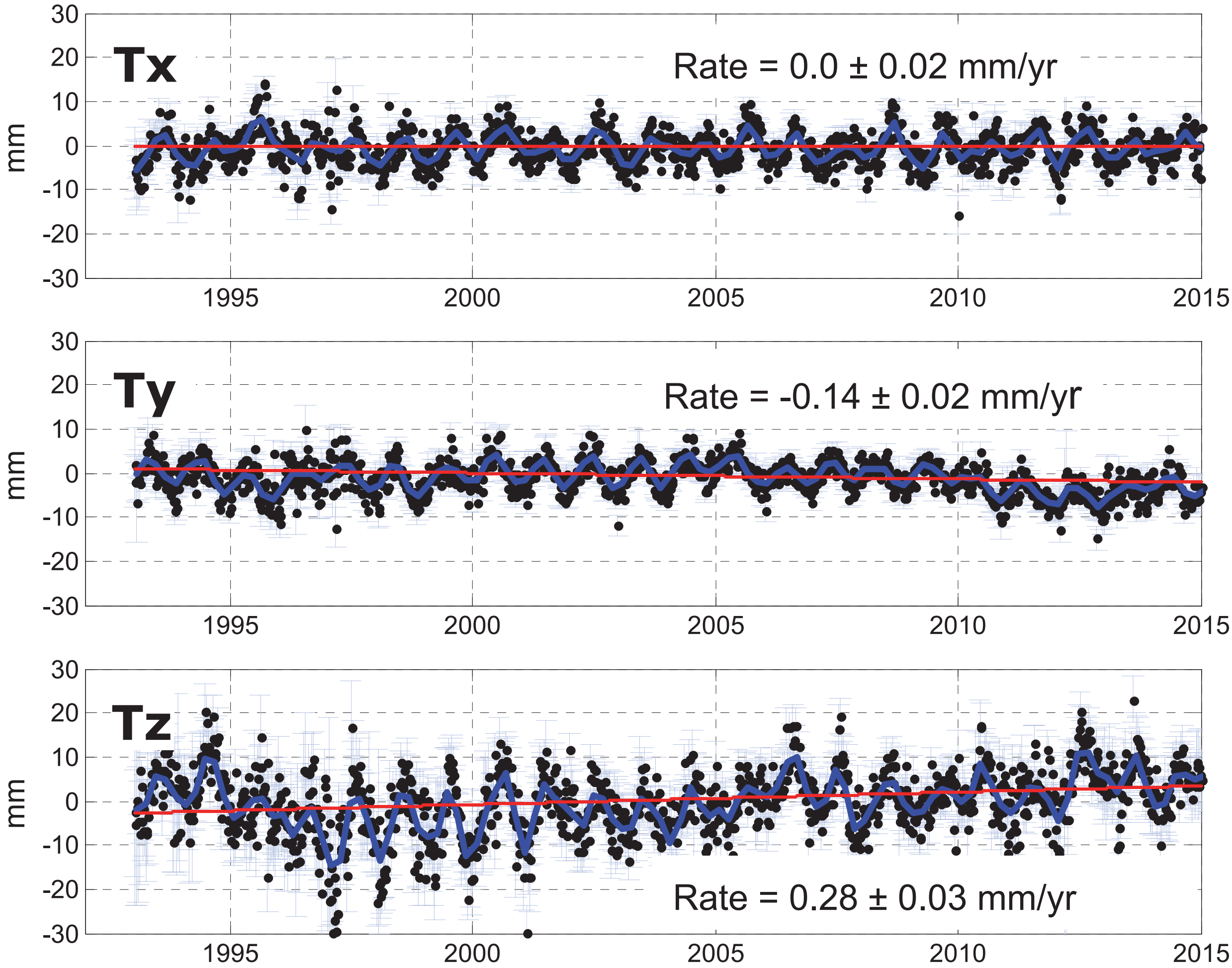



*Fig. 11: The three components of the TRF origin implied by SLR from the official ILRS-A submission to ITRF2014.*

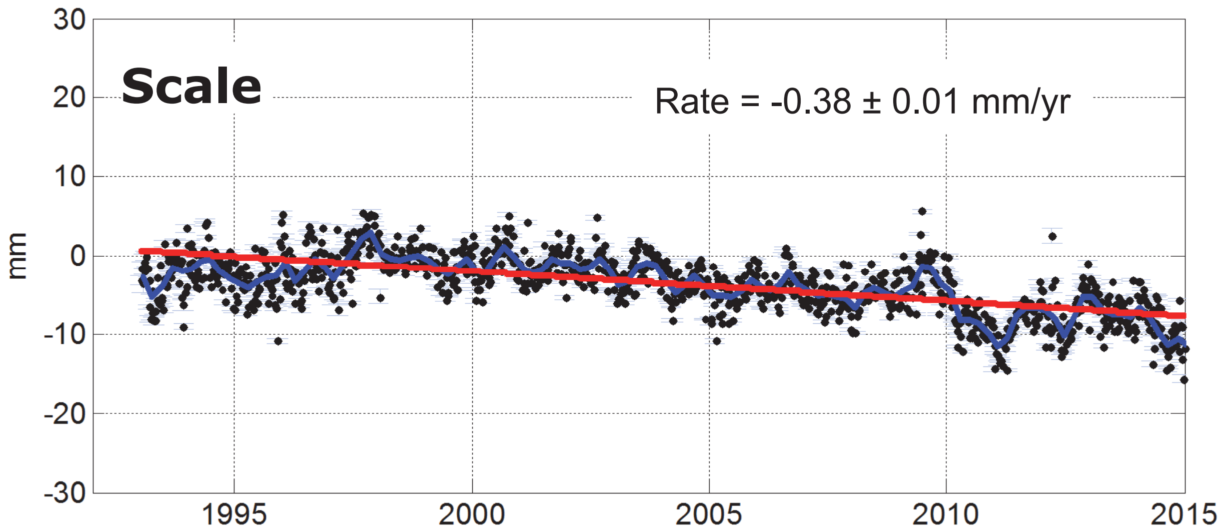



*Fig. 12: Weekly variations of the scale of the SLR network with respect to ITRF2014.*

on October 25 (<http://ilrs.gsfc.nasa.gov/about/organization/govboard/gbmeeting_reports.html>). The ILRS will hold in 2016 the 20th International Workshop on Laser Ranging that will take place in Potsdam, Germany, co-hosted by GFZ (see <http://iwslr2016.gfz-potsdam.de/international-workshop-on-laser-ranging/>).

## Publications

Access all the presentations, posters, and proceedings papers presented at the Technical ILW in Matera, Italy from the official ILRS page for the workshop:
<http://cddis.gsfc.nasa.gov/2015_Technical_Workshop/Program/>

An extensive publications list of interest to ILRS associates can be found at the ILRS website:
<http://ilrs.gsfc.nasa.gov/about/reports/biblio/bibliography.2015.html>

## References

Luceri, V., E. C. Pavlis, B. Pace, M. Kuzmicz-Cieslak, D. König, G. Bianco, and K. Evans (2015) “The ILRS Contribution to the Development of the ITRF2014”, 2015 26th IUGG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015.

Pavlis, E. C., Luceri, V., M. Kuzmicz-Cieslak, D. König and G. Bianco, (2015) “Evaluation of ITRF2014 with ILRS Data and Products”, 26th IUGG General Assembly 2015, Prague, Czech Republic, June 22 – July 2, 2015.

*Erricos C. Pavlis, Jürgen Müller*

## 3.4.3 International VLBI Service (IVS)

### IVS Organization and Activities

During 2015, 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:

| *Event* | *Location* | *Date* |
|---|---|---|
| 8th IVS Technical Operations Workshop | Haystack Observatory, Westford, MA, USA | May 4–7, 2015 |
| 22nd European VLBI for Geodesy and Astrometry (EVGA) Working Meeting | Ponta Delgada, Azores, Portugal | May 17–21, 2015 |
| 16th IVS Analysis Workshop | Ponta Delgada, Azores, Portugal | May 21, 2015 |
| 33rd IVS Directing Board meeting | Ponta Delgada, Azores, Portugal | May 22, 2015 |
| IVS 2015 Retreat | DRAO, Penticton, BC, Canada | October 7–8, 2015 |
| 34th IVS Directing Board meeting | DRAO, Penticton, BC, Canada | October 9, 2015 |
| 4th International VLBI Technology Workshop | Auckland, New Zealand | November 23–26, 2015 |

- In the summer of 2015 the IVS published the 2014 Annual Report. Furthermore, three IVS newsletters were published in April, August and December to keep the community informed about IVS activities.
- The IVS decided to change the rhythm of reporting of its constituent components from annual to two-yearly. The first Biennial Report is planned to cover the years 2015+2016 and will be published in the first half of 2017.
- In October 2015 the IVS Directing Board and six invited experts held a retreat in order to discuss the current and future challenges of developing the service both to meet the needs and to take advantage of the opportunities of the next decade. A summary of the retreat was prepared and posted online. The discussions of the retreat form the basis of a decadal strategy paper that is under development.

### Network Stations and Observing Sessions

A total of 237 geodetic/astrometric 24-hour sessions were observed during the year 2015. The number of observing sessions coordinated by IVS was about ~4.5 days per week, slightly less than in 2014 (~4.7 days/week) but significantly higher than in the years prior (~3.5 days/week). The main reason for the high level of sessions per week was the high number of regional AUSTRAL sessions in the first sixth months of the year. However, in the second half of the year budget restrictions forced the number of AUSTRAL sessions to go back to the pre-2014 level. The major observing programs during 2015 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 2015.

**VLBA** The Very Long Baseline Array (VLBA), operated by the National Radio Astronomy Observatory (NRAO), continued to allocate 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 2015.

**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 2015 six OHIG sessions were observed.

**APSG** The Asia-Pacific Space Geodynamics (APSG) program operated two sessions in 2015.

**AUSTRAL**

In 2015, 57 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.

**JADE**

The JApanese Dynamic Earth observation by VLBI (JADE) had 18 sessions during 2015. These sessions included the dedicated 32-m dish at Tsukuba and the new 13-m dish at Ishioka. The smaller GARNET dishes at Aira, Chichijima, and Shintotsukawa were all retired by the end of March 2015. The main purpose of the JADE sessions in 2015 was thus the establishment of a stable tie between the new antenna at Ishioka and the existing antenna at Tsukuba.

**IVS-R&D**

Ten research and development sessions were observed in 2015. The goals of the 2015 R&D sessions included the observation of link sources between *Gaia* and the ICRF2 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 the CRF, APSG, and some AOV sessions. The Haystack correlator processed R&D sessions and some T2 sessions. The Int2 and JADE 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

**IVS Contribution to ITRF2014**

Towards the end of 2014 Zuheir Altamimi asked if the various space-geodetic techniques would be willing to submit data for the ITRF through the end of 2014 instead of 2013 as originally planned. After internal consultation the IVS agreed to do so. A firm deadline for the submission was February 28, 2015. Hence a major focus for many ACs during the beginning of 2015 was the preparation and submission of the SINEX files to the IVS Combination Center.

The IVS Combination Center combined the submissions into a single IVS contribution. In the process of doing so some anomalies in the individual submissions were noted and the respective ACs notified. This resulted in changing the processing of the data and, in a few cases, fixing some bugs. The various submissions were evaluated for consistency with the other submissions. One of the submissions was not consistent and was ultimately excluded from the IVS combination. The IVS submitted the combination solution before the deadline.

Towards the end of the year many ACs focused on evaluating ITRF2014P – the preliminary version of the ITRF2014. A new feature of ITRF2014P was the inclusion of post-seismic deformation models. The general consensus was that for VLBI processing ITRF2014P provided superior *a priori* station positions than for ITRF2008.

The VLBI contribution to ITRF2014 did not include the effects of pressure loading. Pressure loading is applied in routine VLBI operational analysis. Its omission in ITRF2014 was done primarily because some of the other space-geodetic techniques do not include pressure loading. We believe that this is a serious issue and hope that when the next ITRF is developed all of the techniques will apply pressure loading.

**Analysis Workshop**

The 16th IVS Analysis Workshop was held on May 21, 2015 in Ponta Delgada, Azores, Portugal. One result of this workshop was moving towards higher data rates, 512 Mbps instead of 256 Mbps, for the R1 sessions, which should improve the precision of the results. Higher data rates mean more data is recorded, which impacts how long it takes to transfer data to the correlator and the correlation time. Because of this it was initially decided to use 512 Mbps for one R1 session per month on a trial basis and to increase the number of sessions using the higher data rate based on our experience.

Another topic noted at the Analysis Workshop were differences between ICRF2, which was completed in 2008, and VLBI solutions that use data through the current time. There appear to be systematic differences in the declination of southern sources. This difference is reduced if sessions involving the AuScope array are eliminated. The origin of this difference is still not understood and may just be due to the weakness of ICRF2.

Thomas Hobiger of Onsala announced a software comparison campaign, the goal of which was to ensure consistency of the software. Various analysis packages would submit the results

*Table 1: Progress in the build-out of the VGOS network as of December 2015.*

| Station | Recent milestone | Broadband readiness |
|---|---|---|
| GGAO | test observations | now |
| Westford | test observations | now on legacy RT |
| Wettzell | test observations | now |
| Yebes | test observations | now |
| Ishioka | test observations | now (S/X/Ka) |
| Badary | test observations | now (S/X/Ka) |
| Zelenchukskaya | test observations | now (S/X/Ka) |
| Kokee Park | RT constructed at site | 2016 |
| Santa Maria | RT constructed at site | 2017 |
| Noto | receiver under construction | mid-2017 on legacy RT |
| AuScope | funding for upgrade secured | mid-2017 |
| Tenerife | RT assembled at factory | 2018 |
| Onsala | civil construction underway | 2018 |
| Ny Ålesund | civil construction underway | 2018 |
| Metsähovi | funding secured | 2019 |
| Sheshan | funding secured | 2019 |
| Hartebeesthoek | funding secured | 2019 |

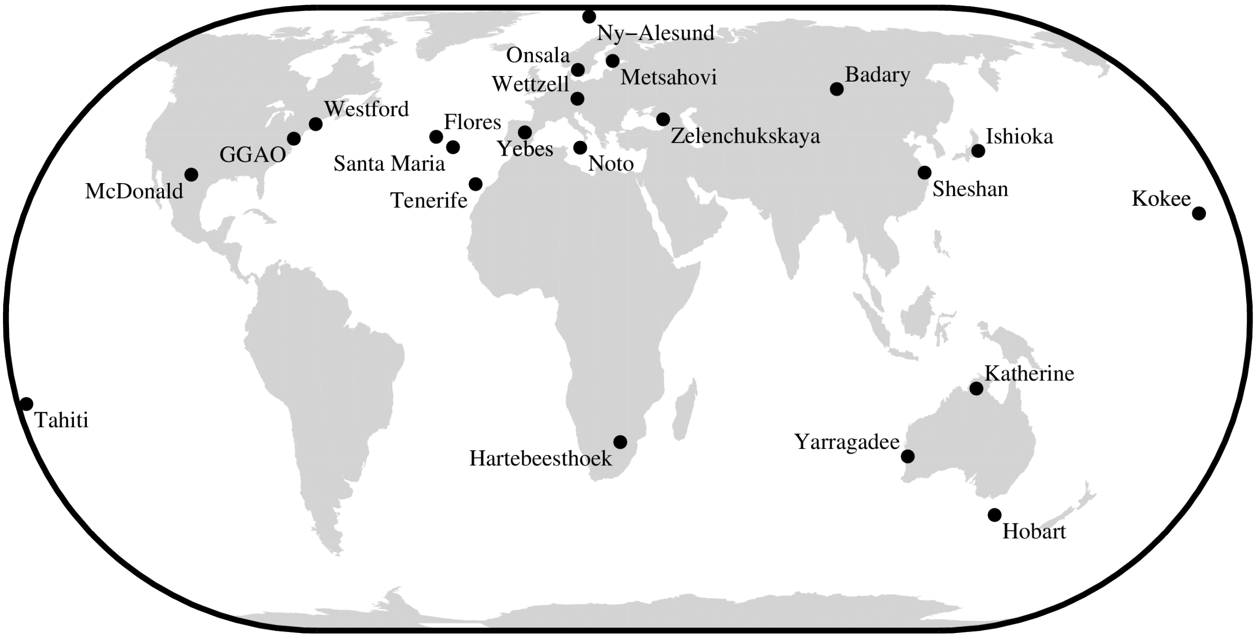



*Fig. 1: Projected VGOS network for the year 2020. There is a scarcity of stations in the equatorial and southern hemisphere (South America, Africa) regions. Discussions are underway to at least fill some of these gaps.*

of calculations such as ‘O−C’ and partials. The deadline for submission was December 2015. This is one of a series of sporadic software comparisons dating back to the 1980s.

## Technology Development

The IVS technology development continued to focus on achieving operational readiness of the broadband observing as part of the VLBI Global Observing System (VGOS). While the VGOS Observing Plan, which was formulated in 2014, could not be implemented as envisioned in 2015 (but was delayed to mid-2016), there were a number of achievements accomplished: among other things, the VEX2 definition was completed, 1-hour test sessions were observed every two weeks on the baseline GGAO to Westford, the broadband system was brought under Field System control, and operational procedures have been set up similar to the legacy operations. A number of new radio telescopes were constructed and the focus shifted to implementing broadband systems. As many as nine antennas could be ready for operations by mid-2016.

A change was made to the VGOS specifications: the frequency range for VGOS operations was set to 3–14 GHz; however, stations were still encouraged to go down to 2.3 GHz if possible. The Internet connection speeds emerged to be an issue. Currently most stations transfer their data electronically. With full VGOS operations the needed speeds will be too high for the correlators to handle. A workaround will be to initially utilize shipment of modules; hence, stations are encouraged to continue to support module shipping.

Following the approval of the VGOS Observation Plan, a VGOS Data Transfer and Correlation Plan was prepared and approved. Work has commenced on a VGOS Analysis Plan.

*Dirk Behrend, John M. Gipson*

# 3.4.4 International DORIS Service (IDS)

## Overview

The current report presents the different activities held in 2015 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.

## 1 DORIS system

### 1.1 DORIS satellites

During this report period (2015), the number of DORIS satellites has decreased to four (see Table 1).

In December 2015, SPOT-5 was decommissioned after 13.5 years of a successful mission. It was launched in 2002 with the last DORIS instrument of the 2$^{nd}$ generation. The constellation is now only composed of DGXX receivers which include the following features:

- The simultaneous tracking capability was increased to seven beacons (from only two in the previous generation of receivers).
- The new generation Ultra Stable Oscillator (USO) design provides better frequency stability while crossing the South Atlantic Anomaly (SAA), and a better quality of Medium Orbit Ephemeris (MOE) useful for beacon location determination.
- New DIODE navigation software (improved accuracy).

Two missions with DORIS onboard will be launched early 2016: Jason-3 (EUMETSAT/NOAA/CNES) and Sentinel-3A (GMES/ESA).

Some other DORIS missions are under development and should guarantee a constellation with at least 4 DORIS contributor satellites through 2032:

*Table 1: DORIS data available at IDS Data Centers. As of December 2015*

| Satellite | Start | End | Type |
|---|---|---|---|
| SPOT-2 | 31-MAR-90<br>04-NOV-92 | 04-JUL-90<br>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 |

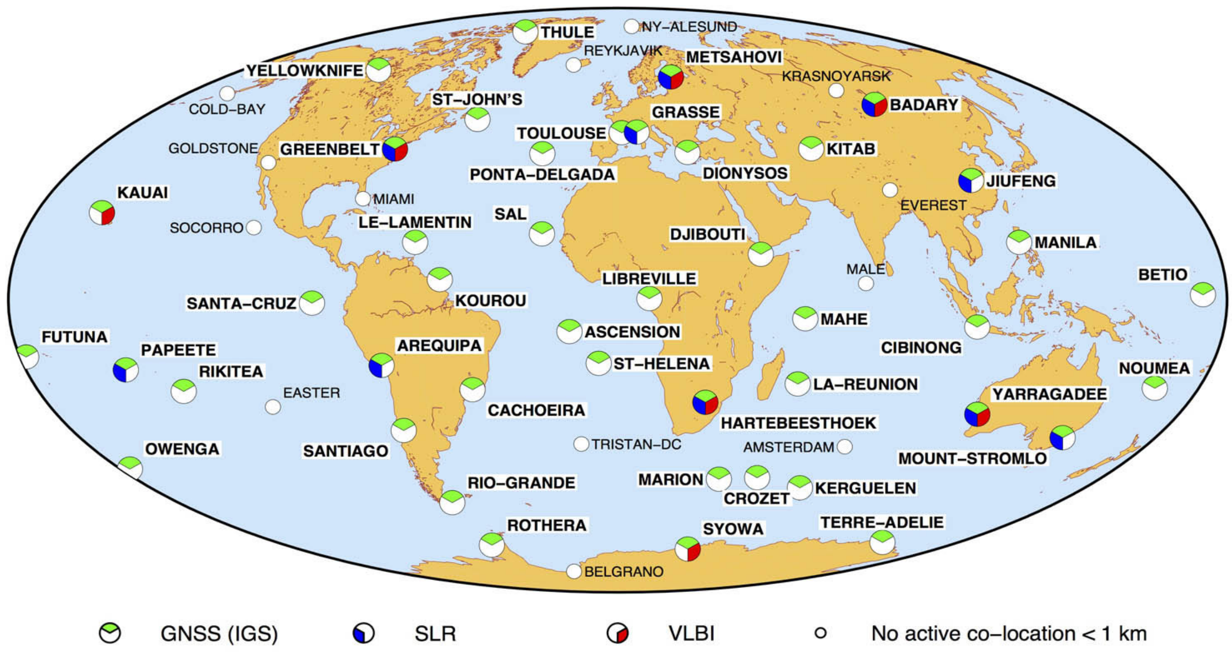



*Fig. 1: The permanent DORIS network – 56 stations – and co-location with other IERS techniques (as of Aug. 2015).*

- Sentinel 3B is planned for 2018, Sentinel 3C and 3D are foreseen for 2020 and 2025.
- HY-2D & 2E (China Academy of Space) are foreseen for 2020, 2021.
- Jason CS1/Sentinel6A (EUMETSAT/ESA/CNES) is expected from 2020, and Jason CS2/Sentinel6B from 2025.
- SWOT is foreseen for late 2020.

## 1.2 DORIS network

The DORIS permanent network is made up of 56 stations achieving 90% coverage (for satellites orbiting at 800 km altitude) (Figure 1). An additional station is dedicated to experimentation: Grasse (France).

A new DORIS station, “GONC”, was installed this year at the Goldstone Deep Space Communications Complex (GDSCC) in California. DORIS actually occupied this site at Goldstone between 1988 and 2004 but the station was moved 300 km south to Monument Peak (east of San Diego, California) for co-location with the SLR tracking station “7110” and the GNSS station “MONP”. Unfortunately, following insoluble conflict at the 2 GHz frequency with a nearby TV microwave relay system, which manifested itself after the US switched to digital television transmissions in 2009, the DORIS station of Monument Peak had to be decommissioned in 2010 after only 4 1/2 years of service. After discussion with NASA, it was determined that the remote location of the GDSCC in the heart of the Mojave Desert was then the best-suited option to ensuring a peaceful and safe environment for the DORIS station. The return to service of DORIS in California is of great importance for the development of altimetry data products. A gap in coverage leads to degradation in orbit determination, which affects both the real-time orbits computed by the DIODE instrument on-board the DORIS satellites, as well as for the precise orbits that are computed later. This much-awaited station fills a hole in the DORIS data coverage over the northern Pacific Ocean.

Other sites out of order for a long time making gaps in coverage are awaiting solutions: Yuznho-Sakhalinsk (Russia), Santa Cruz (Galapagos, Ecuador), Port-Moresby (Papua New-Guinea) and Santiago (Chili). For most of them, a relocation or/and a host agency change is required.

However, the DORIS network still provided a high level of performance and a reliable service with a network availability maintained over 85% of operating stations since 2012 thanks to the responsiveness and the joint effort of CNES, IGN and all agencies hosting the stations.

The number of maintenance operations is greater since the network equipment is ageing: 9 beacons and 5 antennas required replacements in 2015. The 4th DORIS beacon generation currently under development is the eagerly awaited evolution with the delivery of a prototype in 2017 and the start of the deployment in 2019.

When choosing a new site, co-location with other space geodetic techniques remains a priority goal. We use all opportunities to increase the number of co-located sites with over three-quarters of the DORIS network stations (see Figure 1).

In 2015 the following sites were visited:

- Goldstone, CA, USA: new site replacing Monument Peak (Figure 5)
- Arequipa, Peru: visit
- Kourou, French Guyana: tracking oscillator replacement
- Northern Australia: reconnaissance with a view to installing a new station
- Ny-Ålesund, Spitsbergen, Norway: reconnaissance with a view to move.
- Sal, Cape Verde: renovation with a shift of 5 m
- Ponta Delgada, Portuguese island: antenna change

Finally, the overall objectives for the next year are:

- New stations at Managua (Nicaragua), Wettzell (Germany) and San Juan (Argentina)
- Re-location in Kitab (Uzbekistan)
- Restarting at Santa-Cruz (Galapagos, Ecuador)
- Reconnaissance in Mariana Islands (USA), Manchuria (China) and Reykjavik (Iceland)

*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<br>Jean-Michel Lemoine | CLS<br>CNES | France | Analysis Coordination |
| Pascale Ferrage | CNES | France | System representative |
| Brian Luzum | GSFC | 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 |

## 2 IDS Governing Board

On January 1st, 2015, new members took up their duties within the Governing Board (GB) to serve for the period 2015–2018:

- Hugues Capdeville (CLS) and Jean-Michel Lemoine (CNES) as Analysis Coordinators,
- Marek Ziebart (UCL) as a Member at Large.

For the first time, a tandem will share together the responsibility and the work of the Analysis Coordination. Hugues and Jean-Michel can be contact at <ids.analysis.coordination@ids-doris.org>.

The composition of the new Governing Board is given in Table 2.

The IDS Terms of Reference (ToR) have been revised by the GB in May 2015, to include the definition of Associate Analysis Center, clarifications of the definition of Analysis Center, amendments to the definition of IDS Associates. The revised version was approved by the IAG Executive Committee at its meeting on June 26, 2015, in Prague, Czech Republic.

At its meeting in October 2015, the GB has decided to accept GFZ (German Research Center for Geosciences) as an Associated Center, following the recommendation of the Analysis Coordination, on the basis of the GFZ's DORIS analysis activities.

## 3 IDS Central Bureau

In 2015, the Central Bureau (CB) participated in the organization of the AWG meetings held at CLS in Toulouse on May 28 and 29, and at NASA/Goddard Space Flight Center in Greenbelt, Maryland, on October 15 and 16. It 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 IDS Activity Report 2014. In addition, it provided the IDS contributions to IERS Annual report 2014, IAG Travaux 2011–2015, and ICSU World Data System (ICSU-WDS) Biennial Report 2013–2014.

A report of the IDS Workshop 2014 has been written for publication in IAG Newsletter, January 2015 issue.

In January, the Central Bureau launched a new survey to hear from the IDS users about the services and ask them to give their feedback by filling a form on the web site. Questions from users concerning IDS data and products were answered or forwarded to other specialists.

**3.1 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 additions of documents, the website was enriched with new pages and received some slight modifications.

In order to help the access to an ever-increasing number of documents on the website, a new page “Documentation” was created in the section “Reports & Mails”. It gives a table compiling links to the various pages providing documents, grouped in four categories: DORIS system components; IDS information system; Publications, presentations; Documents (see <http://ids-doris.org/report/documentation.html>).

With the aim of giving a broader visibility and making the search easier, the full list of presentations given at DORIS or IDS meetings with the corresponding access links is now available on a unique page “Meeting presentations” in the section “Reports & Mails”. From October 2015, the new pages dedicated to each meeting do no longer contain the list of presentations but a link to this page (<http://ids-doris.org/report/meeting-presentations.html>).

To give an overview of the DORIS and IDS data and products, a new page “Tables of Data & Products” was created in the section “Data & Products”. It shows in tables the data and product provided by IDS with their main characteristics: latency, sample interval, archive locations, format, missions, content, provider (<http://ids-doris.org/data-products/tables-of-data-products.html>).

The section “Combination” in the part “Analysis coordination” was restructured. It contains now the two pages: “Contribution ITRF2008” (<http://ids-doris.org/combination/contribution-itrf2008.html>) and “Contribution ITRF2014” (<http://ids-doris.org/combination/contribution-itrf2014.html>).

The page with the composition of the Governing Board was revised. A table gives the list of the current and former members with position, term, status, affiliation: <http://ids-doris.org/organization/governing-board.html>

A new section “Satellites” in the part “DORIS system” has been open since early 2016: <http://ids-doris.org/satellites.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 IDS

Activity report 2015 (<http://ids-doris.org/report/governing-board.html#activity>).

**3.2 DOR-O-T, the IDS Web service**

The IDS Web service (<http://ids-doris.org/webservice>) named DOR-O-T for DORis Online Tools (pronounced like the French given name Dorothée) has been upgraded with a new plot tool to visualize the time series of Earth Orientation Parameters from the IDS Combination Center analysis (Xp, Yp, LOD) (<http://apps.ids-doris.org/apps/eoptool.html>).

**3.3 IDS Mail system**

Several types of emails are distributed by the IDS Central Bureau:

- DORISMail: general DORIS interest
- DORISReports: reports related to DORIS data and products
- AWG mailing list: technical discussion between analysis centers, combination and coordination
- DORISstations: information about station events (data gap, positioning discontinuities)

Everyone is welcome to subscribe to any of these emails. See more details on <http://ids-doris.org/report/mails.html>.

## 4 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:

- In January 2015, SSALTO developed improvements in the time tagging of DORIS measurements in the RINEX format (missions Jason-2, Cryosat-2, HY-2A, and SARAL). Updates were applied to RINEX data starting on January 20, 2015. Older RINEX data were reprocessed and submitted to the data centers in May 2015; these updated data files were named with a new version number to indicate a revised data set.
- Precise satellite orbits provided by SSALTO were updated to new Geophysical Data Record (GDR) standards (GDR-E) starting in April 2015. Orbit files for Jason-1, Jason-2, Cryosat-2, and SARAL were submitted using these standards with new version numbers; older files were archived to subdirectories by GDR designation. Other satellites (e.g., Envisat, HY-2A) will be updated to the GDR-E standards in the future and upcoming missions (e.g., Jason-3) will also utilize the GDR-E standards.

## 5 IDS Analysis Centers and IDS Analysis Coordination

The activities of the DORIS analysts in 2015 have been dominated by the IDS contribution to ITRF2014 and its evaluation, and the implementation of the DORIS RINEX data processing. Analysis working group meetings were held in Toulouse (France), May 28–29, 2015 at CLS, and in Greenbelt (Maryland, USA), October 15–16, 2015 at NASA/GSFC.

The first period of 2015 was devoted to the processing of the second half of 2014 and to the delivery of that time period to IDS Combination Center (CC) after the extension of ITRF2013 into ITRF2014. An evaluation of the preliminary version of ITRF2014 provided by IERS (Z. Altamimi) has been done by IDS CC, some Analysis Centers (ACs) and one Associated Analysis Center (AAC).

For the participation of the IDS to the realization of ITRF2014, the six active ACs agreed to submit new SINEX solutions. The CNES POD (Precise Orbit Determination) team has greatly contributed to this activity as the source of technical information about the spacecrafts and the measurements, and as the provider of DORIS data and orbit products. Two other institutions performing DORIS data processing participate in the analysis work: GeoForschungsZentrum (GFZ) and TU/Delft. GFZ is involved in the POD analysis of altimeter satellites and brought valuable contributions to the evaluation of the models and standards. TU/Delft routinely performs orbits of Cryosat-2 for calibration and validation, and made available the spacecraft quaternions to the community.

The list of the participating groups is given in Table 3. Some of the centers perform POD processing of DORIS satellites using other geodetic techniques (SLR, GNSS). The multi-technique analyses are useful since they can provide an independent assessment of DORIS system performance, and help validating model changes and implementations of attitude laws when spacecraft quaternions are not available.

We may mention that Marek Ziebart from University College/London and Geir Arne Hjelle from the Norwegian Mapping Authority (NMA) regularly attend the meetings of the Analysis Working Group. UCL is interested in working with individual DORIS ACs on the refinement of non-conservative force modeling for DORIS satellites. NMA plans to include DORIS in a geodetic multi-technique software (Where) under development. The participation of the NMA is, of course, strongly encouraged.

The second major work for the IDS ACs was to implement the RINEX/DORIS data processing in their software. Starting with Jason-2 in 2008, the satellites equipped with a DORIS receiver carry the new generation of receiver called DGXX which is able to track up to seven beacons simultaneously and provides phase and pseudo-range measurements. They are distributed in a dedicated format, called RINEX/DORIS 3.0, derived from the RINEX/

*Table 3: List of IDS Analysis Centers and Associated Analysis Centers participating in the analysis activities in 2015.*

| Group | AC | AAC | Other | Country | Software package | Multi-technique: DORIS + |
|---|---|---|---|---|---|---|
| ESA/ESOC | ✓ | | | Germany | NAPEOS | SLR, GNSS |
| Geodetic Observatory Pecny | ✓ | | | Czech Rep. | Bernese | - |
| CNES-CLS | ✓ | | | France | GINS/DYNAMO | SLR, GNSS |
| NASA/GSFC | ✓ | | | USA | GEODYN | SLR |
| IGN-JPL | ✓ | | | France | GIPSY/OASIS | - |
| INASAN | ✓ | | | Russia | GIPSY/OASIS | - |
| GFZ | | ✓ | | Germany | EPOS-OC | SLR, GNSS |
| CNES | | | ✓ | France | ZOOM | SLR, GNSS |
| TU Delft | | | ✓ | The Netherlands | GEODYN | SLR |

GPS 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 will be made available for the future missions, starting with Sentinel-3A and Jason-3.

Processing this new data format requires software upgrades for the Analysis Centers. Some groups have started this work and two ACs have completed. GRG AC has implemented the processing of RINEX/DORIS data files in the GINS software. GSC showed in Washington DC (October 2015) that they obtain encouraging results. Work is underway for GOP in cooperation with the Technical University of Munich (TUM), and for IGN.

This activity will prevail in 2016. The objective is to be ready to process the data of the new coming missions Jason-3 and Sentinel 3A.

## 6 IDS Combination

The IDS Combination Center started in 2015 by extending the IDS contribution to ITRF2014. Thus, the IDS contribution to ITRF2014 consists in a set of 1140 weekly solution files (including station coordinates and earth orientation parameters) from 1993.0 to 2015.0. All the details on the processing as well as on the evaluation of the IDS contribution to ITRF2014 can be found in Moreaux et al. (2016). Then, the IDS Combination Center developed a new chain to compute a DORIS position/velocity cumulative solution. The first objective of that new chain was to validate the IDS 09 series which is the IDS contribution to ITRF2014. The second objective was for the IDS Combination Center to succeed to P. Willis in the realization of ITRF extensions for precise orbit determination (the so-called DPOD cumulative position/velocity solutions). To validate its first cumulative solution from the 1140 SINEX files of the IDS 09 series, we compared the horizontal velocities with two global plate models. The validation of the DORIS vertical velocities were obtained by comparison with the ULR6 GNSS solution from La Rochelle University at 31 DORIS-GNSS co-localized sites. Late 2015, the IDS combined solution was updated by the addition of the first six months of 2015. In addition, the IDS Combination Center participated in the evaluation of the preliminary version of the IGN ITRF2014 realization. Last but not least, in 2015, the IDS Combination Center joined both EGU and AGU fall meetings where it presented one oral presentation and one poster respectively titled “IDS Combined Solution improvements between ITRF2008 and ITRF2014” and “Horizontal and vertical velocities derived from the IDS contribution to ITRF2014, and comparisons with external models”.

Moreaux, G., Lemoine, F.G., Capdeville, H., et al., 2016. The International DORIS Service contribution to the 2014 realization of the International Terrestrial Reference Frame. Adv. Space Res., doi: 10.1016/j.asr.2015.12.021.

## 7 Meetings

In 2015, the IDS organized two DORIS Analysis Working Group (AWG) meeting, first in Toulouse, France, on May 28 and 29, then in Greenbelt, Maryland, USA, on October 15 and 16.

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-05-2015.html>

<http://ids-doris.org/report/meeting-presentations/ids-awg-10-2015.html>

## 8 Publications

IDS published a 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

Again, the DORIS community had a productive year in 2015. The activities of the DORIS analysts have been dominated by the IDS contribution to ITRF2014 and its evaluation, and the implementation of the DORIS RINEX data processing. The effort will continue in 2016. On one hand, several issues raised during the ITRF processing remain to be addressed. On the other hand, the Analysis Centers must prepare for the new missions Jason-3 and Sentinel-3A launched early 2016.

*Laurent Soudarin*

# 3.5 Product Centres
## 3.5.1 Earth Orientation Centre

This section presents over the year 2015 the activities and main results of the Earth Orientation Centre located at Paris Observatory. According to the IERS Terms of Reference, this component is responsible for monitoring Earth Orientation Parameters including long term consistency, publications for time dissemination (DUT1) and leap second announcements. Earth Orientation Parameters (EOPs: Polar motion, Universal Time (UT1), Length of Day (LOD) and Celestial pole offsets) are available to a broad community of users in various domains such as astronomy, geodesy, geophysics, space sciences and time. EOPs are firstly collected in the form of combined solutions derived by the Technique Centres (IGS, IVS, ILRS and IDS). Two main solutions are computed: a long-term solution (IERS C01) since 1846 until the end of last year and the Bulletin B / C04 given at one-day intervals and which is published monthly with a 30 day delay (Gambis, 2004; Bizouard and Gambis, 2009; Gambis and Luzum, 2011).

An important issue is the maintenance of the consistency between the EOP system and both the terrestrial and celestial reference frames. So far, Earth Orientation Parameters and the terrestrial frame are separately computed. This lead in the past to increasing inconsistencies between both systems. At the end of 2009, these inconsistencies were small but significant for polar motion (negligible for the x-pole component and about 50 microarcseconds for the y-pole component). All IERS reference solutions (C01, Bulletin B, C04 as well as Bulletin A derived by the Rapid Service/Predictions Center, US Naval Observatory) were recomputed and aligned to the EOP solution associated to the current ITRF2008. Inconsistencies are now negligible compared to the current accuracies, i.e. limited to about 10 microarcseconds for polar motion and a few microseconds for UT1.

Recently C04 software and data base procedures have been upgraded. We combine directly the celestial pole offsets with respect to IAU 2000 precession-nutation model. If IVS analysis centres provide them with respect to the IAU 1980 model, they are transformed into IAU 2000 consistent offsets according to a rigorous procedure based upon Standards of Fundamental Astronomy software libraries (SOFA). Moreover uncertainties are directly estimated from the formal uncertainties of the individual series and their weights reflecting the intra-technique dispersion.

**Combined daily series: Bulletin B and C04, statistics over 2014–2015**

Tables 1 to 3 present statistics in term of formal errors and Weighted Root Mean Square (WRMS) of the combined technique centres and individual solutions with respect to the combined solution Bulletin B / C04 over the period 2014–2015. Combined solutions

*Table 1: Standard deviation of the intra-techniques solutions with respect to the combined solutions Bulletin B / C04 over 2014–2015. The satellite techniques provide information on the length of day excess (LOD) – equal to the opposite of the daily variation of Universal Time – contaminated by effects due to non-modelled orbit node motion. VLBI-based results have been used to minimize drifts in LOD estimates. Solutions contributing to Bulletin B / C04 combined solutions are referred to with a star (*).*

| Intra-technique solutions | Estimated uncertainties | | | | |
|---|---|---|---|---|---|
| | Time sampling | Terrestrial Pole µas | UT1 µs | LOD µs | Celestial Pole µas |
| **VLBI – 24 h** | | | | | |
| EOP(AUS) | ~ 4 d | 313.5 | 21 | | 116.0 |
| EOP(BKG)* | ~ 3 d | 246.5 | 15 | | 78.5 |
| EOP(GSFC)* | ~ 3 d | 413.0 | 22 | | 67.5 |
| EOP(IAA) * | ~ 4 d | 172.0 | 13 | | 113.5 |
| EOP(OPA) * | ~ 3 d | 428.0 | 19 | | 162.5 |
| EOP(USNO) | ~ 4 d | 151.5 | 12 | | 40.5 |
| EOP(IVS) * | ~ 4 d | 70.5 | 13 | | 25.0 |
| **VLBI – Intensive** | | | | | |
| EOP(BKG) * | ~ 1 d | | 23 | | |
| EOP(GSFC) * | ~ 1 d | | 25 | | |
| EOP(IAA) * | ~ 2 d | | 31 | | |
| EOP(PUL) | ~ 1 d | | 26 | | |
| EOP(USNO) * | ~ 1 d | | 138 | | |
| **SLR** | | | | | |
| EOP(MCC) | ~ 1 d | 169.5 | | 193 | |
| EOP(IAA) | ~ 1 d | 208.0 | | 25 | |
| EOP(ASI) | ~ 1 d | 255.0 | | 66 | |
| EOP(ILRS) * | ~ 1 d | 204.5 | | 27 | |
| **GPS** | | | | | |
| EOP(CODE) * | ~ 1 d | 43.5 | | 10 | |
| EOP(JPL) | ~ 1 d | 54.0 | | 17 | |
| EOP(GFZ) | ~ 1 d | 50.5 | | 12 | |
| EOP(ESOC) | ~ 1 d | 50.0 | | 12 | |
| EOP(NOAA) | ~ 1 d | 53.0 | | 11 | |
| EOP(SIO) | ~ 1 d | 54.5 | | 25 | |
| EOP(EMR) | ~ 1 d | 56.0 | | 23 | |
| EOP(IAA) | ~ 1 d | 63.0 | | 13 | |
| EOP(GRGS) | ~ 1 d | 49.5 | | 24 | |
| EOP(ASI) | ~ 4 d | 43.5 | | 48 | |
| EOP(MIT) | ~ 1 d | 51.5 | | 12 | |
| EOP(IGR) * | ~ 1 d | 41.5 | | 8 | |
| EOP(IGS) * | ~ 1 d | 42.5 | | 9 | |

*Table 2: Mean and standard deviation in microarcsecond of the differences between various combined techniques solutions entering the combination and Bulletin B / C04 over 2014–2015.*

| EOP | IGS Comb – IERS 08C04 | | ILRS Comb – IERS 08C04 | | IVS Comb – IERS 08C04 | |
|---|---|---|---|---|---|---|
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation |
| X (μas) | –18 | 26 | 171 | 214 | 69 | 68 |
| Y (μas) | –5 | 27 | 15 | 176 | 38 | 13 |
| UT1 (μs) | | | | | 2 | |
| LOD (μs) | 0 | 9 | 2 | 27 | | 32 |
| Dψsinε (μas) | | | | | 44 | 29 |
| Dψ (μas) | | | | | 24 | 49 |

*Table 3: Mean and standard deviation for Pole components and UT1 of the differences between combined solutions derived by both the Rapid Service/Prediction Center at USNO, the JPL and Bulletin B / C04 over 2014–2015.*

| EOP | Unit | Bull A – Bull B | | Comb JPL – Bull B | |
|---|---|---|---|---|---|
| | | Mean | Standard deviation | Mean | Standard deviation |
| X | μas | –13 | 51 | 62 | 88 |
| Y | μas | –20 | 47 | –185 | 41 |
| UT1 | μs | 3 | 21 | 13 | 29 |

derived by the various Technique Centres (IGS, ILRS, and IVS) are mostly used in the IERS combinations with the additions of some VLBI series for Universal Time and nutation for time series densification (intensive for UT1 and standards for nutation). Statistics concerning individual series are currently given as a feedback to the analysis centres.

## New format of Bulletin B since January 2010

A new presentation is available since January 2010. The new Bulletin B and its content description are available at <ftp://hpiers.obspm.fr/iers/bul/bulb_new/bulletinb.dat> and <ftp://hpiers.obspm.fr/iers/bul/bulb_new/bulletinb.pdf>.

The content of Bulletin B is:

1 – DAILY FINAL VALUES AND PRELIMINARY VALUES OF x, y, UT1–UTC, dX, dY
and their respective uncertainties. Angular unit is milliarcsecond (mas), time unit is millisecond (ms).

2 – DAILY SMOOTHED VALUES OF CELESTIAL POLE OFFSETS (dPsi1980, dEps1980)

with respect to IAU 1980 precession-nutation model and their uncertainties.

3 – EARTH ANGULAR VELOCITY: DAILY VALUES OF LOD, OMEGA AT 0hUTC
LOD: Excess of the Length of day – 86400 s TAI
OMEGA: Earth angular velocity

4 – INFORMATION ON TIME SCALES: TAI–UTC, leap second announcements

5 – SUMMARY OF CONTRIBUTED EARTH ORIENTATION PARAMETERS SERIES

### Content of Bulletin B / C04

According to the IERS Message 198 (<http://datacenter.iers.org/eop/-/somos/5Rgv/getTX/2/message_198.txt >) and starting on 1 December 2012, the EOP C04 series is now delivered with 30-day latency. In other words, only final definitive values are included in it.

Users needing a long-term continuous series extending up to a recent date (including rapid solution over the most recent 30 days) have two possibilities:

1) Getting the C04 solution extending until the date 30 days back and available at

<ftp://hpiers.obspm.fr/iers/eop/eopc04/eopc04_IAU2000.YY> where YY is current two digit year,

and concatenate it with the Rapid solution (Bulletin A) issued from the Rapid Service/Prediction Center available at <ftp://maia.usno.navy.mil/ser7/finals2000A.daily>.

Due to differences in the delivery times of the two products, users should exercise caution in blending the files to ensure that there is continuity between Bulletin B / C04 and Bulletin A.

2) Getting the new OPA EOP solution consisting of a continuous series derived from the concatenation of the C04 series and the OPA rapid solution available at

<ftp://hpiers.obspm.fr/iers/series/opa/eopc04_IAU2000>.

### Long-term series: C 01 (1846–2014)

EOP(IERS) C01 is a series of Earth Orientation Parameters given at 0.1 year intervals from 1846 to 1889 (polar motion only) and 0.05 year interval from 1890 until now (polar motion, celestial pole offsets, UT1–UTC since 1962). For many decades, the observations were made using mostly visual and photographic zenith telescopes. Since the advent of the space era in the 1960’s, new geodetic techniques were used for geodynamics. Now, the global observing activity involves Very Long Baseline Radio Interferometry (VLBI), Lunar (LLR) and Satellite Laser Ranging (SLR), Global Positioning System (GPS) and more recently DORIS.

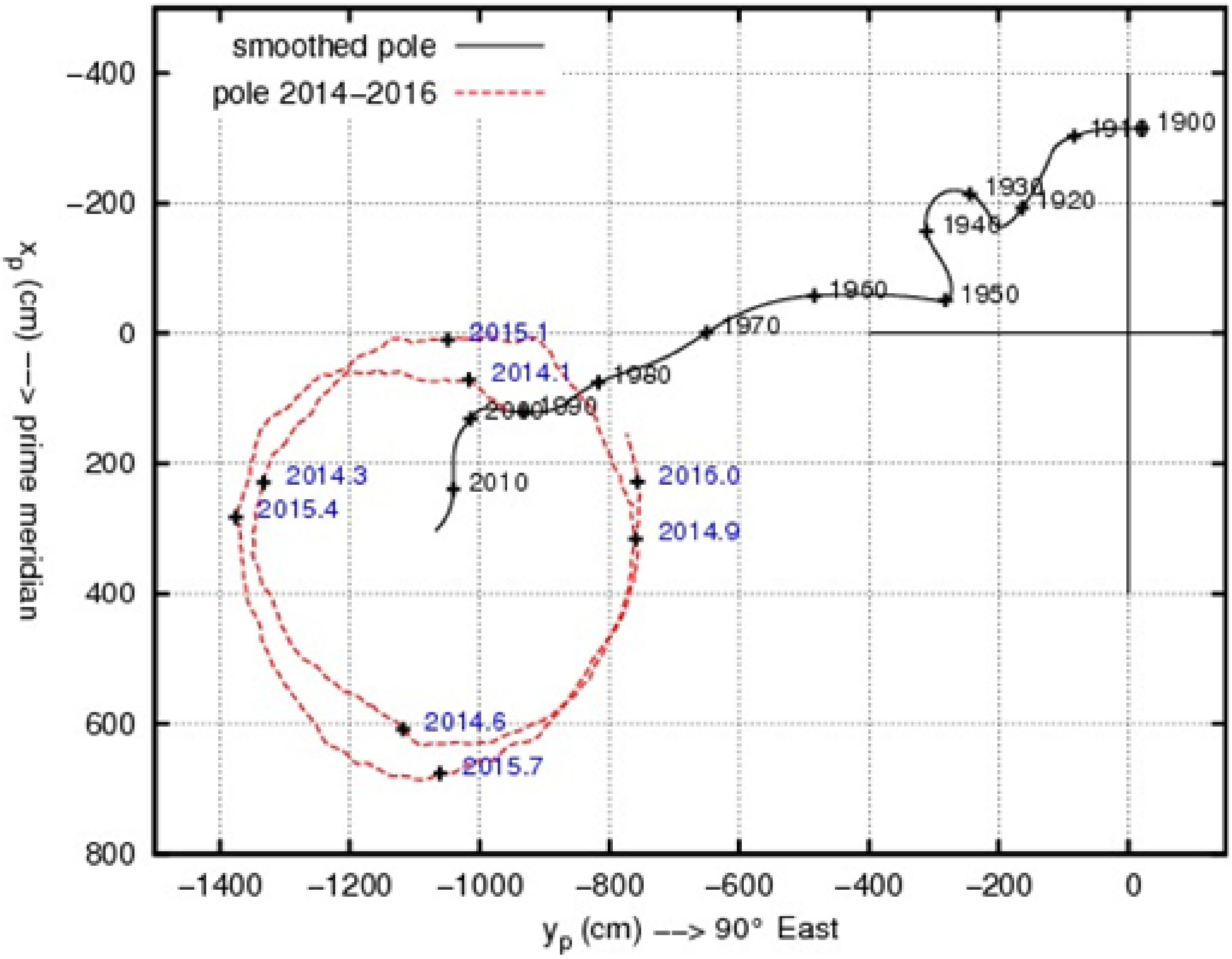



*Fig. 1: Mean polar motion (1900–2016.0) and IERS C04 polhody over 2014–2016.0.*

The C01 series is a composite series based on following temporal solutions:

1846–1899: Fedorov et al. (1972) polar motion solution derived from three series of absolute declination programs (Pulkovo, Greenwich, Washington).

1900–1961: Vondrak et al. (1995) solution derived from optical astrometry analyses based on the Hipparcos reference frame. The series gives polar motion, celestial pole offsets and Universal Time since 1956.

1962–2016.0: BIH and IERS solutions (BIH and IERS annual reports).

Figure 1 shows the mean polar motion over 1900–2016.0 as well as the C04 polhody over 2004–2016.0. The change of direction of the mean pole since the beginning of the 2000s is apparent. The origin can be attributed to a change in the Earth inertia momentum probably due to the ice cap melting effect.

## Mean Pole with respect to the IERS reference origin

The mean rotation axis with respect to the International Terrestrial Reference Frame can be considered as the long-term trend obtained after filtering out the sub-decadal polar motion, composed of Chandler, inter-annual, seasonal and sub-seasonal terms.

Figure 1 represents the polar motion over 2014–2016.0 and the path of the mean pole since 1900.

Until the 2000's the mean polar motion was affected by a long-term drift westward (direction 70.7 degree West, rate: 4.2 mas/yr). It appears clearly that since 2000, the mean pole direction has changed and is directed towards Greenwich meridian.

The mean pole since 1900 that is provided is obtained by applying a Gaussian filter on C01 pole coordinate time series. Corresponding data is available at <ftp://hpiers.obspm.fr/iers/eop/eopc01/mean-pole.tab>.

Mean pole coordinates have a great practical interest for estimating the effect of pole tide on C21 and S21 tesseral coefficients of the geopotential in light of the Earth response: for the solid Earth visco-elastic deformation for low frequency, quasi-elastic deformation for high frequency band; for sea level hydrostatic variation. As the frontier between both frequency domain for solid Earth response (decadal? pluri-decadal? secular?) is more a continuum than a cut-off frequency, Wahr et al. (2015) recommend to use a linear mean pole motion, compatible with glacial isostasic adjustment, rather than the IERS provided time series.

## Long term UT1/LOD (EOP C02: 1830–now)

For geophysical study, we propose a new product: a long term UT1/LOD series (with the label EOP C02). This series is extending from 1830 until now and is monthly updated.

This series is composite is available at <http://hpiers.obspm.fr/eoppc/series/longterm/eopc02.1830-now>.

It is composed of the following series:

1) 1830–1955: Delta T = TE – UT = TE – TAI – (UT – TAI) from Jordi et al. (1994), and obtained from the analysis of lunar occultations – mean sampling time of 120 days.

2) 1955–1962: from Vondrak et al. (1995) UT1 time series from optical astrometry.

3) 1962–now: Combined C04 time series free from short term zonal tides (< 2 years).

The series is realized according to the following steps:

- For optical astrometric data (Jordi et al., AICAS), prior to 1962, UT–TE / UT1–TAI series are smoothed by Gaussian filter with 365 day interpolation step.
- C04 series are smoothed using a Gaussian filter with a 200 day interpolation step.

- After filtering the total series, composed of UT–TE (prior to 1958) and UT1–TAI (after 1958), are interpolated by a cubic spline at 100 days step.
- Variation of the length of day LOD, given by LOD / D = –dUT1/dt where D = 86400 s is the duration of the day, is then obtained from a two point time derivative of the 100 day UT1 time series.

## Dissemination of UT1–UTC through the use of virtual observatory

Information concerning UT1–UTC and the occurrence of the leap seconds are currently made available via IERS Bulletin D and C. However, this old-fashioned procedure does not satisfy automatic systems. We have investigated the way to develop a new service based on the concept of Virtual Observatory (VO). This concept, provided by the International Virtual Observatory Alliance (IVOA), allows scientists and the public to access and retrieve UT1–UTC information using on-line distributed computational resources. We derived the concept, using the XML-based VO Table format to build this UT1–UTC dedicated new service (Deleflie et al., 2011).

The scientific community working in different field and requiring in particular UT1–UTC on a regular and reliable basis can benefit from the VO concept. The concept of metadata allows making available a single file with a description. Such tools can enhance the visibility of earth orientation parameters as well as UT1–UTC derived by the IERS.

## Development of a leap second Web service

A simple ASCII file giving the dates of insertion of leap seconds is available on the front page of the IERS Earth Orientation Centre at <http://hpiers.obspm.fr/iers/bul/bulc/Leap_Second_History.dat>.

The information about the potential introduction of a leap second is currently broadcast via Bulletin C. However, a procedure more adapted to the development of networks of servers becomes necessary and in particular, for programs like the NTP daemon which can use this file as authoritative server source. Such a procedure of providing and maintaining a leap second file via a secure protocol is now being developed at the Earth Orientation Centre.

## Staff

| | |
|---|---|
| Daniel Gambis | Astronomer, Head (until 31 Aug. 2015) |
| Christian Bizouard | Astronomer, Head (since 1 Sep. 2015) |
| Christian Bizouard | Astronomer (until 31 Aug. 2015) |
| Olivier Becker | Engineer |
| Teddy Carlucci | Engineer |
| Jean-Yves Richard | Engineer |
| Pascale Baudoin | Secretary |
| Sébastien Lambert | Astronomer (since 2015) |
| Daniel Gambis | Astronomer, retired (since 1 Sep. 2015) |

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*Christian Bizouard*

# 3.5.2 Rapid Service/Prediction Centre

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 2015. 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. Lastly, this section also contains an overview of the combination processing techniques and the prediction processing techniques, the activities under development to improve EOP results, and the web and FTP locations available to users for obtaining results.

## 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 08 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 2015 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 2015.

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 ($\delta\psi$, $\delta\varepsilon$, 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.

The 2015 UT1–UTC GSFC, USNO, and GSI VLBI Intensives Estimated Accuracy values, listed in Table 1, all improved as compared to the corresponding 2014 values[1]. The largest decrease in the RMS of the residuals was for the USNO intensives – 0.019 milliseconds in 2014 and 0.010 milliseconds in 2015; the second largest improvement was for the GSI intensives – 0.016 in 2014 and 0.010 in 2015; and the 3rd largest improvement was for the GSFC intensives – 0.020 in 2014 and 0.015 in 2015. There were also decreases in accuracy of UTGPS and the integrated IGS Ultra LODs; for UTGPS the residuals went from 0.016 in 2014 to 0.027 milliseconds in 2015 and for the integrated IGS Ultra LODs, the residuals went from 0.027 to 0.046.

Part of the reason for the improvement in VLBI intensives estimated accuracies (and the corresponding decrease in UTGPS and integrated IGS Ultra LODs) might be explained by the decrease in formal error that was reported by all the VLBI Intensives. The formal error is an internal estimate of the errors that occur during the observations, processing, and estimated solutions – a kind of precision estimate reported by each input contributor. As discussed earlier, the weightings – used in the smoothing, weighted

[1] The 2014 statistics are located in Table 1 of Section 3.5.2 of the IERS Annual Report 2014; located by clicking on the “Rapid Service/Prediction Centre” tab at <https://www.iers.org/AR2014>.

*Table 1: Estimated accuracies of the contributions to the IERS RS/PC combination results in 2015 with respect to the IERS RS/PC EOP series. Units are milliseconds of arc for x, y, δψ, δε, 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 | δψ (dX) | δε (dY) |
| ILRS SLR | 0.20 | 0.23 | | | |
| IAA SLR | 0.19 | 0.23 | | | |
| MCC SLR | 0.24 | 0.26 | | | |
| GSFC VLBI Intensives | | | 0.015 | | |
| USNO VLBI Intensives | | | 0.010 | | |
| GSI Intensives | | | 0.010 | | |
| GSFC VLBI | 0.16 | 0.11 | 0.006 | 0.32 | 0.18 |
| IAA+ VLBI | 0.27 | 0.19 | 0.009 | (0.11) | (0.16) |
| IVS+ VLBI | 0.10 | 0.21 | 0.003 | (0.05) | (0.04) |
| USNO VLBI | 0.14 | 0.20 | 0.006 | 0.41 | 0.16 |
| IGS Final | 0.01 | 0.01 | | | |
| IGS Rapid | 0.04 | 0.03 | | | |
| IGS Ultra* (observations) | 0.04 | 0.04 | 0.046* | | |
| USNO GPS UT* | | | 0.027* | | |

*All satellite techniques provide information on the rate of change of Universal Time contaminated by effects due to unmodeled orbit node motion. VLBI-based results have been used to correct for LOD biases and to minimize drifts in UT estimates.
+ IAA and IVS VLBI nutation values are in terms of dX/dY using IAU 2000A Nutation Theory (see Petit and Luzum, 2010).

cubic spline of the EOP combination – are partly a function of the formal error. There was a 17% decrease in formal error for USNO intensives, a 24% decrease for GSI intensives, and a 10% decrease for Goddard intensives. The reason for the improvement in formal error is currently being reviewed; and since it is possible that the decrease in formal error is only partly responsible for the improvement in estimated accuracy of the VLBI intensives, other reasons for the decreased residuals of the VLBI intensives are also being considered.

Although there was not much improvement in the VLBI 24-hour estimated accuracies from 2014 to 2015, there were small, but noticeable decreases in the formal error of the VLBI 24-hour results. The effect is to also increase the weighting these inputs have on the smoothing, cubic spline, while decreasing the relative weighting of other inputs.

The decrease in accuracy of UTGPS, from 2014 to 2015 (and as mentioned above), is also being reviewed. One partial explanation for this decrease is that since the UTGPS estimated accuracy is assigned a constant in the combination software, its relative weighting versus the VLBI intensives effectively decreased because the intensives weightings increased, as discussed in the previous paragraphs. Other factors are being considered as well.

The decrease in accuracy of the integrated IGS Ultra LODs is also being reviewed, and its relative weighting is also possibly affected by the decrease in the VLBI formal errors mentioned above when discussing the UTGPS estimated accuracies.

Operationally, the spline, which combines the contributors, 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, $\delta\psi$, and $\delta\varepsilon$ values are computed for the midnight (00:00) UTC epoch for each day.

While the celestial pole offset combination software can combine either $\delta\psi$ and $\delta\varepsilon$ or dX and dY, it uses $d\psi$ and $d\varepsilon$ for historical reasons. Therefore, the Institute of Applied Astronomy (IAA) and the International VLBI Service (IVS) VLBI dX and dY values are converted to $\delta\psi$ and $\delta\varepsilon$ 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.

Two groups of data points are excluded from the combination process. One group consists of the EOP inputs whose errors, as reported by the contributors, are 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[2] 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 removed, the input data are not corrected for these effects (see IERS Gazette No. 13, 30 January 1997).

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 2015; 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 – the

[2] The value of 4 was chosen to eliminate 4-sigma outliers and was determined via an empirical approach (email communication with Dr. Dennis McCarthy, 2015).

*Table 2: Mean and standard deviation of the differences between the Rapid Service/Prediction Center combination solutions and the 08 C04 EOP solutions for 2015. Polar motion x and y values are in milliseconds of arc and UT1–UTC values are in units of milliseconds of time. For the polar motion residuals, the values to the left of the "|" symbol have all outliers included; those to the right have outliers greater than 5-σ removed.*

| | Bulletin A – C04 | |
|---|---|---|
| | Mean | Std. Deviation |
| ***Bulletin A Rapid Solution (finals.data)*** | | |
| x | –0.02 \| –0.01 | 0.20 \| 0.05 |
| y | –0.02 \| –0.02 | 0.14 \| 0.04 |
| UT1–UTC | 0.003 | 0.021 |
| ***Bulletin A Weekly Solution (finals.data)***[1] | | |
| x | 0.01 \| 0.02 | 0.20 \| 0.08 |
| y | –0.02 \| –0.01 | 0.15 \| 0.06 |
| UT1–UTC | –0.007 | 0.037 |
| ***Bulletin A Daily Solution (finals.daily)*** | | |
| x | –0.02 \| 0.00 | 0.20 \| 0.06 |
| y | –0.00 \| 0.00 | 0.15 \| 0.05 |
| UT1–UTC | –0.017 | 0.056 |

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

"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. In addition, each day, the IERS RS/PC computes and publishes an EOP solution in the file "finals.daily". This file is also in 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.

As shown in Table 2, for the polar motion residuals, there were several large outliers, which were mainly due to unexpected and potentially suspect (for reasons explained below) 08 C04 results, and therefore, the polar motion statistics each have two reported results – one in a left and another in a right column, separated by the "|" symbol. The left column contains the statistics with all outliers included, and the right column has outliers greater than approximately 5-σ removed.

The 08 C04 is an IERS EOP reference series. It is customary in the international scientific community that (a) significant changes in algorithms used to compute such series and (b) changes to already-published series values are announced to the community prior to being made. However, the polar motion values for 2015 in the 08 C04 series have been changed several times per month since the start of 2016. This unusual circumstance has caused several challenges in determining the accuracies of the IERS RS/PC polar motion EOP solution. The reference series to which the RS/PC solution is compared, 08 C04, has not had stable 2015 values and also appears to have accuracy problems for polar motion, as will be shown below. For UT1–UTC, the 08 C04 solution does appear to be stable and reasonably accurate.

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 2015. The finals.data file used in computing these statistics was computed on January 14, 2016 (and also archived). Nominally, the last observational input data for the year (in this case, 2015) is processed and provided to the IERS RS/PC by January 14 of the following year (in this case, 2016); the last observational data is 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 2015 versus the 08 C04 series. These combination values for 2015 are the concatenation of all 53 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 8, 2015 has EOP combination results from January 2 through January 8, 2015.)

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 2015, versus the respective 08 C04 series solution for that epoch when it becomes available. The following will illustrate the process used in generating this section of Table 2. On May 6, 2015 (MJD = 57148), an EOP solution is produced a few minutes after 17:00 UTC on that day, and the solution is contained on the EOP server at <ftp://maia.usno.navy.mil/ser7/finals.daily> (and is archived appropriately). Within that file are generally 90 past EOP combination solutions, the solution on the current day, and 90 future EOP predictions starting from MJD 57059 to MJD 57239. (Note, the number of epochs before and after the current solution day may occasionally vary depending on the most recent observational data provided.) The EOP values on the row of the file corresponding to MJD 57148 is compared to the 08 C04 combination values corresponding to the same date and a residual is produced. This process is repeated for each MJD of 2015, and statistics on the set of residuals are computed.

Figures 1a and 1b contain plots of the 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. For 2015, there were several outliers for polar motion, as illustrated in Figure 1a. All the outliers for polar motion x, except for two, were determined to be due to issues with the 08 C04 series; all the polar motion y outliers were probably due to 08 C04 issues. As mentioned previously, an outlier was considered to be any residual with a value greater than 5-σ; there were 22 outliers for polar motion x and 10 for polar motion y.

The IERS RS/PC polar motion series had no significant outliers when compared to the ITRF 2014 series, which ended on February 14, 2015. When compared to the JPL Space[3] series, USNO had only two outliers for polar motion x and none for polar motion y. The potential, two identified IERS RS/PC polar motion outliers occurred on MJDs 57089 (March 8, 2015) and 57092 (March 11, 2015).

One cause of the large IERS RS/PC polar motion x outliers on those epochs was probably the removal of IGS ultra observation results. There was a problem with the UT1 solution that occurred on those two epochs, and in order to obtain a reasonable solution in LOD/UT1, some of the IGS ultra observations were removed from the combination; as a result, it was assumed that several of the IGS ultra EOP observations might have been poor for that day, and the polar motion contribution was removed as well.

Note that the statistics provided in Table 2 for polar motion (to the right of the "|" symbol) under "Bulletin A Daily Solution (finals. daily)" were provided with those two outliers and all other outliers removed. The IERS RS/PC can supply statistics with the associated outliers included upon request.

Starting on June 12, 2014 and continuing throughout 2015, the electronic transfer of VLBI data (e-VLBI) from the Kokee Park (Kk) radio telescope ceased, and this lack of e-VLBI transfer caused an increased latency in the time from VLBI intensive INT1 (Stamatakos et al., 2008) observation to correlation, fringing, analysis, and finally inclusion in the IERS RS/PC EOP UT1–UTC solution. The INT1 observational data from Kk had to be recorded on media and shipped via FedEx to USNO instead of being electronically transferred via e-VLBI. The latency increased from about 1 day before June 12, 2014 to 2 or 3 days (and occasionally longer) after that date. (During early 2016, e-VLBI was restored.)

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[3] The JPL SPACE series is the "JPL Operational Kalman Earth Orientation Series" found at
<ftp://euler.jpl.nasa.gov/keof/predictions/latest_midnight.eop>.

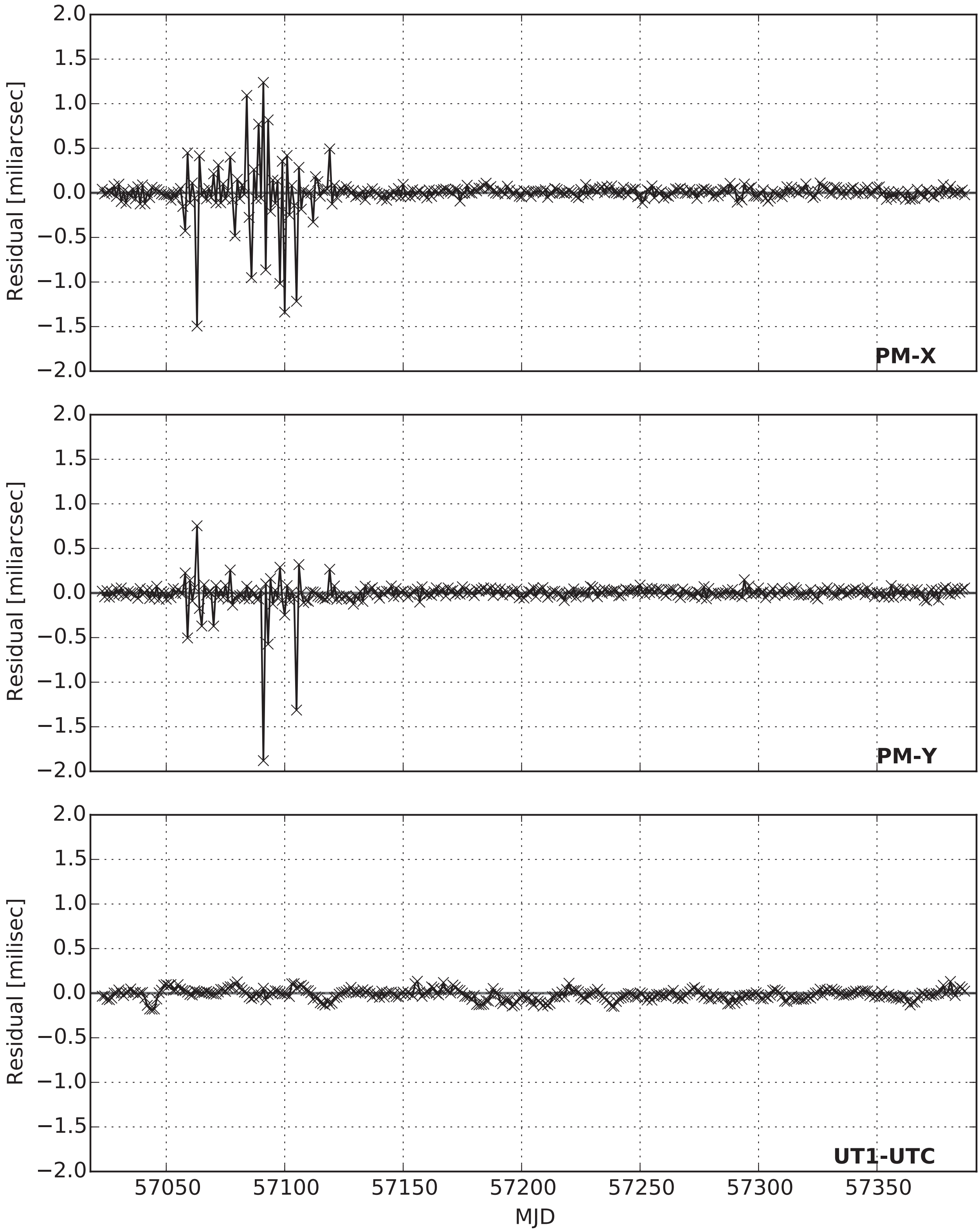


*Fig. 1a: Differences between the EOP solution updated daily (called the 'daily solution') for 2015 and the respective 08 C04 series combination solution (produced on 01 April 2016). For the polar motion residual plots, the y-axis limits were chosen to show all outliers; there were no such large outliers as shown on the UT1–UTC residual plot. The Earth Orientation Parameters shown are: a) Polar Motion X; b) Polar Motion Y; c) UT1–UTC.*

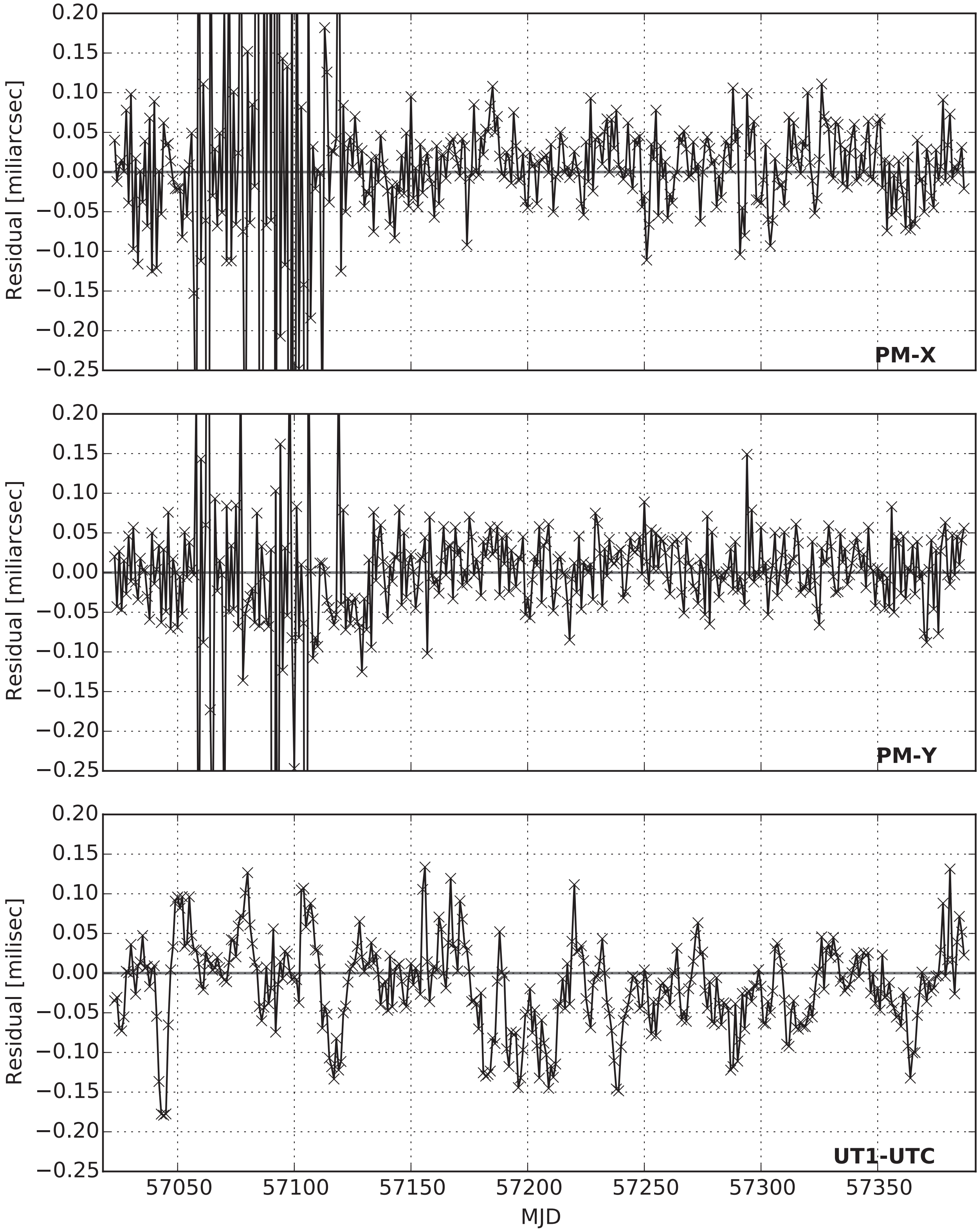


*Fig. 1b: Differences between the EOP solution updated daily (called the 'daily solution') for 2015 and the respective 08 C04 series combination solution (produced on 01 April 2016). For the polar motion residual plots, the y-axis limits were chosen to better show the signal of the non-outlier residuals; there were no such large outliers for the UT1–UTC residual plot. The Earth Orientation Parameters shown are: a) Polar Motion X; b) Polar Motion Y; c) UT1–UTC.*

There were no significant outliers for the UT1–UTC residuals. However, the RMS of the 0-day prediction residuals for 2015 was larger than that obtained for 2014. For 2015, the RMS was 0.058 milliseconds; whereas, for 2014, the RMS was 0.039 milliseconds. We suspect that part of the increase is due to the extra latency from VLBI intensives observation to inclusion of the result into the EOP combination. The lack of e-VLBI occurred for all of 2015; whereas, e-VLBI was functional from January 1 to June 11, 2014. This period from January to June, 2014, which had e-VLBI functioning, possibly had the effect of lowering the RMS of the residuals computed over the entire year of 2014.

## 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 Chandler terms is used to predict the deterministic process. The polar motion prediction is the addition of the deterministic and stochastic predictions. The additional unused terms in the deterministic solution help to absorb errors in the deterministic model caused by the variable amplitude and phase of the deterministic components (T. Johnson, personal communication, 2006). For more information on the implementation of the LS+AR model, see Stamatakos *et al.* (2008). A deficiency with the current implementation of this algorithm occasionally causes poor quality short-term polar motion predictions. Mitigation strategies are being investigated.

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

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

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

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 $\delta\psi$ and $\delta\varepsilon$ are based on the IERS Conventions (McCarthy, 1996; McCarthy and Petit, 2004).

Table 3a shows, for 2015, the RMS of the differences between the polar motion and UT1–UTC solution predictions produced daily at 17:00 UTC and those of the 08 C04 series. In computing the statistics for polar motion listed in Table 3a through 3d, several outliers greater than 5-σ were identified; the statistics shown for polar motion in these tables were computed with outliers greater than 5-σ removed. This issue is very similar to what was discussed earlier in the Combination Processing Techniques and Results section, which reviewed the polar motion residuals and associated outliers in Table 2; it has been determined that the outliers are mainly due to problems with the 08 C04 reference series. Statistics for the polar motion values listed in Tables 3a through 3d with all outliers included are available from the IERS RS/PC upon request.

Note that while choosing a 5-σ threshold for removing outliers was quite conservative and reasonable, it also left large outliers in the residuals negatively affecting the polar motion residual statistics for 2015. It has been determined that the vast majority of these smaller, but significant outliers are likely due to issues with the 08 C04 series. Therefore, the polar motion residuals statistics show

*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 2015. Note that the prediction length starts counting from the day after the date of the solution epoch.*

| Days in Future | PM-x Mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 0 | 0.06 | 0.05 | 0.058 |
| 1 | 0.34 | 0.24 | 0.073 |
| 5 | 2.02 | 1.18 | 0.207 |
| 10 | 3.42 | 2.01 | 0.567 |
| 20 | 5.50 | 3.09 | 2.319 |
| 40 | 9.34 | 4.69 | 5.897 |
| 90 | * | * | 17.253 |

*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 2015.*

| Days in Future | PM-x mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 0 | 0.07 | 0.05 | 0.056 |
| 1 | 0.30 | 0.21 | 0.071 |
| 5 | 1.97 | 1.13 | 0.206 |
| 10 | 3.39 | 2.01 | 0.567 |
| 20 | 5.46 | 3.07 | 2.321 |
| 40 | 9.31 | 4.68 | 5.909 |
| 90 | * | * | 17.273 |

*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 2015.*

| Days in Future | PM-x mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 0 | 0.07 | 0.06 | 0.055 |
| 1 | 0.25 | 0.09 | 0.070 |
| 5 | 2.02 | 1.08 | 0.206 |
| 10 | 3.68 | 1.97 | 0.567 |
| 20 | 5.71 | 2.98 | 2.322 |
| 40 | 9.59 | 4.68 | 5.909 |
| 90 | N/A | N/A | 17.278 |

*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 2015.*

| Days in Future | PM-x mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 0 | 0.07 | 0.06 | 0.053 |
| 1 | 0.22 | 0.09 | 0.068 |
| 5 | 1.86 | 1.09 | 0.205 |
| 10 | 3.50 | 1.96 | 0.566 |
| 20 | 5.60 | 3.00 | 2.323 |
| 40 | 9.54 | 4.69 | 5.915 |
| 90 | N/A | N/A | 17.301 |

** The number of days from the midnight epoch associated with the EOP solution generated at 17:00 UTC. E.g., the 1-day prediction epoch for all Nxdaily EOP solutions is shown in Figure 3.*

*** The 08 C04 combination solutions used for the residuals listed in Tables 3a through 3d were determined on April 4, 2015. Also, the statistics for polar motion do not include outliers greater than 5-σ Statistics with all outliers included are available from the IERS RS/PC upon request.*

a distinct decrease in accuracy from 2014 to 2015; this decrease, however, is probably not an issue with the IERS RS/PC solution, but rather a problem with 08 C04.

A plot of the polar motion path, with the corresponding 1-day prediction residual values for 2015, is shown in Figure 2. Each colored circle on the plot corresponds to the pole location at a midnight epoch during 2015, and the colors indicate the corresponding residual. The residual values correspond to the color-coded vertical bar at the right of the plot. The residuals are the RMS of the combined polar motion x and y residual values at each epoch. For this plot, the outliers greater than 5-σ were removed; and, therefore, gaps appear in the plot.

*Table 3e: RMS of the differences between the EOP time series predictions produced by the 2015 17:00 UTC daily EOP solutions and the corresponding 08 C04 combination solutions downloaded in May, 2016. The statistics for polar motion do not include outliers greater than 5-σ.*

| Days in Future | PM-x Mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 90 | 15.97 | 12.87 | 17.253 |

*Table 3f: RMS of the differences between the EOP time series predictions produced by the 2015 21:10 UTC daily EOP solutions and the corresponding 08 C04 combination solutions downloaded in May, 2016. The statistics for polar motion do not include outliers greater than 5-σ.*

| Days in Future | PM-x mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 90 | 15.93 | 12.85 | 17.275 |

*Table 3g: RMS of the differences between the EOP time series predictions produced by the 2015 03:10 UTC daily EOP solutions and the corresponding 08 C04 combination solutions downloaded in May, 2016. The statistics for polar motion do not include outliers greater than 5-σ.*

| Days in Future | PM-x mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 90 | 15.99 | 13.01 | 17.278 |

*Table 3h: RMS of the differences between the EOP time series predictions produced by the 2015 09:10 UTC daily EOP solutions and the corresponding 08 C04 combination solutions downloaded in May, 2016. The statistics for polar motion do not include outliers greater than 5-σ.*

| Days in Future | PM-x mas | PM-y mas | UT1–UTC ms |
|---|---|---|---|
| 90 | 15.97 | 12.97 | 17.301 |

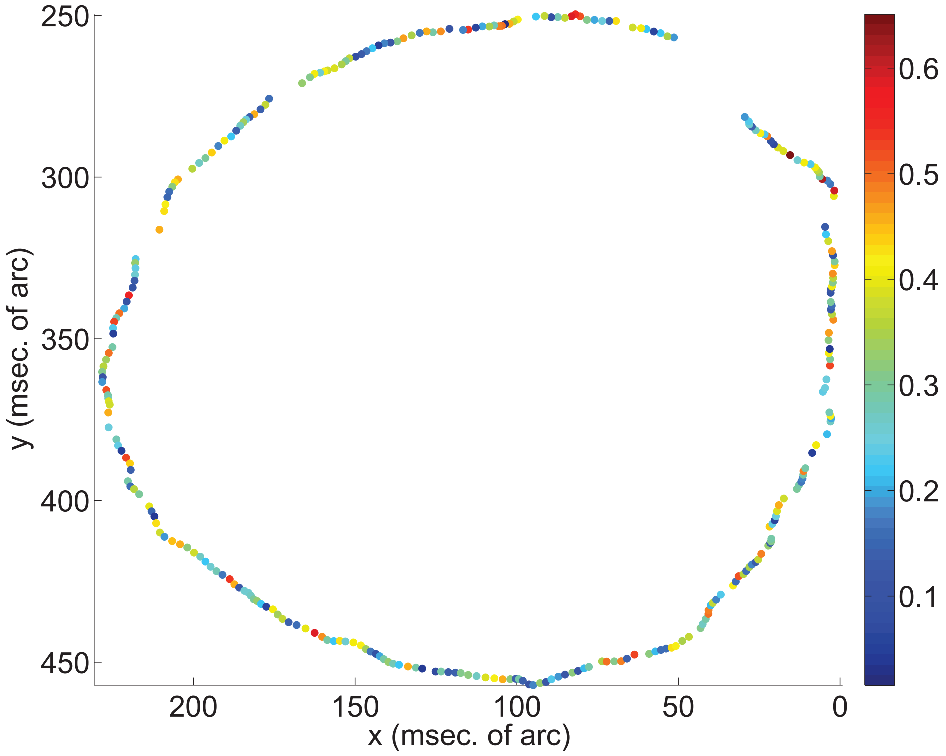


*Fig. 2: Plot of the polar motion path for 2015 with corresponding 1-day prediction residual values. Residual outliers values greater than 5-σ were removed. The residual is the RMS of the combined polar motion x and y residual values and is in units of milliseconds of arc. The error values correspond to the color-coded vertical bar at the right – ranging from less than 0.1 (dark blue) to greater than 0.6 (dark red) milliarcseconds.*

It has been noticed, as mentioned previously, that the polar motion section of the 08 C04 series has been changing its results for 2015 several times per month since the start of 2016. For previous annual reports, the Table 3 statistics were computed for rows, corresponding to 0 through 40-day predictions, using the 08 C04 series determined in April of the following year. The 08 C04 series is only updated up to 30 days prior to the current date. So, for example, on April 30, 2016, the latest possible EOP solution whose accuracy could be evaluated would be for March 31, 2016. Since it is desired to write this contribution to IERS Annual Report as early as possible, as much of the statistics as possible was computed in early April.

In order that the results in Table 3a through 3d remain self-consistent, the 90-day prediction results were omitted from those tables for polar motion. The 90-day prediction residual results for polar motion were made using the 08 C04 from early May 2016 and are listed in Tables 3e through 3f. In previous annual reports, in early May of the following year, the 90-day prediction statistics are normally computed (and simply added onto the rows in Tables 3a through 3d); that way all of the 365 90-day residuals versus the 08 C04 can be obtained. However, for 2016, the 08 C04 series results for polar motion changed significantly between April and May 2016. Therefore, for polar motion, the statistics for the 0 to 40-day predictions presented in Tables 3a through 3d that were computed using the early April 2016 08 C04 would have been different if using the 08 C04 results from May, 2016. Note, that the 08 C04 solution created in early May, 2016 also had significant outliers for polar motion, and the 08 C04 solution has been updated several times in June 2016.

Since the 08 C04 has not been changing for UT1–UTC, the prediction results for Table 3a through 3d are self-consistent. Therefore, the 90-day prediction is included in those tables.

The UT1–UTC RMS prediction statistics for 2015 were generally worse than for 2014. For example, for the 17:00 UTC solution 1-day prediction results, the RMS for 2015 was 0.073 milliseconds; for 2014 it was 0.058 milliseconds. A possible reason for part of the decrease in accuracy was that the e-VLBI was not functioning for all of 2015; whereas, it functioned for part of 2014. As discussed in the Combination Processing Techniques and Results, when the e-VLBI is not functioning there is extra latency from VLBI intensives observation to inclusion of the result into the EOP combination; the e-VLBI was not functioning for all of 2015 (but was resumed in early 2016). The e-VLBI was functioning from January 1 to June 11, 2014; however, it became non-functional starting on June 12, 2014.

In annual reports up through 2013, the prediction length (as shown in Tables 3a) was determined from the epoch of the last known VLBI or IGS observation, and not based on the date of the solution epoch. It has been determined that many EOP users base their inputs on the prediction from the date of the solution epoch, and also using this new paradigm simplifies the comparison of results among the 17:00 UTC EOP solution and the 21:10, 03:10 and 09:10 UTC solutions (which are discussed below). In general, the results are very similar since on most days an observation is made either on the solution day or the day before. The statistics based upon the older paradigm could be made available upon request from ser7@maia.usno.navy.mil.

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

At each Nxdaily UTC solution time listed in Tables 4a and 4b, major contributors, whose latencies between observations to availability to 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, a similar pattern for UT1–UTC to what was described above for polar motion is shown. 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. (After June 12, 2014 and throughout all of 2015, there was an e-VLBI outage at Kokee Park, and therefore, the INT1 VLBI intensive had an additional 2 to 3 days of latency. So, the Epoch at Midpoint value for this VLBI intensive was actually -24*X -05:00 hours, where “X” is the number of days of latency.) 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*.

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.

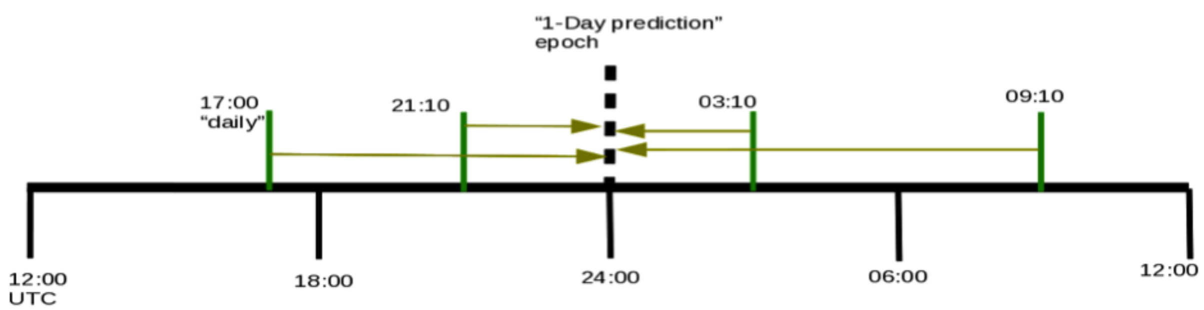


*Fig. 3: Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP “daily” solution produced at 17:00 UTC.*

*Tables 4a and 4b: Tables describing the data available for each of the Nxdaily solutions. Note: 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: Major Contributors for the Polar Motion EOP solution at the Nxdaily Solution Update Times.*

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

*Table 4b: Major Contributors for the UT1-UTC EOP solution at the Nxdaily Solution Update Times.*

| **1700 UTC solution** | | **2110 UTC solution** | | **0310 UTC solution** | | **0910 UTC solution** | |
|---|---|---|---|---|---|---|---|
| **Contributor** | **Epoch at Midpoint*** | **Contributor** | **Epoch at Midpoint*** | **Contributor** | **Epoch at Midpoint*** | **Contributor** | **Epoch at Midpoint*** |
| AAM LOD[3] | | AAM LOD[3] | | AAM LOD[3] | | AAM LOD[3] | |
| INT2 / 3 VLBI intensive[1] | +08:00 | INT2 / 3 VLBI intensive[1] | +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 intensive[1] | +08:00 | IGS 0 hr Ultra | +12:00 |
| INT1 VLBI intensive[2] | -05:00 | IGS 12 hr Ultra | 00:00 | IGS 18 hr Ultra | +06:00 | INT2 / 3 VLBI intensive[1] | +08:00 |
| IGS 6 hr Ultra | -06:00 | INT1 VLBI intensive[2] | -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 intensive[2] | -05:00 | IGS 12 hr Ultra | 00:00 |
| | | IGS Rapid | -12:00 | IGS 6 hr Ultra | -06:00 | INT1 VLBI intensive[2] | -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 EOP reported is the observation mid-point.

1 INT2 intensives are normally observed Saturday and Sunday and INT3s on Monday; both sets with an epoch at midpoint at approximately 08:00 UTC.

2 INT1 intensives are normally observed Monday through Friday with an epoch at midpoint at approximately 19:00 UTC. The Epoch at Midpoint value of -05:00 is an idealized situation. After June 12, 2014 and throughout 2015, there was an e-VLBI outage at Kokee Park; therefore the INT1 VLBI intensive had two or more days of latency. So, the Epoch at Midpoint was actually (-24*X -05:00) hours, where "X" is the number of days of latency.

3 The AAM LOD inputs contain 7.5 days of forecast data from 00:00 to 180:00 hours.

In general, each of the Nxdaily solutions for UT1–UTC made after the 17:00 UTC solution on day MJD, i.e. at 21:10 on day MJD, and 03:10 and 09:10 on day MJD+1, will have reduced residuals. For example, by examining the 1-day UT1–UTC prediction residual statistics in Tables 3a through 3d, one sees an improvement from 0.073, 0.071, 0.070, and to 0.068 milliseconds in the RMS, respectively. However, because of the outlier issues that occurred for polar motion (which was discussed previously in this section and in the Combination Processing Techniques and Results section), there is no consistent pattern when comparing polar motion RMS statistics among Tables 3a through 3d.

The predictions of celestial pole offsets (both dX/dY and $\delta\psi/\delta\varepsilon$ 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 2015 are provided in Table 5.

Predictions of TT–UT1, up to 1 January 2026, are given in Table 6. They are derived using a prediction algorithm similar to that employed in the Bulletin A predictions of UT1–UTC. Up to twenty years of past observations of TT–UT1 are used. Estimates of the expected one-sigma error for each of the predicted values are also given. These errors are based on analyses of the past performance of the model with respect to the observations.

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

*Table 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 2015.*

| Days in Future | dX mas | dY mas | $\delta\psi$ mas | $\delta\varepsilon$ mas |
|---|---|---|---|---|
| 0 | .14 | .14 | .34 | .17 |
| 1 | .15 | .14 | .35 | .17 |
| 5 | .15 | .15 | .37 | .17 |
| 10 | .17 | .16 | .40 | .18 |
| 20 | .19 | .17 | .45 | .20 |
| 40 | .23 | .21 | .56 | .24 |

*Table 6: Predicted values of TT–UT1, 2016–2026. 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) |
|---|---|---|
| 2016 Oct 1 | 68.47 | 0.01 |
| 2017 Jan 1 | 68.6 | 0.01 |
| 2017 Apr 1 | 68.8 | 0.02 |
| 2017 Jul 1 | 68.9 | 0.02 |
| 2017 Oct 1 | 69.1 | 0.2 |
| 2018 Jan 1 | 69.3 | 0.3 |
| 2018 Apr 1 | 69.4 | 0.4 |
| 2018 Jul 1 | 69.6 | 0.5 |
| 2018 Oct 1 | 69.7 | 0.6 |
| 2019 Jan 1 | 69.8 | 0.8 |
| 2019 Apr 1 | 69.9 | 0.9 |
| 2019 Jul 1 | 70.0 | 1.0 |
| 2019 Oct 1 | 70. | 1. |
| 2020 Jan 1 | 70. | 1. |
| 2020 Apr 1 | 70. | 1. |
| 2020 Jul 1 | 71. | 1. |
| 2020 Oct 1 | 71. | 2. |
| 2021 Jan 1 | 71. | 2. |
| 2021 Apr 1 | 71. | 2. |
| 2021 Jul 1 | 71. | 2. |
| 2021 Oct 1 | 71. | 2. |
| 2022 Jan 1 | 71. | 2. |
| 2022 Apr 1 | 71. | 2. |
| 2022 Jul 1 | 72. | 3. |
| 2022 Oct 1 | 72. | 3. |
| 2023 Jan 1 | 72. | 3. |
| 2023 Apr 1 | 72. | 3. |
| 2023 Jul 1 | 72. | 3. |
| 2023 Oct 1 | 72. | 3. |
| 2024 Jan 1 | 72. | 4. |
| 2024 Apr 1 | 72. | 4. |
| 2024 Jul 1 | 73. | 4. |
| 2024 Oct 1 | 73. | 4. |
| 2024 Oct 1 | 73. | 4. |
| 2025 Jan 1 | 73. | 4. |
| 2025 Apr 1 | 73. | 4. |
| 2025 Jul 1 | 73. | 5. |
| 2025 Oct 1 | 73. | 5. |
| 2026 Jan 1 | 73. | 5. |

## Center Activities in 2015

During 2015, 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 v1.2 to v1.3 in April, 2015;

b) the USNO VLBI 24-hour and intensive data series was upgraded from the usno2014a to usno2015a series on April 30, 2015;

c) the USNO VLBI 24-hour and intensive data series was upgraded from the usno2015a to usno2015b series on December 10, 2015.

Also, 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) using combined AAM and OAM inputs to improve polar motion predictions (Stamatakos *et al.*, 2016), and c) studying methods to better optimize the use of the IGS Ultra-rapid observations for LOD inputs to the EOP solution.

In addition, preparations were made to change the methodology used to compute IERS RS/PC celestial pole offsets. This new code uses computations based on the dX and dY as opposed to the $\delta\psi$ and $\delta\varepsilon$ paradigm, and thus it will accept VLBI dX and dY inputs. Only minor changes to the code are needed to make it operational; however, it was decided to delay operational implementation until the next OP series after the 08 C04, since OP has stated that they will also use computations based on the dX and dY paradigm. By waiting for the new C04 series, the IERS RS/PC and EOC series for celestial pole offsets can then be cross-validated.

The Earth Orientation transformation matrix calculator[4] 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 will provide 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

[4] <http://maia.usno.navy.mil/t2c36e/t2c36e.html>

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

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

[a] The word “Int” is an abbreviation for the word Intensive.

[b, c, d, e, f] Defined in the Acronyms section of the Appendix of this report.

[g] Both combination and prediction values are available.

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, $\delta\psi$ and $\delta\varepsilon$ from International Radio Interferometric Surveying (IRIS) VLBI.

The data described above are available from the IERS RS/PC in a number of forms. You may also request a weekly machine-readable version of the IERS Bulletin A containing the current 365 days’ worth of predictions via electronic mail from ser7@maia.usno.navy.mil or through <http://www.usno.navy.mil/USNO/earth-orientation>.

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>.

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; the actual solution time may occur 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 server locations and update times.*

| EOP solution time (UTC)[1] | Subdirectory Location | Approximate time solution is posted[1] |
|---|---|---|
| 17:00 | ser7 | 17:15[2] |
| 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 at 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; Research Astronomer, EOP C/P Division |
| Mr. Nathan Shumate | Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division |
| Ms. Maria Davis | Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division |

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Report contributors:

*Nicholas Stamatakos, Maria Davis, Nathan Shumate, Merri Sue Carter*

Report reviewer:

*Christine Hackman*

## 3.5.3 Conventions Centre

The Conventions Center is operated jointly by the Bureau International des Poids et Mesures (BIPM) and the U.S. Naval Observatory (USNO).

The Conventions Center provides updated versions of the IERS Conventions in electronic form, after approval of the IERS Directing Board. 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 2015, the work accomplished or in progress includes the following:

### 1. Technical content of the IERS Conventions

Work started on the updates to the IERS Conventions (2010) soon after the publication of this new reference edition. Note that the published IERS Conventions (2010) is available in electronic form (<http://tai.bipm.org/iers/conv2010/>) and as IERS Technical Note 36. The list below summarizes the updates made in 2015. See <http://tai.bipm.org/iers/convupdt/convupdt.html> (or the site at <http://maia.usno.navy.mil/conv2010/convupdt.html>) for details.

- Revision to adopt the new conventional mean pole coordinates for Chapter 7 (Displacements of reference points) was implemented. In addition, typos in the paragraph following Table 7.1 and in Section 7.1.5 were corrected.

### 2. Conventions software

The most significant update was the addition of the routine IERS_CMP_2015 that provides the IERS Conventional Mean Pole. The routines HARDISP, ETUTC, DAT, and DEHANTTIDEINEL were updated to account for the leap second of 30 June 2015. The subroutine TDFRPH was corrected for a typo and the test case was updated in the TDFRPH.F subroutine. The test run of the ocean pole tide model had missing information provided so that the complete inputs are defined. Finally, routine CAL2JD was updated from the eleventh release of the SOFA package.

### 3. Planned Changes

A study group was established to review compatibility of models for VLBI and SLR in an effort to reduce the discrepancy in scale observed by the two techniques. Discussions continued regarding the update of the conventional geopotential model (Chapter 6), notably its time-varying part (low degree coefficients, seasonal variations). Associated topics such as conventional models for the geocenter motion in the ITRF and the IERS mean pole were also covered. Investigation into non-tidal displacement of reference markers continues and may lead to a new section for Chapter 7. In response to concerns regarding the quality of existing models for diurnal and semi-diurnal EOP variations in Chapter 8, efforts to identify improved models continued. In addition to improvements in content, the IERS Conventions Center is considering the electronic content of the document, version control, and other ways to improve the quality and usability of the IERS Conventions.

## 4. Dissemination of information

The Conventions web pages at the BIPM (<http://tai.bipm.org/iers/>) and the USNO (<http://maia.usno.navy.mil/conv2010/>) were maintained.

Past updates to the IERS Conventions (2003), from 2004 until the release of the IERS Conventions (2010), were archived separately from the current updates, at <http://tai.bipm.org/iers/conv2010/convupdt/convupdt.html>.

## 5. Conventions Center staff

Felicitas Arias (BIPM)
Christian Bizouard (OP), co-director (since 1 September 2016)
Merri Sue Carter (USNO)
Maria Davis (USNO)
Brian Luzum (USNO), co-director (until 31 December 2015)
Gérard Petit (BIPM), co-director (until 31 August 2016)
Nick Stamatakos (USNO), co-director (since 1 January 2016)

*Brian Luzum, Gérard Petit*

# 3.5.4 ICRS Centre

## Introduction

The IAU has charged the IERS with the responsibility of monitoring the International Celestial Reference System (ICRS), maintaining its current realization, the International Celestial Reference Frame (ICRF), and maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities have been run jointly by the ICRS Centre (Observatoire de Paris and US Naval Observatory) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU. The present report was jointly prepared by the Paris Observatory and US Naval Observatory components of the ICRS Centre. The ICRS Centre web site <http://hpiers.obspm.fr/icrs-pc> provides information on the characterization and construction of the ICRF (radio source nomenclature, physical characteristics of radio sources, astrometric behavior of a set of sources, radio source structure). This information is also available by anonymous ftp (<hpiers.obspm.fr/icrs-pc>), and on request to the ICRS Centre (icrspc@hpopa.obspm.fr).

## Maintenance and extension of the ICRF and investigation of future realizations of the ICRS

The International Celestial Reference System (ICRS), adopted by the International Astronomical Union (IAU) in 1997, forms the underlying basis for all astrometry by defining the reference directions of a quasi-inertial celestial coordinate system that are fixed with respect to the most distant objects in the universe. Since 1 January 1998, the ICRS has been realized by the International Celestial Reference Frame (ICRF), which is based on the radio wavelength astrometric positions of compact extragalactic objects determined by the technique of very long baseline interferometry (VLBI).

At the XXVII General Assembly of the IAU held in Rio de Janeiro, Brazil, a second realization of the International Celestial Reference Frame (ICRF2; Fey, Gordon and Jacobs 2009; Fey et al. 2015) was adopted as the fundamental celestial reference frame as of 1 January 2010. ICRF2 is again based on the radio wavelength astrometric positions of compact extragalactic objects determined by the technique of VLBI. Significant developments and improvements in geodetic/astrometric VLBI observing and analysis have been made since the initial generation of the ICRF, hereafter ICRF1. Sensitivity of VLBI observing systems to weaker sources and overall data quality have improved significantly due to advances in VLBI receiver and recording systems and due to better observing strategies coordinated by the International VLBI Service for Geodesy and Astrometry (IVS). The use of newer and more modern radio telescopes, such as the 10-station Very Long Baseline Array (VLBA) of the National Radio Astronomy Observatory (NRAO) has also greatly improved the sensitivity and quality of recent data. Further, enhanced geophysical modeling and computers with faster processors have allowed significant improvements in data analysis techniques and astrometric position estimation.

ICRF2 contains precise positions of 3414 compact extragalactic sources, more than five times the number as in ICRF1. The ICRF2 has a noise floor of approximately 40 micro-arcseconds, some 5–6 times better than ICRF1, and an axis stability of approximately 10 micro-arcseconds, nearly twice as stable as ICRF1. Alignment of ICRF2 with the ICRS was made using 138 stable sources common to both ICRF2 and ICRF1. Maintenance of ICRF2 is made using a set of 295 "defining" sources selected on the basis of positional stability and the lack of extensive intrinsic source structure. The stability of these 295 defining sources and their more uniform sky distribution addresses the two largest weaknesses of ICRF1.

At the IAU General Assembly in Beijing in August 2012, ICRS Centre personnel organized an effort to establish an IAU Working Group on ICRF3. The effort was well received by the IAU. A steering committee was established which met in Beijing and subsequently in October 2012 in Bordeaux. The steering committee wrote a charter for the working group, established working group membership, and selected a working group chair. The IAU subsequently accepted all these and formally established the working group.

The ICRF3 Working Group has since pursued new observations that filled gaps and improved weaknesses of ICRF2, including additional observing at higher radio frequencies, e.g., K-band (24 GHz), Ka-band (32 GHz), and Q-band (43 GHz), where contributions to source position uncertainties from intrinsic source structure and from the Earth's ionosphere will be less than that at the radio frequencies currently used for astrometric/geodetic VLBI, and second epoch observations of VLBA Calibrator Survey sources (Gordon et al. 2016). The ICRF3 Working Group presented a progress report to the IAU General Assembly in 2015 and continued to pursue the completion of ICRF3 in 2018.

In the coming decades, there will be significant advances in the area of space-based optical astrometry. Missions such as the European Space Agency's (ESA) Gaia mission, which launched 19 December 2013, are expected to achieve astrometric positional accuracies equal to or better than the accuracies presently obtained by ground-based radio interferometric measurements. Whether future versions of the ICRF exist at multiple wavelengths or are transitioned from the radio to the optical depends at least partially upon the relative astrometric accuracy of future radio- and optical-based reference frames.

## Analysis of recent VLBI catalogs

### Data sets

Six catalogs were submitted respectively in 2015 by the Italian Space Agency (ASI; asi2015a), Geoscience Australia (aus2015c; aus2016a/b), the Federal Agency for Cartography and Geodesy (BKG Leipzig) and Institute of Geodesy and Geoinformation of the University of Bonn (IGGB) (bkg2015a), and the US Naval Observatory (usn2015b). All these catalogs provide right ascension ($\alpha$) and declination ($\delta$) of extragalactic radio sources, as well as their respective uncertainties, the correlation coefficient between $\alpha$ and $\delta$ and the number of sessions and delays. Note that bkg2014a and usn2015a were produced with the same geodetic VLBI analysis software package SOLVE developed at NASA GSFC. Solutions aus2015c and aus2016a/b were produced with OCCAM.

Table 1 displays the total number of sources of each catalog, as well as the number of ICRF2 sources (out of 3414) and ICRF2 defining sources (out of 295). Some catalogs do not provide values for some defining sources, likely because they do not process some sessions that were present in the session list processed to generate the ICRF2 catalog. We recommend that the analysis centers pay attention to their session list in order to get values for all 295 ICRF2 defining sources. As well, none of the catalogs provide values for all 3414 ICRF2 sources (as was previously noted in the 2014 Annual Report).

The median error reported in Table 1 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 asi2015a 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.

### Frame orientation

We evaluate the consistency of the submitted catalogs with the ICRF2 by modeling the coordinate difference (in the sense catalog minus ICRF2) by a 6-parameter transformation as used at the IERS ICRS Center in previous comparisons:

*Table 1: Number of sources by categories and median error. Unit is µas. Values for right ascension are corrected from the cosine of the declination.*

| | No. Sources | | | Median Error | |
|---|---|---|---|---|---|
| | Total | ICRF2 | Def | RA | Dec |
| asi2015a | 944 | 936 | 294 | 37.3 | 41.2 |
| aus2015c | 3683 | 3235 | 295 | 1276.5 | 1780.0 |
| aus2016a | 3900 | 3282 | 295 | 526.5 | 728.0 |
| aus2016b | 3917 | 3288 | 295 | 520.5 | 700.0 |
| bkg2015a | 3398 | 3112 | 294 | 284.6 | 430.2 |
| usn2015b | 4110 | 3316 | 287 | 231.0 | 333.7 |

$$A1 \tan \delta \cos \alpha + A2 \, \mathrm{tg} \, \delta \sin \alpha - A3 + DA (\delta\text{-}\delta_0) = \Delta\alpha,$$
$$-A1 \sin \alpha + A2 \cos \alpha + DD (\delta\text{-}\delta_0) + BD = \Delta\delta,$$

where A1, A2, A3 are rotation angles around the X, Y, and Z axes of the celestial reference frame, respectively, DA and DD represent linear variations with the declination (which origin $\delta_0$ can be arbitrarily chosen but was set to zero in this study), BD is a bias in declination, and $\Delta\alpha$ and $\Delta\delta$ are coordinate differences between the studied and the ICRF2 catalogs. The 6 parameters were fitted by weighted least squares to the coordinate difference of the defining sources (upper part of Table 2) and ICRF2 sources (lower part of Table 2) found in the catalog. The standard deviation of the offsets to ICRF2 after removal of the systematics of Table 2 is reported in Table 3 together with the median offset.

The three Australian solutions show non statistically significant rotations and deformations with respect to the ICRF2. Significant misorientation around A2 larger than 10 mas (4 sigmas) are found

*Table 2: Rotation parameters with respect to ICRF2. A1, A2, A3 and BD are in µas. DA and DD are in µas per degree.*

| | A1 | A2 | A3 | DA | DD | BD |
|---|---|---|---|---|---|---|
| Defining sources | | | | | | |
| asi2015a | -2.3 | 16.4 | -13.1 | 0.2 | 1.0 | -68.5 |
| +- | 3.6 | 3.6 | 3.3 | 0.1 | 0.1 | 3.5 |
| aus2015c | -9.5 | 2.9 | 2.2 | -0.0 | 0.2 | 3.0 |
| +- | 3.0 | 3.0 | 2.9 | 0.1 | 0.1 | 2.9 |
| aus2016a | -6.3 | 2.1 | 4.5 | -0.0 | -0.0 | 4.2 |
| +- | 3.4 | 3.4 | 3.2 | 0.1 | 0.1 | 3.3 |
| aus2016b | -4.6 | -0.3 | 4.8 | 0.1 | -0.1 | 4.8 |
| +- | 3.0 | 3.0 | 2.8 | 0.1 | 0.1 | 2.9 |
| bkg2015a | -9.3 | 12.3 | -9.1 | 0.2 | 1.1 | -64.2 |
| +- | 4.3 | 4.3 | 3.8 | 0.1 | 0.1 | 4.2 |
| usn2015b | -7.2 | 16.3 | -0.4 | 0.2 | 0.9 | -53.2 |
| +- | 3.8 | 3.8 | 3.3 | 0.1 | 0.1 | 3.6 |
| All common sources | | | | | | |
| asi2015a | 2.5 | 18.9 | -14.1 | 0.2 | 1.2 | -70.6 |
| +- | 2.8 | 2.8 | 2.6 | 0.1 | 0.1 | 2.6 |
| aus2015c | -4.4 | 2.2 | -3.9 | -0.1 | 0.3 | 0.6 |
| +- | 1.2 | 1.2 | 1.2 | 0.0 | 0.0 | 1.1 |
| aus2016a | -1.8 | 1.3 | -3.3 | -0.2 | 0.1 | 1.2 |
| +- | 1.2 | 1.2 | 1.1 | 0.0 | 0.0 | 1.1 |
| aus2016b | -0.5 | 0.1 | -0.2 | -0.0 | 0.0 | 0.2 |
| +- | 0.2 | 0.2 | 0.2 | 0.0 | 0.0 | 0.2 |
| bkg2015a | -4.1 | 14.7 | -10.9 | 0.1 | 1.3 | -66.2 |
| +- | 1.5 | 1.5 | 1.4 | 0.1 | 0.0 | 1.4 |
| usn2015b | -2.8 | 20.4 | -7.1 | -0.0 | 1.1 | -57.2 |
| +- | 1.4 | 1.4 | 1.3 | 0.0 | 0.0 | 1.3 |

*Table 3: Statistics after removal of systematics given in Tables 2. Unit is µas. Values for right ascension are corrected from the cosine of the declination.*

| | Standard Deviation | | | | Median Offset | | | |
|---|---|---|---|---|---|---|---|---|
| | Defining | | All | | Defining | | All | |
| | RA | Dec | RA | Dec | RA | Dec | RA | Dec |
| asi2015a | 55.5 | 64.8 | 141.6 | 323.6 | 49.7 | 61.4 | 50.3 | 61.4 |
| aus2015c | 53.6 | 48.5 | 128.4 | 161.2 | 247.5 | 488.0 | 269.2 | 450.6 |
| aus2016a | 51.9 | 43.9 | 139.4 | 173.0 | 247.9 | 442.3 | 261.7 | 438.3 |
| aus2016b | 7.8 | 5.5 | 33.2 | 39.3 | 242.4 | 455.6 | 246.6 | 414.8 |
| bkg2015a | 53.7 | 61.8 | 362.7 | 364.1 | 118.1 | 222.5 | 121.5 | 209.2 |
| usn2015b | 60.0 | 65.4 | 565.1 | 863.2 | 126.5 | 238.4 | 134.7 | 230.4 |

for other catalogs. The largest deviation from ICRF2 axes is observed for the bias in declination. Values of BD are significantly larger than the ICRF2 axis stability of 10 mas measured at the time of the ICRF2 release in 2009 (Fey et al. 2015). This fact may indicate some systematics in source declinations with respect to solutions of the previous years and may have to be considered in parallel to the zonal declination error raised in the 2012–2015 ICRF3 WG documentation (e.g., Jacobs et al. 2014). Note that this particular point should be addressed rigorously in the framework of the 2016–2018 ICRF3 WG.

**Zonal errors**

Figure 1 displays the offset to ICRF2 (in the sense catalog minus ICRF2) averaged over declination bins of 5 degrees. All solutions but Australian ones exhibit declination errors offset to the negative part of the plot, that may reflect the large values of BD found in the coordinate difference to ICRF2. However, no pronounced dependence in declination shows up for any solution.

**Standard error and noise**

Figure 2 illustrates how the overall formal error, defined as the square root of $\sigma_{\alpha\cos\delta}{}^2+\sigma_\delta{}^2+c\sigma_{\alpha\cos\delta}\sigma_{\alpha\delta}$ where σ is the formal error listed in the catalogs and c is the correlation coefficient between estimates of $\alpha$ and $\delta$ as provided in the catalogs, varies with the number N of observations. The circled dots represent defining sources. The figure for aus2016b clearly shows that the defining 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 imposed to these sources. Similar fact was pointed for solution aus2015a in the IERS Annual Report 2014.) The formal error of the same sources in solution aus2015c and aus2016a, in which the no-net rotation condition is less severe, appears to be at a level comparable to other sources.

Figure 2 also shows how the error on delays is propagated to the estimated source coordinates. For white noise measurements,

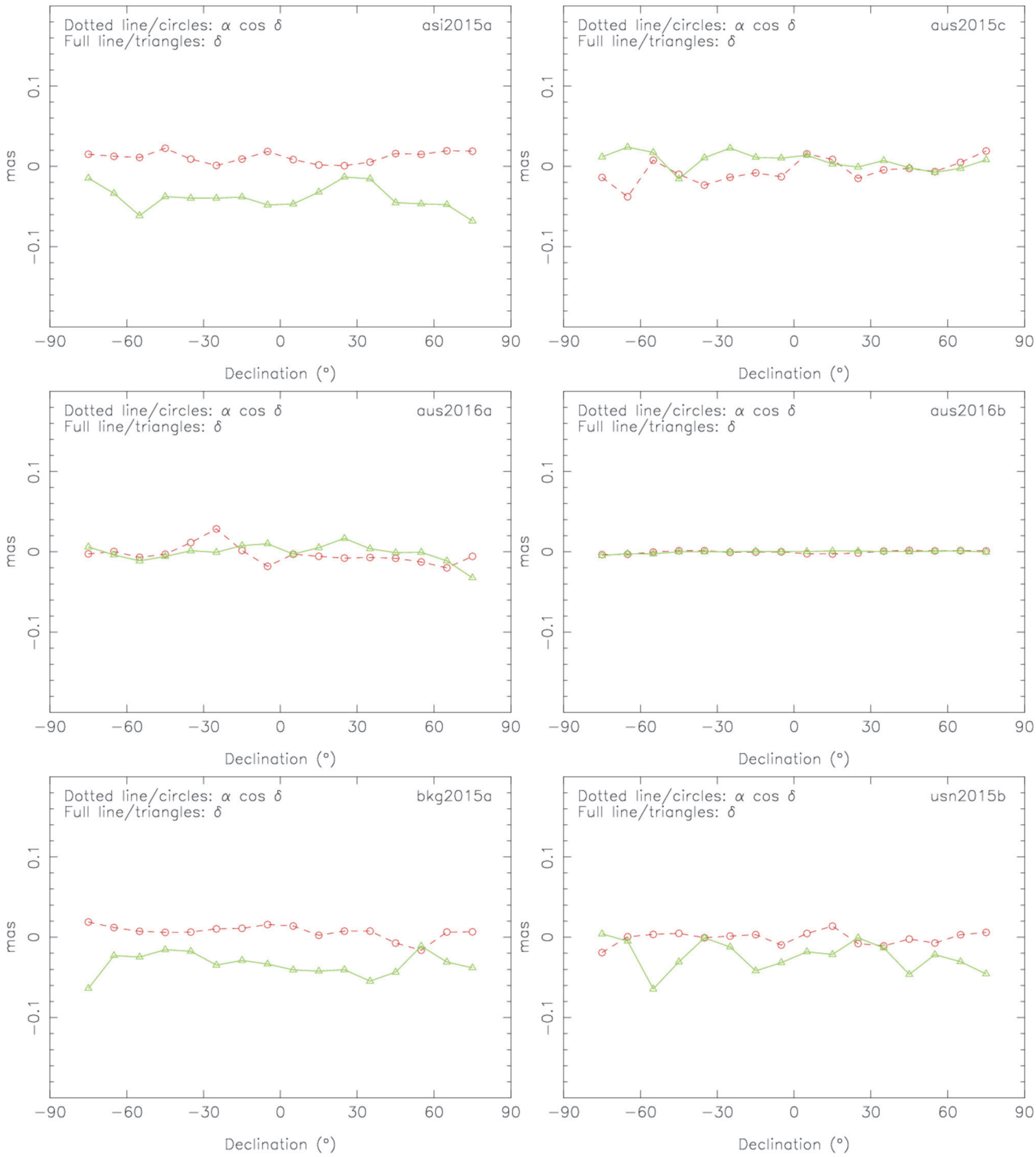


*Fig. 1: Offset to ICRF2 for right ascension (dotted line with circles) and declination (full line with triangles) by bins of declination of 5 degrees.*

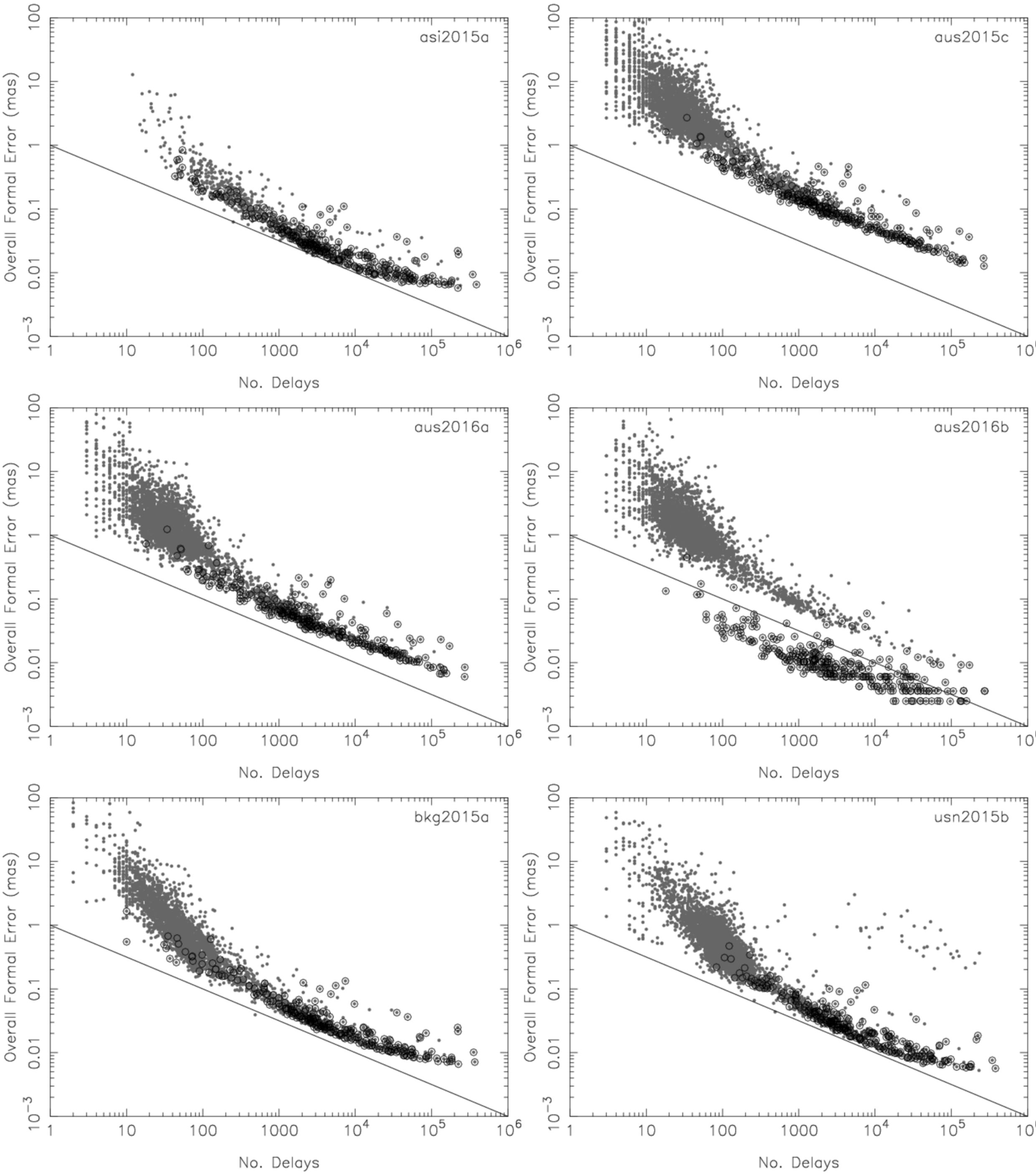


*Fig. 2: Overall formal error as a function of the number of observations. The circled dots represent defining sources. The solid line indicates a decrease as $N^{-1/2}$ where N is the number of delays.*

the formal error on source coordinates is expected to decrease as $N^{-0.5}$. The figure reveals that this regime exists for N between ~100 and ~10000. For N lower than a hundred observations (e.g., VCS sources or sources observed in only one session) the formal error varies as $N^{-1}$. Beyond 10000 observations, the formal error generally tends towards a limit lower than ~10 mas. Such a deviation is visible for all catalogs but the Australian ones for which the formal error seems to continue to decrease more closely (but not exactly) to $N^{-0.5}$. The deviation for large N observed for all other catalogs is likely the signature of non-Gaussian correlated errors: as N increases, thermal baseline-dependent error tends to zero and the station-dependent error arising from time- and space-correlated parameters becomes dominant (see, e.g., Gipson 2006 or Romero-Wolf et al. 2012; see also Lambert 2014).

A last test was performed to assess the consistency between the formal errors and the offset to ICRF2. This test was motivated by the consideration that, although the ICRF2 is not the "truth", it nevertheless provides accurate values of well-observed sources. As a consequence, for most of the sources, the addition of new observations after 2009 should not perturb significantly the estimated position but only improve the formal error. Figure 3 displays the scatter around the ICRF2 position computed for bins of increasing formal error. For a white noise, one should get values close to the first diagonal (i.e., the formal error fully explains the offset to ICRF2). For formal errors lower than 0.1 mas, one sees that the scatter is over the diagonal, indicating a possible underestimation of the formal errors. To quantify this scale factor, one can estimate it together with an error floor so that a realistic error Er (i.e., that explains the observed offset to ICRF2) is given by

$$Er = ((E\ s)^2 + f^2)^{-0.5}$$

where E is the error, s a scale factor and f a noise floor. Values of s and f estimated over sources whose offset to ICRF2 is smaller than 1 mas are reported in Table 4. Uncertainties are ~0.01 mas on s and ~0.01 on f. SOLVE solutions tend to have scale factors larger than unity while OCCAM catalogs have scale factors smaller than 1. Note that the noise floor does not represent the catalog internal error since one considers the offset to ICRF2: the quantity f therefore contains the internal noise of the ICRF2. The global noise lies between 0.05 and 0.12 mas. If one assumes 0.04 mas for the ICRF2 internal noise (Fey et al. 2015), it means that the analyzed catalog internal noises are larger by a factor between 1 and 3.

**Conclusions and recommendations**

The above results lead to some recommendations for analysis centers who plan new submissions in the future. First, it is recommended to include all ICRF2 sessions in the processed session list, in order to get values of, at least, all 3414 ICRF2 sources. Second,

*Table 4: Noise floor and scale factor estimated for sources with offset lower than 1 mas. Unit is μas. Values for right ascension are corrected from the cosine of the declination.*

| | Floor RA | Floor Dec | Scale RA | Scale Dec |
|---|---|---|---|---|
| asi2015a | 42.7 | 55.6 | 3.65 | 3.07 |
| aus2015c | 46.7 | 40.5 | 0.60 | 0.60 |
| aus2016a | 48.3 | 43.6 | 1.14 | 1.11 |
| aus2016b | 7.3 | 7.7 | 1.17 | 1.12 |
| bkg2015a | 50.7 | 66.4 | 1.34 | 1.18 |
| usn2015b | 57.6 | 71.2 | 1.64 | 1.54 |

analysis centers should focus on understanding several points: (i) the significant systematics in orientation (~0.05 mas) showing up in Table 2, (ii) the zonal errors appearing in Fig. 1 for some solutions, and (iii) the non-Gaussian errors dominating for large number of observations raised by Fig. 3. About the latter item, one should understand particularly why the OCCAM solutions decreases differently than SOLVE catalogs for larger numbers of delays. In the future, the correction of this defect should be achieved by better modeling and parameterization of clock and troposphere correlated errors, consistently in all VLBI analysis software.

## The Large Quasar Astrometric Catalog (LQAC) and related studies

### The Large Quasar Astrometric Catalog

The ICRS Center is in charge of the LQAC (Large Quasar Astrometric Catalog), a whole sky compilation of information on known QSOs, as well as of its regular up-dates. The second release of the LQAC, (LQAC-2) (Souchay et al., 2012) was published as a CDS catalog. It contained 187 504 quasars. A third release, the LQAC-3, was published in 2015 (Souchay et al., 2015). It contains 321 957 objects, which represent a 71.7% increase with respect to the LQAC-2.

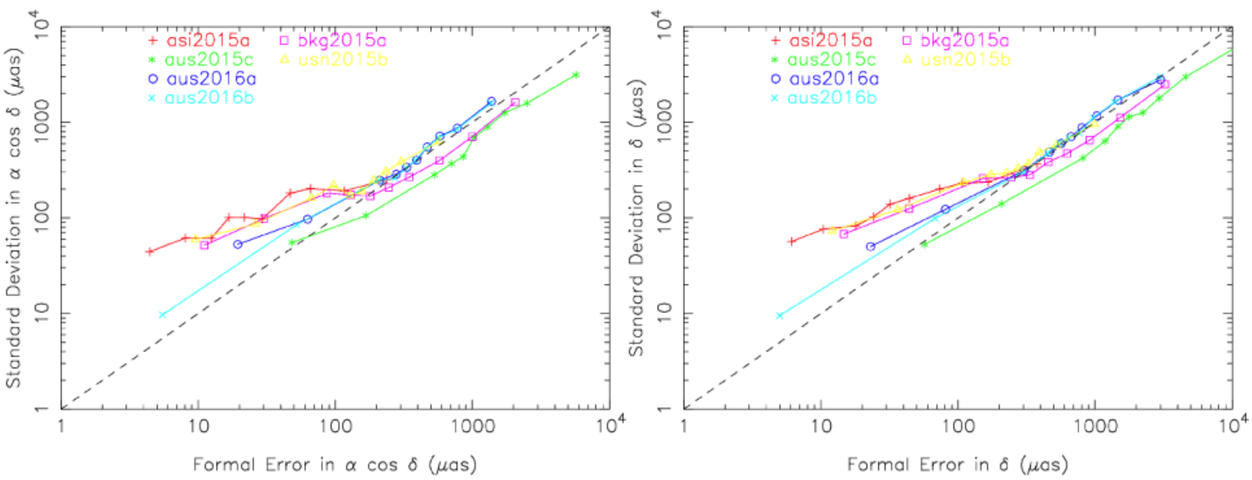


*Fig. 3: Scatter of the offset to ICRF2 versus the formal error.*

Basically, the LQAC delivers complete information (when available) as a set of optical magnitudes and radio fluxes, the redshift, original and consolidated equatorial coordinates, together with re-calculated absolute magnitudes and morphological indexes (see IERS Annual Report, 2010, 2012).

**Related studies**

The construction of the third edition of the Large Astrometric Quasar Catalog – LQAC3 (Souchay et al., 2015) enabled the in-depth study of the large, coherent sample of quasars represented by the SDSS-III DR10Q (Pâris et al., 2014). Its astrometric properties could be independently checked out from the 190,184 new SDSS quasars, as compared to the ones determined in previous editions of the LQAC (Souchay et al., 2012). It is likewise concerning the PSF-morphology properties, in this case specially interesting because the new quasars in the DR10Q come from the Baryon Oscillation Spectroscopic Survey – SDSS-III: BOSS (Ross et al., 2013), with redshift in the range z = [2.2,3.5], which corresponds to a very relevant stretch of the quasar luminosity function, when the quasar number density and luminosity were maximal.

To render the LQAC3 astrometric positions compliant to the ICRF2, the steps presented in the Large Quasar Reference Frame (LQRF and LQRF2) (Andrei et al. 2009; Souchay et al. 2012) were followed. For 123,448 SDSS sources the LQAC2 positions are recognized in the LQAC3 (1” matching), meaning just minor corrections on the prior SDSS releases. On average the difference of positions is very small (–0.1 mas in R.A. and 4.2 mas in DEC.) but the mean distance between corresponding positions is non-negligible (61.2 mas). As for the quasars not belonging in the LQAC2, the local corrections and magnitude corrections were found negligible. The global analysis confirms the previous findings in that the director cosines around the ICRF equinox and contra-equinox axis are small. However, the director cosines representing corrections to the right ascension and declination origins are significant. Their values are respectively –9.1 (± 1.8) mas, and 4.1 (± 2.0) mas. Also as expected the systematic corrections for zonal warps are small (–0.9 mas in R.A. and 1.0mas in DEC.), nevertheless the resulting average displacement is of 54.5 (± 12.8) mas. The combination of corrections for the global rotation and for the systematic local deviations is effective and the mean distance between the ICRF and LQRF-type positions is slashed to 21.6 (± 13.4) mas. In conclusion, these positions or a conveniently chosen subset can provide a good independent comparison for the alignment to the ICRF for the Gaia first data release.

The aspects of morphology and variability were crucial for selecting the quasars to form the ICRF (Ma et al., 2009), based on radio VLBI observations. Also on the optical band these two aspects are increasingly addressed in programs of high astrometric precision.

For the Gaia mission, we can use the morphological indexes included in the Gaia Initial QSO Catalog – GIQC (Andrei et al., 2012). In radio waves bright spots are commonly formed where shocks traveling up the jets exchange energy with the external medium (Begelman et al., 1984), and are often taken as the radio centroid. In contrast to this, light emitted in (and around) the optical window originates mostly from the very central part of the quasar, either by thermic processes in the accretion disk, or relativistic processes at the bases of the jets. But light also originates from the host galaxy and, though comparatively less, from line emission processes and as a consequence of the heating of more distant surrounding dust. Thus much effort has been put in disentangling the central source and the galaxy isophotes by modeling. This was indeed proposed in the formulation of the GIQC and is implemented for all quasars observations in the Gaia mission (Ducourant et al., 2014). To characterize the extent of the influence of the host on the compound image, which is crucial for astrometric purposes, the analysis of a single PSF fitting can be made.

For the LQAC3 the approach of analyzing the PSF of the quasar image in comparison with the local mean PSF of stars of similar magnitude is the same adopted in the former versions of this compilation. The elements of comparison are the parameters SHARP, SROUND, and GROUND, determined by IRAF's DAOFIND on the Johnston B, R, and I digitized plates of the DSS. The morphological indexes of each quasar are given by the same formula as (Andrei et al., 2008):

$$M_{PC} = | P_Q - P_s | / \sigma$$

where $M_{PC}$ is the morphological index of quasar Q for the PSF parameter P in the color C, given in comparison to the mean value from the stars Ps, and normalized by the stellar standard deviation $\sigma$.

As we have noted previously, while a great majority of quasars are stellar-like in appearance, a significant proportion of quasars display a PSF that is apparently disturbed by an otherwise not-easily-detectable host. Furthermore, the more conspicuous the host, the more we observe a shift from B to I. For every quasar at least one morphological index was obtained (that is, at least one good image exists). For 59% of the entries we got all the 9 morphological indexes. The direct comparison with the same morphological indexes for the stars provided a sanity test verifying null averages and standard deviations of about 0.9 for SHARP, 0.7 for SROUND, and 0.8 for GROUND, slightly smaller at I than B, but without statistically significant evolution over magnitude from R = 9 to 22. DAOFIND has been largely and successfully used, for instance, in the detection of clusters (Bastian et al., 2011). The way to circumvent its performance degradation in low illumination regimes is to use a “logical training process” (Mähönen and Hakala, 1995), which was done in the present case by using the nearby, similar magnitude stars.

The main features of the morphological indexes for the new sources in the LQAC3 are the same as in the former versions. However the populations from which the sources are drawn present differences, as described above. The quasar luminosity function is such that increasing redshift is counterbalanced by increasing luminosity, with the result that the dimming of apparent magnitudes is much reduced. As the energy is fed back from the active nuclei to the host galaxy, the later often presents as a massive elliptical with significant quantities of dust and high rate of star formation, compatible with both infrared and UV emission. But direct imaging is unlikely to be feasible due to the cosmological dimming in surface brightness. In order to maximize the certainty of the morphological indexes for the new, more distant sources included in the LQAC3, three conservative steps were taken. The source count was calculated and then convolved with the one from Mähönen and Hakala (1995) that downsizes the indexes. The analysis was restricted to only sources brighter than R = 19 magnitude. The DSS images matches were concurrently searched for in the PPMXL catalogue, limiting the matches to those close in angular distance, in magnitude, and of negligible proper motion.

Comparing the PPMXL- and non-PPMXL-found quasars, the correlation over all plates and morphological indexes is 99.9%, thus clearly implying that the images on the DSS plates were found correctly and that the training of the morphological indexes renders magnitude effects unimportant. The end-result is that mostly stellar-like close-to-zero values are found, as before, increasingly from B to I. Much less obviously, within each color, the averages of the morphological remain nearly constant on redshift, which would favor a scenario of coevolution of galaxies and supermassive black holes (Heckman and Best, 2014).

## Monitoring of QSOs

During the year 2015 the magnitude monitoring of QSO for the link between reference systems (ICRF/GCRF) was achieved with the help of small and medium size optical telescopes. The TAROT program (<http://tarot.obs-hp.fr/>) was the first effort. It has produced series of observations with long temporal baselines and relatively high frequencies (one observation every two days over five years). Taris et al. (2016) describes the results through 2016. As shown in the paper, some sources display clear periodic variations in brightness. For the 14 targeted QSO’s observed with these instruments, we determined periods, with confidence levels above 90% in all cases. Some of the periods found were not previously known. For the other targets, we did a comparative study of the periods previously studied by other authors and confirmed their values. All the periods given by the two methods are in good agreement with each other, with differences less than 7.9% for the worst case. Finally we also presented the structure functions for our two sets of objects (BL Lac and Seyfert galaxies).

A second program, in close collaboration with G. Damljanovic from Belgrade Observatory, was achieved using three 60cm optical telescopes. They are located at Vidojevica (<http://vidojevica.aob.rs/index.php?option=comcontent&view=article&id=22&Itemid=29>), Rozhen (<http://www.nao-rozhen.org/telescopes/fr16_en.html>) and Belogradchik (<http://www.astro.bas.bg/~aobel/equipment.html>) observatories. The LFOA 1.5m telescope (<https://astro.univie.ac.at/foa/teleskope-instrumentation/15m-teleskop/>) and the TJO telescope 0.8m (<http://www.oadm.cat/en/content/45/tjo.htm>) were also included in this program devoted to photometric monitoring of targets other than those mentioned previously. The goal of this program is to compare the brightnesses of the QSO's with the G magnitudes that will be provided by the first release of the Gaia catalogue (DR1 to be published in 2016).

A third program began in 2015 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 lists of target suitable for the link between the reference systems.

The programs mentioned are all very time consuming due to the large number of targets that must be monitored. Moreover these programs are done within the framework of competitive international calls for proposal. This last point could be an issue when the total observation time requested is important. To avoid these constraints, the SYRTE department of Paris Observatory plans to build a robotic telescope dedicated to the photometric monitoring of QSO's. The first part of this project began in 2015 by the choice of a site with a good atmosphere, characterized by its good seeing. During the 1970s the French government wanted to build a four meter telescope that became later the 3.6m Canada France Hawaii Telescope (CFHT) on top of Mauna Kea volcano. For this purpose, sites were selected in Europe with respect to their high quality in terms of astronomical seeing. We choose one of them, Saint-Véran (alt. 3000m), in the French Alps, near the Italian border, for implementing a site seeing monitoring campaign (<http://stveran.obspm.fr/index.php?page=statistiques>). The goal of this campaign is to show, with modern instruments, that the site seeing is effectively the expected one.

## Quasar Source Structure Databases

### Radio Reference Frame Image Database

The Radio Reference Frame Image Database (RRFID) is a web-accessible database of radio frequency images of ICRF sources. The RRFID currently contains 7279 VLBA images of 782 sources at radio frequencies of 2.3 GHz and 8.4 GHz. Additionally, the RRFID contains 1867 images of 285 sources at frequencies of 24 GHz and 43 GHz. Imaging of additional radio sources has been temporarily suspended due to lack of available resources. The RRFID can be accessed from the Analysis Center web page or directly at <http://rorf.usno.navy.mil/rrfid.shtml>.

### Bordeaux VLBI Image Database

The Bordeaux VLBI Image Database (BVID) is a web-accessible database of radio frequency images of ICRF sources. The BVID currently contains 5719 VLBA images of 1273 sources mostly at radio frequencies of 2.3 GHz and 8.4 GHz, but includes images for some sources at 24 GHz and 42 Ghz. Corresponding structure correction and visibility maps are also available. The BVID can be accessed from the Analysis Center web page or directly at <http://www.obs.u-bordeaux1.fr/BVID/>.

## Link Between Optical and Radio Reference Frames

Work continued to assess the potential magnitude and explanation for offsets in position between extra-galactic reference frame objects in the optical and in the radio. Analysis of data obtained at CTIO from 1997 to 2004 that used a combination of simultaneous UCAC astrograph and CTIO 0.9m observations in the same bandpass, indicates systematic differences in positions between the optical and radio positions of ICRF2 sources exceeding 100 mas in some cases with suspected general, random offsets of most sources of order single mas (see Zacharias and Zacharias, 2014). If this new and potentially significant source of error holds for alignment sources common to both Gaia and the ICRF, then the optical/radio system alignment error of a significant fraction of a milliarcsecond could result. Results of the reference frame link work were presented at the December 2014 Extra-Galactic Science with Gaia (EGSG) meeting, held at Observatoire de Paris-Meudon and the July 2015 Gaia for AGN and Extragalactic Science (GAGNES) meeting at Paris Observatory. Additional analysis of this issue, along with new optical and radio observations have been conducted in 2015, and the results communicated to the Gaia team and ICRF3 working group.

During 2015, USNO concluded a decade-long monitoring program of 12 selected ICRF sources with optical counterparts using the NOFS Strand 1.55 m astrometric telescope. Relative positions with respect to selected reference stars in the same field of view were derived in a fashion similar to the trigonometric parallax program at that telescope. Changes in optical position of these extragalactic targets as a function of observing epoch were fitted with a parallax and proper motion contribution to remove the average reflex motion of the reference stars in each field.

For at least one source, ICRF 0754+100, a significant change in optical position as a function of brightness is found. A possible explanation is an astrophysical position offset of the bright AGN core with respect to the surrounding light of the host galaxy. The average light of the host galaxy is assumed to be constant over the 10 year period while the core of this ICRF defining BL-Lac object varies by about 2 magnitudes over the period of our observations causing the combined center of light to shift. Details will be published in an upcoming paper (Harris et al. 2016).

## Optical Astrometric Catalogs

In June 2015 the three-year observing program with the USNO Robotic Astrometric Telescope (URAT) concluded at its northern hemisphere site, the Naval Observatory Flagstaff Station (NOFS) (see Figure 4). The URAT1 catalog, covering the Northern Hemisphere and red magnitudes 3–18, was published in February 2015 (Zacharias, Finch, Subasavage et al., 2015) (see also IERS Annual Report 2014), which gives accurate positions of over 200 million objects based on the first two years of observing at NOFS. These data were supplemented by preliminary proper motions using 2MASS as early epoch.

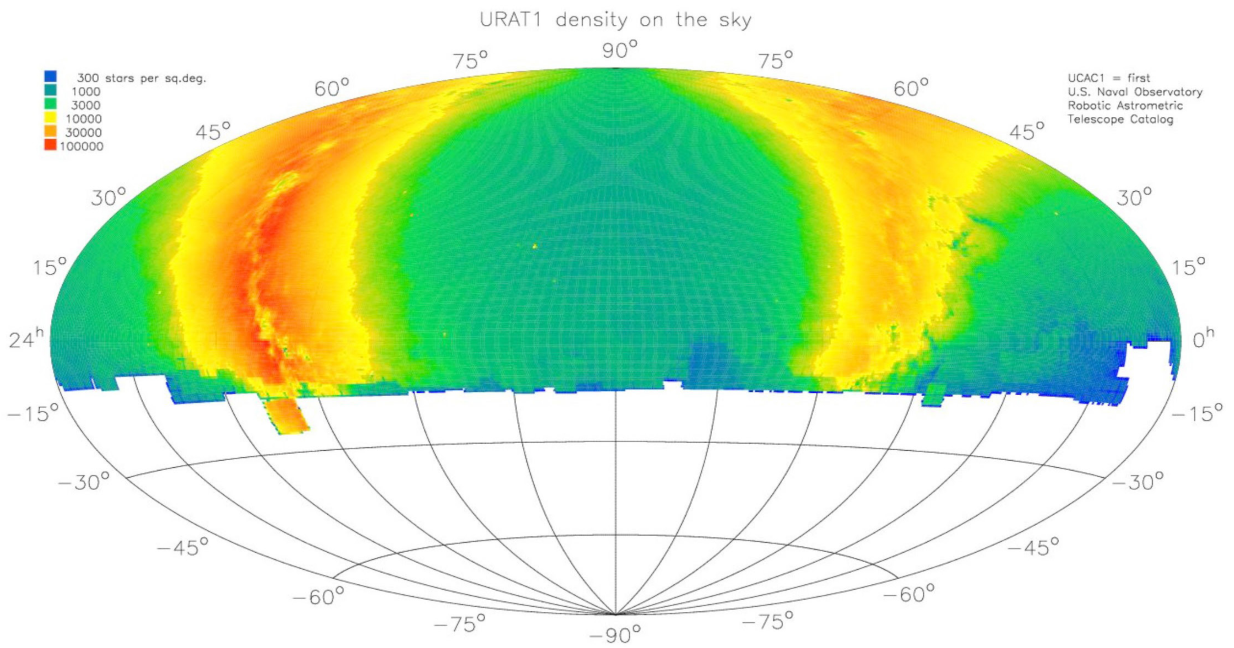


*Fig. 4: URAT sky overage as of late 2014. The 2015 URAT1 release consists of over 228 million stars covering the sky north of approximately –15 deg DEC. URAT1 includes observations from April 2012 to June 2014, along with extensive validation using a variety of sources.*

An internal catalog (URAT2) covering the full three-year northern program was constructed providing access to mean positions as well as individual observations. The optical positions have been put on the ICRF by using UCAC4 as reference star catalog. These data were used to look at optical counterparts of radio reference frame sources. Over 2100 sources in common with the 2014 version of the Radio Fundamental Catalog (RFC, Petrov, <http://astrogeo.org/rfc/>) were found in the URAT data. Position differences (separation on the sky in mas) divided by the combined, formal errors of the radio and optical position (also in mas) for each source were calculated (unit is standard error or sigma). Figure 5 shows a plot of these normalized position differences as a function of redshift z after excluding sources with 9 or more sigma position differences (to eliminate grossly wrong data) and binning to better show systematic trends. Nearby sources clearly show a larger position difference than cosmologically more distant sources indicating a contribution likely from real astrophysical optical to radio position center offsets. These results and other ground-based catalog data related to radio-optical sources were presented at the 2015 GAGNES meeting in Paris.

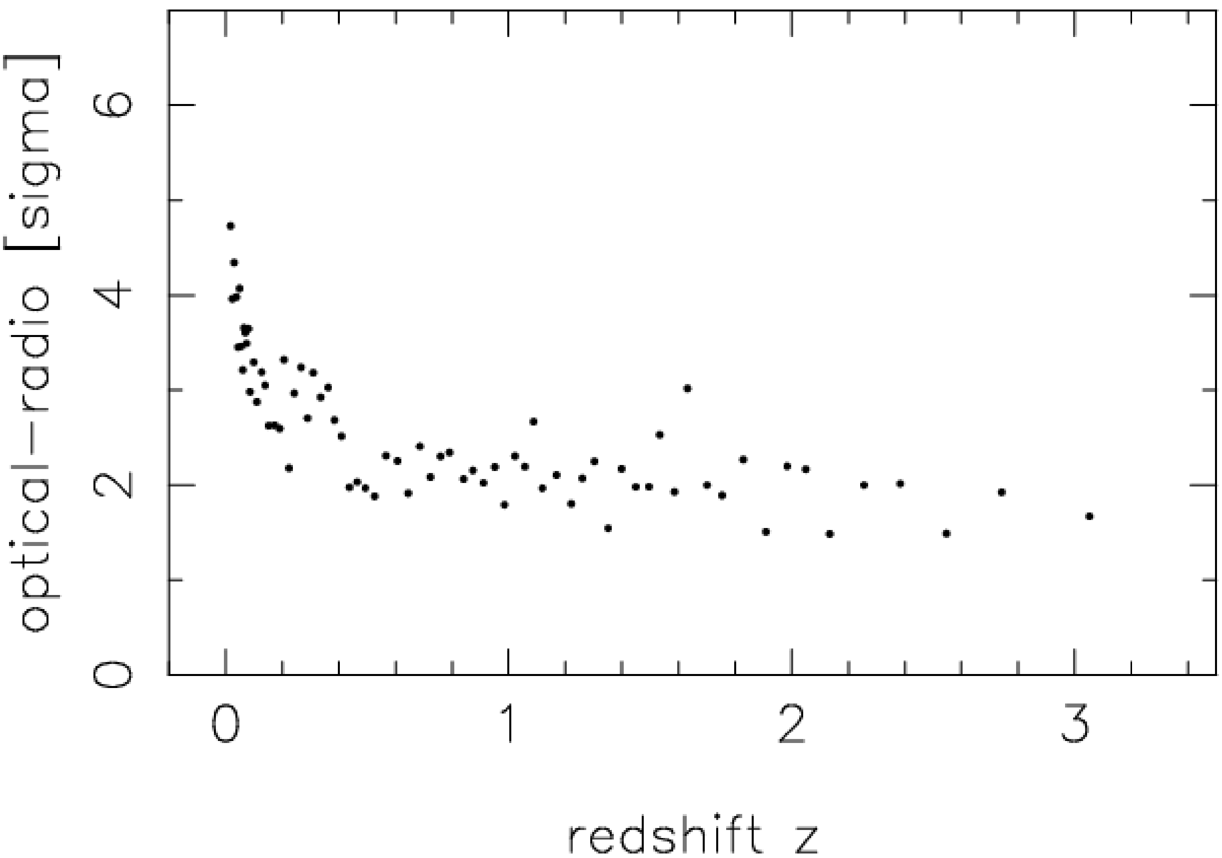


*Fig. 5: Normalized position differences between URAT1 and RFC sources (AGN) as a function of redshift. Obvious mismatches (sigma ≥ 9) have been excluded.*

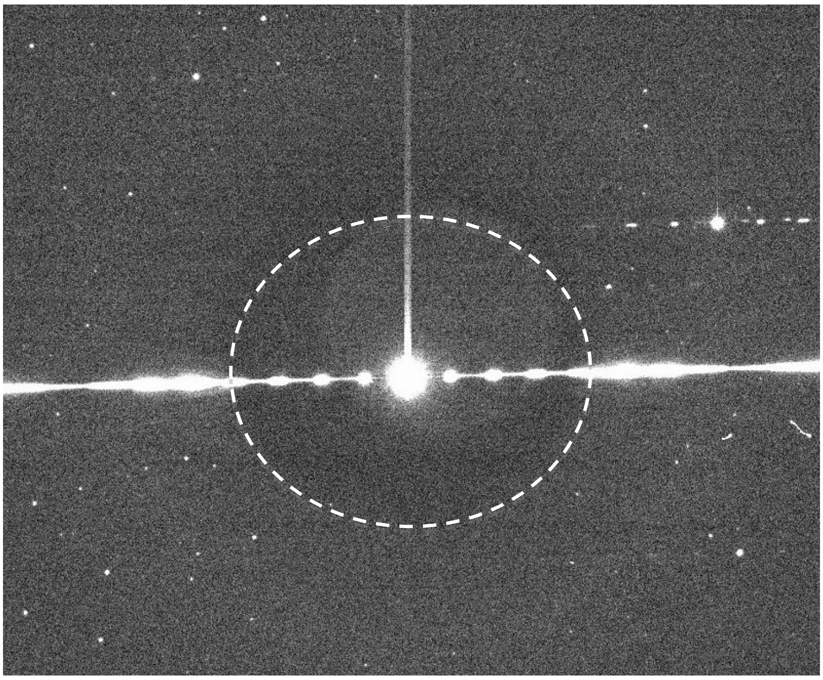

*Fig. 6: URAT five second exposure of Sirius (v = –1.46) with grating in place showing approximate extent of ND filter.*

In October 2015 the URAT astrograph began a southern hemisphere survey after successful relocation to the Cerro Tololo Interamerican Observatory (CTIO). Because of the upcoming 1st Gaia data release, this southern survey is concentrating on the very bright stars. For this purpose, a new neutral density spot has been added to the camera dewar window that is large enough to include the 1st order grating images.

Figure 6 shows a single, five-second exposure taken with the URAT astrograph of Sirius, the brightest star in the sky. The central image is overexposed beyond recovery for a good astrometric position. However, the flux of the first order grating images is well below saturation. The extent of the neutral density spot can be inferred from the grating images. Further out images suddenly become about five magnitudes brighter once outside the spot. This observing program will provide accurate positions on the ICRF of such bright stars at current epochs to improve the proper motions when combined with Hipparcos data until being superseded in future years when Gaia data for these stars may become available.

Simultaneously, the USNO Bright-Star Astrometric Database (UBAD) program will observe the brightest stars in the Northern Hemisphere. UBAD will utilize a camera similar in some respects to the URAT camera, with an ND-12 spot and will be deployed on the NOFS 1.55m Strand astrometric telescope to survey the entire Northern Hemisphere. Also, as with URAT, UBAD will use

Gaia astrometric data for the reference stars. Both catalog projects will supplement Gaia data at the bright end, and will be on the Gaia system.

## Staff

Dorland, Bryan, Director (USNO)
Souchay, Jean, Co-director (OP)
Andrei, Alexandre, Assoc. Astronomer (OP, Obs. Nat. Rio, Brasil)
Arias, E. Felicitas, Assoc. Astronomer (BIPM / OP)
Barache, Christophe, Engineer (OP)
Bouquillon, Sébastien, Astronomer (OP)
Fey, Alan, Astronomer (USNO)
Lambert, Sébastien, Astronomer (OP)
Taris, François, Engineer (OP)
Titov, Oleg, Astronomer (OP, Geoscience Australia)
Zacharias, Norbert, Astronomer (USNO)

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

### 3.5.5 ITRS Centre

This report summarizes the activities of the IERS ITRS Centre during the year 2015.

#### 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 numbers 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).
At the occasion of the ITRF2014 analysis, several new stations, mainly GNSS permanent stations where added to the ITRF network and database.

#### ITRF web site

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

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

#### Preparation for a new ITRF web site

The ITRS Centre has started in 2011 the 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 specification document is finalized and the development started in 2013. The new web site which was expected to be operational beginning 2016 experienced some delay, unfortunately, and will be open hopefully around mid-2017.

### Local ties of ITRF co-location sites

The ITRS Centre collects all new surveys operated by either IGN or the hosting agencies of ITRF co-location sites. The reports of these surveys are posted at the ITRF web site and 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. These new survey results will be made available via the ITRF web site after the release of the ITRF2014.

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 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;
- Contribution to the text of the UN GA resolution on the Global Geodetic Reference Frame for Sustainable Development adopted February 26, 2015;
- Participation in the UN-GGIM related meetings, August, 2015.

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

## 3.5.6 Global Geophysical Fluids Center (GGFC)

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.

We also organized a session "Modeling Global Geophysical Fluids" at 2015 AGU Fall Meeting in San Francisco.

Since 2016, J.-P. Boy acts as the chair of GGFC, with T. van Dam as a co-chair.

### Special Bureau for the Oceans

The oceans have a major impact on global geophysical processes of the Earth. Non-tidal changes in oceanic currents and ocean-bottom pressure are a major source of polar motion excitation and also measurably change the length of the day. The changing mass distribution of the oceans causes the Earth's gravitational field to change and causes the center-of-mass of the oceans to change which in turn causes the center-of-mass of the solid Earth to change. The changing mass distribution of the oceans also changes the load on the oceanic crust, thereby affecting both the vertical and horizontal position of observing stations located near the oceans. As part of the IERS Global Geophysical Fluids Center, the Special Bureau for the Oceans (SBO) is responsible for collecting, calculating, analyzing, archiving, and distributing data relating to non-tidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocenter. The oceanic products available through the SBO website (<http://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 (<http://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.

A problem with assimilating the altimetric sea surface height measurements into the ECCO/JPL ocean model was discovered in 2015. This manifested itself as a sudden change in the modeled ocean-bottom pressure. After correcting the problem, the ECCO/JPL ocean model was re-run from the beginning (01 January 1993) with the results designated as data assimilating run kf080g. The oceanic angular momentum, oceanic excitation functions, and oceanic center-of-mass from the entire kf080g run was computed and uploaded to the SBO website, replacing the results from the previous, erroneous, data assimilating run kf080. The problem with assimilating the altimetric sea surface height measurements into the ECCO/JPL ocean model did not affect the results of the simulation run kf079.

During 2015, the SBO website was maintained and products from the ECCO/JPL ocean model were updated. Daily values of oceanic angular momentum, oceanic excitation functions, and oceanic center-of-mass from the kf079 (simulation) and kf080g (data assimilating) runs of the ECCO/JPL ocean model are now available from 01 January 1993 through 26 December 2015. These values can be extended back to 01 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 (<http://ecco.jpl.nasa.gov>) from which grids of modeled ocean-bottom pressure can be obtained, a link is provided to the GGFC website (<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 (<http://www.ntslf.org/files/acclaimdata/gloup/gloup.html>). Finally, a link is provided to the GFZ Helmholtz Centre Potsdam's Effective Angular Momentum Functions (EAM) website (<http://www.gfz-potsdam.de/en/section/earth-system-modelling/services/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.

**Acknowledgements**

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## 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 <https://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>. 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

## 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 LadWorld 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 1979 to December 2014. GLDAS gravity spherical harmonic coefficients have also been updated to cover the period January 2002 to December 2014. 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 April 2015.

## Combinational Products

A new dataset has been introduced in 2014 as an official GGFC product from Wei Chen (School of Geodesy and Geomatics, Wuhan University, China), providing an optimized excitation functions from a multi-model combination (including GRACE and low-degree Stokes coefficients from SLR).

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

| GGFC Operational Products | Principal Investigator | GGFC Operational Center |
|---|---|---|
| – UNB Vienna Mapping Function Service<br>– http://unb-vmf1.gge.unb.ca/Products.html | M. Santos | University of New Brunswick |
| AAM analysis (and forecast*) series from:<br>– NCEP Reanalysis (1948– )<br>– NCEP operational (1976– )*, also known as NMC<br>– JMA operational (1993– )*<br>– UKMO operational (1986–2006; and also to present)*<br>– ECMWF operational (1988–01.2000)<br>– ECMWF ERA-40 reanalysis (1959–2002) | D. Salstein | Atmospheric and Environmental Research |
| – Vienna Mapping Function Service<br>– AAM series from 6-hourly ERA-40 and operational analysis data starting in 1980<br>– AAM series from 10-day forecast data<br>– Cartesian coordinates of the center of mass of the atmosphere and total mass of the atmosphere at 6-hourly intervals<br>– Atmospheric loading ECMWF<br>– Atmospheric gravity coefficients: thin layer approach and vertical integration approach | J. Boehm<br>M. Schindelegger | Technical University of Vienna |
| – Global Mass Change Fields from GRACE (1 degree)<br>– GLDAS Monthly Water Storage (1x1 deg)<br>– Gravity Spherical Harmonics from GLDAS Monthly Water Storage Change<br>– NOAA LadWorld Monthly Water Storage (1x1 deg)<br>– CPC Monthly Water Storage (1x1 deg)<br>– Daily hydrological excitations of polar motion and LOD from NCEP/NCAR Reanalysis<br>– List of Major Artificial Reservoirs with Water Capacity Exceeding 10 km$^3$<br>– http://geophy.uni.lu/ggfc-hydrology.html | J.L. Chen | University of Texas at Austin<br><br>GGFC Special Bureau for Hydrology |
| – Atmospheric loading: NCEP (2.5 deg; 6-hr)<br>– http://gemini.gsfc.nasa.gov/aplo/<br>– Continental water loading: GLDAS<br>– http://lacerta.gsfc.nasa.gov/hydlo/ | D. MacMillan | Goddard Space Flight Center |
| – Site displacements due to atmospheric pressure loading<br>– Low degree harmonic time series from LAGEOS[1]<br>– ftp://gfzop.gfz-potsdam.de/nt-atml/ | J.-C. Raimondo<br>R. Koenig | Helmholtz Centre Potsdam - GFZ |

| | | |
|---|---|---|
| – High resolution atmospheric loading (3-hr; 0.5 deg): ECMWF (Operational)+IB and ECMWF+MOG2D<br>– ERA Interim+IB 6 hours<br>– Continental water loading: GLDAS/NOAH (3hr), ERA interim (6 hours)<br>– Effects on gravity and tilt<br>– http://loading.u-strasbg.fr | J.-P. Boy | EOST, University of Strasbourg |
| – Atmospheric loading (NCEP 2.5 x 2.5; 6 hourly)<br>– http://geophy.uni.lu/ggfc_atmosphere/NCEP-loading.html<br>– GLDAS continental water storage loading (2.5 x 2.5; monthly)<br>– http://geophy.uni.lu/ggfc-hydrology.html<br>– ECCO bottom pressure (2.5 x 2.5; 12 hourly)<br>– http://geophy.uni.lu/ggfc-oceans.html<br>– GRACE AOD ATM + OBP mass data (1.8 x 1.8 deg; 6 hourly) see Section on Combination Products<br>– GRACE AOD ATM + OBP loading effects (2.5 x 2.5 deg; 6 hourly)<br>– http://geophy.uni.lu/ggfc-combination/about-2.html<br>– S1/S2 tidal loading calculator<br>– http://geophy.uni.lu/ggfc-atmosphere/tide-loading-calculator.html | T. van Dam | University of Luxembourg |
| – Hydrological Loading from LSDM water (0.5 x 0.5; 24 hr)<br>– http://www.gfz-potsdam.de/en/section/earthsystemmodelling/services/hydl/ | R. Dill | GFZ |
| – AAM, HAM, OAM (ECMWF operational, ECMWF forecasts, ERA-Interim, ERA40)<br>– http://www.gfz-potsdam.de/en/section/earthsystemmodelling/services/data-products/ | M. Thomas | GFZ |
| – GRACE AOD dealiasing products (6 hourly)<br>– http://www.gfz-potsdam.de/en/section/earthsystemmodelling/services/aod1b-product/ | F. Flechner | GFZ |

[1] The system is not operational yet as we decided to augment our data basis to the ensemble of geodetic satellites (AJISAI, STARLETTE, STELLA, and LARES in addition to the LAGEOS satellites).

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

# 3.6 ITRS Combination Centres
## 3.6.1 Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)

In 2015, the focus of the ITRS Combination Centre (CC) at DGFI-TUM was on the ITRS realization DTRF2014. This ITRS realization is based on the same input data as the realizations of the CC at IGN and JPL, namely the ITRF2014 and the JTRF2014. But, in contrast to these realizations, the DTRF2014 was computed by combining free normal equation systems (NEQs). Furthermore, it is the first ITRS realization which considers non-tidal atmospheric and hydrological loading signals of station positions. In 2015, a first realization was computed and provided to the users. Compared to the final DTRF2014 solution, this preliminary solution did not consider non-tidal loading signals. This solution plays an important role for the validation of the final DTRF2014 solution including the comparisons with the ITRS realizations of IGN and JPL.

### DGFI combination strategy for the DTRF2014

The ITRS realization strategy of DGFI-TUM is based on the combination of datum-free NEQs which are reconstructed from the input SINEX series provided by the IAG technique services. The ITRS realization consists of two main parts: (1) the technique-wise analysis of the input data and the generation of one combined NEQ per technique and (2) the combination of the technique-specific NEQs (Fig. 1).

The analysis of VLBI and DORIS data was described in the IERS Annual Report 2014. In 2015, the analyses of all final series of input data as well as the combination of the techniques and the computation of the preliminary DTRF2014 solution were performed.

### Analysis of input data

For the computation of the DTRF2014, data series of the four space geodetic techniques GNSS, VLBI, SLR and DORIS were provided in the SINEX format by the corresponding technique services (Tab. 1). Compared to the DTRF2008, six additional years of observations are available. The data are provided as NEQs or solutions.

*Tab. 1: Input data for the DTRF2014. ITRF2014 and JTRF2014 are based on the same data set.*

| | Service | Solution type | Resolution | Time span | |
|---|---|---|---|---|---|
| **VLBI** | IVS | Free NEQ | session-wise | 04/80 - 12/14 | **35 years** |
| **SLR** | ILRS | Loosely constrained solution | before 1993.0: 15 days<br>after 1993.0: weekly | 12/82 - 01/15 | **32 years** |
| **GNSS** | IGS | Minimum constrained solution | daily | 01/94 - 02/15 | **21 years** |
| **DORIS** | IDS | Minimum constrained solution | weekly | 01/93 - 01/15 | **22 years** |

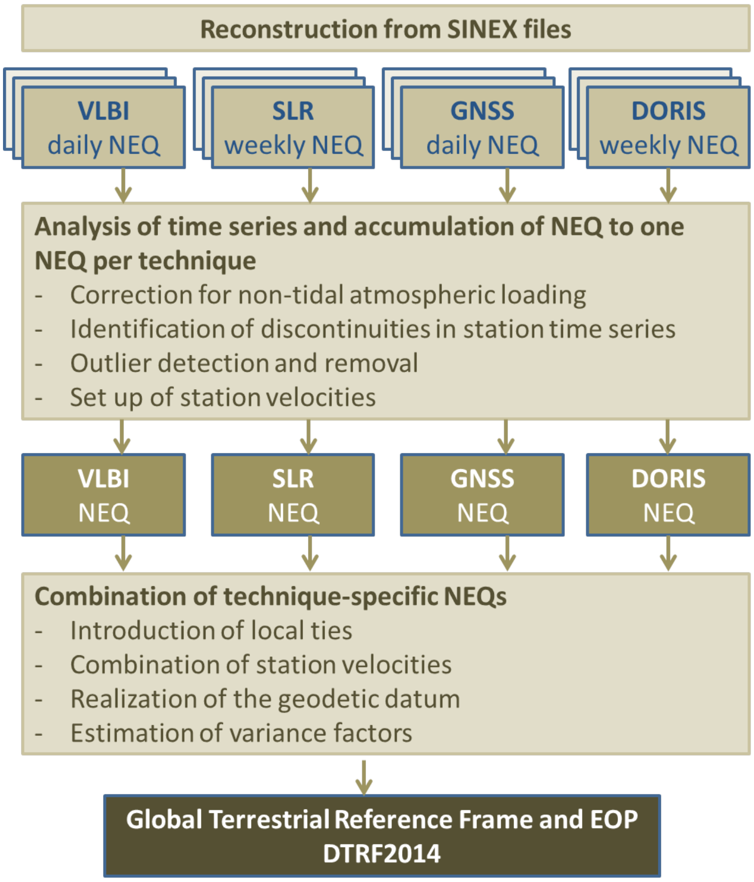


*Fig. 1: Combination strategy applied by ITRS CC DGFI-TUM.*

The four techniques are sensitive to different parameter types. Table 2 shows the parameters provided for ITRS realization and the parameters of the DTRF2014 solution, respectively.

Analysing the input data series, the most important steps are the analysis of the station position time series in order to identify

*Tab. 2: Input parameters and final parameters of the DTRF2014.*

| | | | | daily EOP at noon epochs | | |
|---|---|---|---|---|---|---|
| | station positions | station velocities | geocenter coordinates | terrestrial pole | UT1 | celestial pole |
| VLBI | X | | | offsets & rates | UT1 & LOD | offsets |
| SLR | X | | | offsets<br>before 1993.0: 1/3d<br>after 1993.0: daily | LOD<br>before 1993.0: 1/3d<br>after 1993.0: daily | |
| GNSS | X | | X | offsets & rates | LOD | |
| DORIS | X | | | offsets | | |
| DTRF2014 | X | X | reduced | offsets & rates | UT1 & LOD | offsets |

discontinuities and outliers and the analysis of the datum parameter time series. In particular, those parameters used for the datum realization of the DTRF2014 solution (SLR origin, SLR and VLBI scale) are important. Moreover, the EOP time series are analysed for systematic linear or periodic artefacts. Finally, the NEQs are accumulated to one NEQ per technique considering the discontinuities, removing the outliers and parameterizing station velocities.

### Analysis of station position time series

The analysis of station position time series is a very complex task because the long-term stability and the precision of the reference frame have to be balanced carefully. In addition, discontinuities at co-location sites have to be homogenized. In particular, the large number of GNSS stations (1347) is affected by many discontinuities (1409) mainly caused by instrumental changes. The following graphs impressively demonstrate the dominance of GNSS w.r.t. the number of stations and even more the number of discontinuities.

### Analysis of datum parameter time series

For the realization of the geodetic datum of the ITRS, SLR and VLBI data are used as they are very sensitive to the origin (SLR) and the scale (SLR and VLBI). The analyses of the datum parameter time series show that they are not affected by significant systematic effects. Therefore, the complete input data series of SLR and VLBI are used for the DTRF2014 datum realization.

In case of the scale, the difference between the scale obtained from VLBI and SLR was investigated. A lot of different tests were performed. However, for the reference epoch 2000.0, no significant difference in the scale was determined. This result agrees with that obtained from the input data for DTRF2008. However, a difference in the scale rate of about 0.4 and 0.8 mm/yr could be detected. More detailed investigations together with the IVS and the ILRS have to be performed in order to identify the reasons for that difference.

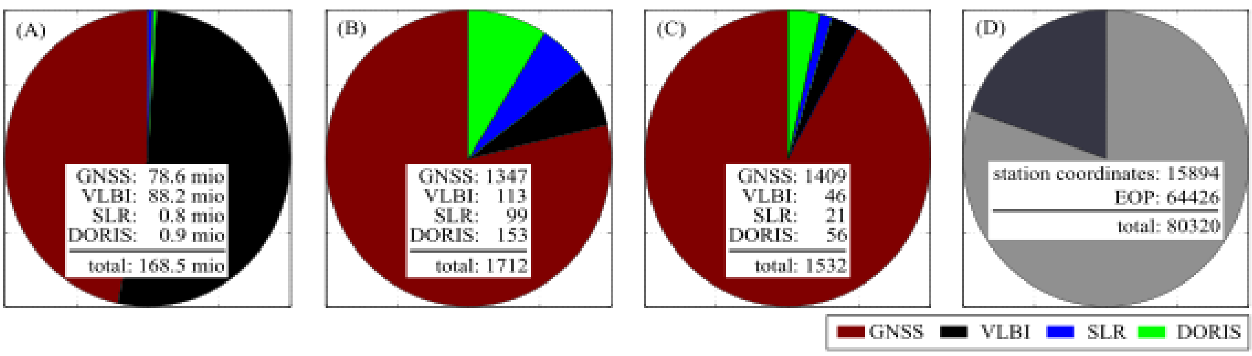


*Fig. 2: Statistics of the DTRF2014 solution: (A) number of observations, (B) number of sites, (C) number of introduced discontinuities, (D) number of estimated parameters.*

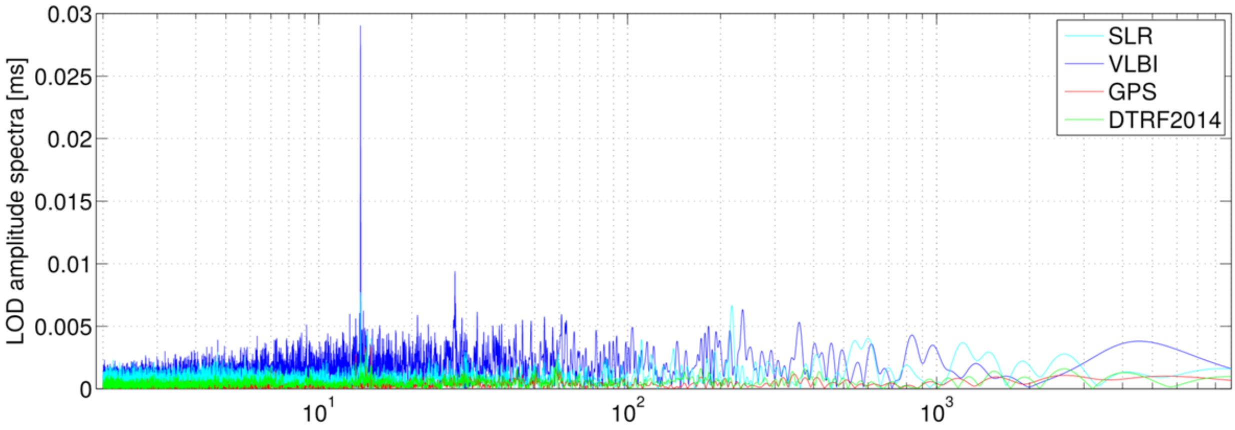


*Fig. 3: Amplitude spectra of LOD time series of the technique-specific input data and the DTRF2014 w.r.t. IERS 08 C04. Horizontal axis: period [days].*

## Analysis of EOP time series

Table 2 gives an overview of the EOP provided by the different techniques. To identify possible systematics in the EOP time series, they are compared with the IERS 08 C04 time series but also with the contributions of the other techniques. Spectral analyses were performed to track differences in periodic signals. For LOD, a signal of 13.65 days was found in the VLBI series compared to GNSS or IERS 08 C04 (Fig. 3). The reason for this difference could not be identified yet. However, the combined DTRF2014 EOP are not affected. Furthermore, the analyses of the terrestrial pole components derived from DORIS data show periods related to multiples of the draconitic period of the Jason-2 satellite. Also in this case, the combined DTRF2014 pole series are not affected.

## Combination of techniques and computation of the preliminary DTRF2014

The DTRF2014 solution is computed by combining the technique-specific NEQs accumulated from the input data NEQ series of the individual techniques. Within the combination process, the selection of local ties, the combination of velocities at co-location sites, the relative weighting of the techniques and the datum realization are the most important tasks to do (see Fig. 1).

The local ties are available in the SINEX format. For each local tie, it was tested, whether it fitted well to the space geodetic technique solutions or whether it showed significant discrepancies. In case of two or more local ties with a good fitting, the one with the smallest discrepancy was introduced. Within the combination of the station velocities, the velocities of co-located stations were tested for significant discrepancies. For all stations with insignificant differences, the velocities were combined.

The relative weighting of the techniques was performed in two steps. In the first step, the variance factors of the individual techniques were considered. In the second step, mean technique-specific standard deviations for station positions are computed from the DTRF2014 solutions. These values are assessed in relation to mean standard deviations of station positions derived from the weighted RMS of the corresponding station position time series. For each technique the relation of these two types of standard deviations was computed. If it differed from 1.0, the technique was scaled in DTRF2014 computation accordingly.

The origin of the DTRF2014 was realized from the complete SLR input data series. The scale was realized as a weighted mean of the SLR and the VLBI scale, as, in contrast to the ITRF2014, no scale offset between SLR and VLBI was detected. The orientation of the DTRF2014 was realized by applying no-net-rotation conditions w.r.t. DTRF2008 using a set of well determined and homogeneously distributed GNSS stations. Figure 4 shows the estimated global horizontal velocity field of the combined DTRF2014 solution. The dominating motions visible in this figure are the long-term motions of the tectonic plates.

## Validation and comparison with DTRF2008 and ITRF2014

To validate the DTRF2014 preliminary solution, it was compared to the single-technique solutions, to the DTRF2008 and to the ITRF2014. The EOP are, in addition, compared to the IERS 08 C04 time series. The agreement between all solutions is on the level of a few millimeters and shows the high quality of the ITRS realizations. The agreement of the preliminary DTRF2014 with the ITRF2014 is 1.3–3.5 mm for positions and 0.1–0.3 mm/yr for velocities of GNSS, VLBI and SLR stations. For DORIS stations, the estimated offsets are larger: 7.0 mm for positions and 1.0 mm/yr for velocities, respectively.

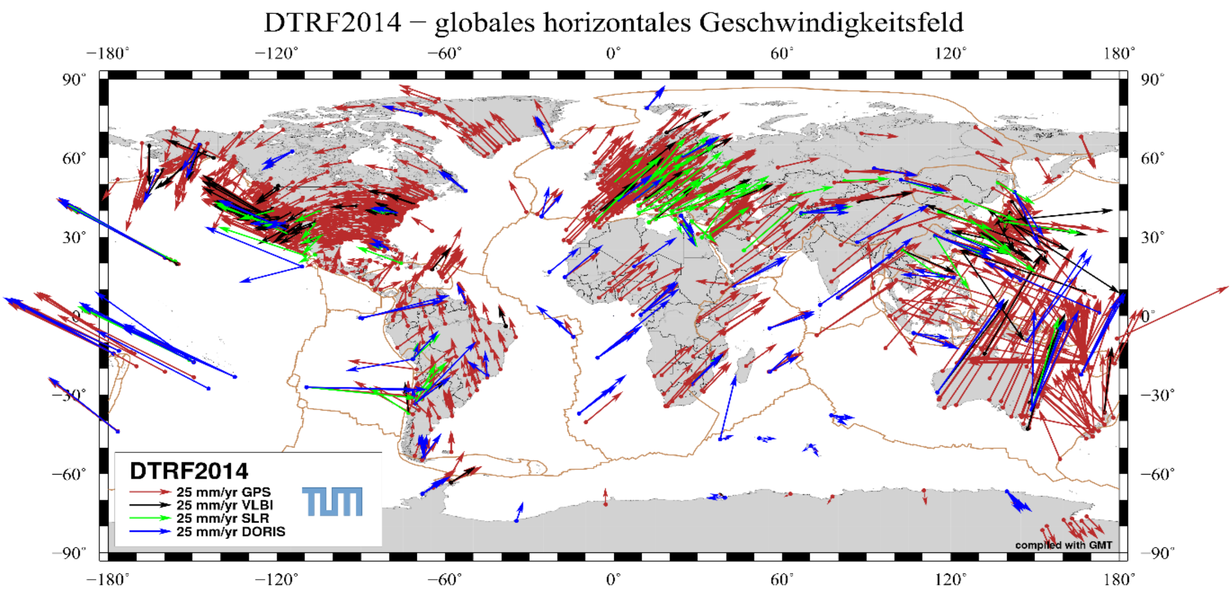


*Fig. 4: The global horizontal velocity field of the DTRF2014 solution.*

The scale differences between the DTRF2014 and the ITRF2014 of ±3.5 mm for SLR and VLBI, respectively, are related to the differences in the scale realization of DTRF2014 and ITRF2014. Due to a suspected significant difference between the SLR and VLBI scale, a scale offset between both techniques was introduced in the ITRF2014 solution. Within the DTRF2014 computation, no such offset was detected and therefore, the scales of both techniques were combined without introducing any offset.

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*Manuela Seitz, Detlef Angermann, Mathis Bloßfeld,*
*Michael Gerstl, Horst Müller*

## 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 2015. These research activities are mainly related to the preparation for 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.

### Preparation for ITRF2014

Specific new developments were achieved and validated in preparation for the ITRF2014: 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 are intended to be applied to the technique solutions which were submitted to the ITRF2014.

Other developments were also finalized and validated, such as modelling of post-seismic deformations for sites affected by major Earthquakes, as well as an improved strategy for the detection of discontinuities in the technique station position time series.

First and early results of the ITRF2014 input data analysis were presented at various conferences in 2015.

A preliminary ITRF2014 solution called ITRF2014P was generated and submitted on September 09, 2015 to the Technique Centres of the four techniques for evaluation. A certain number of feedbacks were then received and all concerns were answered and taken into account for the final ITRF2014 solution.

### Publications

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, 3775–3802, doi:10.1002/2014JB011622.

*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/smoother (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.

### Data Sets

Table 1 lists the input data sets that were used to determine JTRF2014. These are the data sets that the IAG Services submitted to the IERS for the determination of ITRF2014. Before using these data sets to determine JTRF2014 they were edited and pre-processed. Because KALREF uses a fixed time step of one week, the daily GNSS station position (but not the EOP) data were averaged to 1-week intervals, as were the session-wise VLBI data. Stations with observing histories less than 2.5 years were removed, as were regional VLBI sessions. And only those GNSS stations that were included in ITRF2008 were used, augmented by additional IGS stations that were not included in ITRF2008, usually because they started observing after 2008. After this data selection process, data from 671 GNSS, 71 SLR, 159 DORIS, and 71 VLBI stations remained.

*Table 1: Data Sets Submitted by the IAG Services for ITRF2014 and Used for JTRF2014*

| SG | TC | Time Span | Solution | TR | # SINEX | # Sites |
|---|---|---|---|---|---|---|
| **P** | IGS | 1994.0 - 2015.1 | **V**ariance-**C**ovariance | Daily | 7714 | 1845 |
| **R** | IVS | 1979.5 - 2015.0 | **N**ormal **E**quations | Session-Wise | 5796 | 158 |
| **L** | ILRS | 1983.0 - 2015.1 | **V**ariance-**C**ovariance | Fortnightly-Weekly (*) | 1392 | 138 |
| **D** | IDS | 1993.0 - 2015.0 | **V**ariance-**C**ovariance | Weekly | 1140 | 160 |
| **Local Ties** | | | **V**ariance-**C**ovariance | Sporadic | 142 | |

*The SLR data is given at fortnightly intervals before 1993, at weekly intervals thereafter.

SG: space-geodetic data type; P: GNSS; R; VLBI; L: SLR; D: DORIS; TC: technique center; TR: temporal resolution

Outliers were removed after first individually stacking each technique's data by applying intrinsic constraints. After stacking, any observation having an absolute residual greater than 10 cm or a normalized residual greater than 7 sigma (5 sigma for GNSS) was removed. Because the stated formal uncertainties of the observations are generally overly optimistic, the measurement error covariance matrices were scaled by a factor of $(3.07)^2$ for the GNSS data, $(2.98)^2$ for the VLBI data, $(2.61)^2$ for the SLR data, and $(1.36)^2$ for the DORIS data. These variance factors were iteratively determined from the *a posteriori* variance factors obtained from individual stacks of each technique's data and preliminary reference frame solutions.

For the EOPs, daily observations of the x- and y-components of polar motion from all four space-geodetic measurement techniques were used, as were daily observations of the polar motion rates from GNSS, and session-wise observations of UT1 and LOD from VLBI. No editing was done to the EOP data, and the scale factors that were applied to the measurement error covariance matrices of the EOPs were derived from the scale factors that were applied to that technique's station position measurement error covariance matrices.

Both site ties and polar motion data were used to tie the individual technique's station networks together. All of the site ties available for ITRF2008 were used along with the new ties that became available for ITRF2014. The site ties were applied once, at the epoch of the measurement. And the full vector measurement error covariance matrices were used after rescaling them to make the normalized residuals at the co-located sites be less than 4 sigma.

An indication that the station position, EOP, and site tie measurement error covariance matrices have been properly scaled can be obtained by computing the reduced chi-squared of the post-fit residual. If the reduced chi-squared value is close to unity, then the scaled uncertainties are consistent with the post-fit residuals. For JTRF2014, the reduced chi-squared values of the station positions, EOPs, and site ties are 0.93, 1.02, and 1.02, respectively, indicating that their measurement error covariance matrices have been reasonably adjusted. The total reduced chi-squared value of all the measurements used to determine JTRF2104 was 1.07.

### Solution Strategy

After editing and pre-processing, the data sets listed in Table 1 were combined with a Kalman filter to determine JTRF2014. The model for the station position process noise in the Kalman filter included both a deterministic and a stochastic part. The deterministic part consisted of a linear trend and annual and semiannual periodic terms. The linear trend is meant to account for station motion caused by, for example, plate tectonics, glacial isostatic adjustment, etc. The periodic terms are meant to capture the major component of the station motion caused by surface loading. The stochastic part of the process noise model is meant to capture the non-seasonal signals in the station motion caused by surface loading. For that, we used the atmospheric, non-tidal oceanic, and hydrologic loading models available from the IERS Global Geophysical Fluids Center. A best fitting model for a linear trend and annual and semiannual periodic terms was first fit to and removed from the sum of the weekly averaged loading models. Since KALREF assimilates the first difference of the station position data, not the station positions themselves, first differences of the residual loading displacements at each station were formed and the variance of the first-differenced residual computed. These station-dependent variances then formed the stochastic component of the process noise that was used in the Kalman filter. The median variance of the first-differenced residual displacement caused by the sum of atmospheric, non-tidal oceanic, and hydrologic loading was about $(0.9\ \text{mm})^2$ in the north, about $(0.7\ \text{mm})^2$ in the east, and about $(1.7\ \text{mm})^2$ in the vertical.

These values for the variance of the station-dependent process noise were the nominal values used when filtering the station position data between discontinuities. At a discontinuity in the station position the variance was set to a large value, $(5\ \text{m})^2$, in order to allow the Kalman state to follow the jump in station position. After the discontinuity in the station's position it was reset to its nominal value. Discontinuities in station position can be caused by geophysical events such as earthquakes or by man-made events such as equipment changes. Discontinuities in the station position time series were empirically determined using tools available in GIPSY.

For the EOPs, the process noise models consisted of random walks driven by white noise. The variances of the white noise were set to large values in order to accommodate the day-to-day fluctuations in the EOP values.

Following usual practice, the origin of JTRF2014 was determined solely from SLR data and the orientation was constrained by applying a no-net-rotation condition to ITRF2008. The scale was

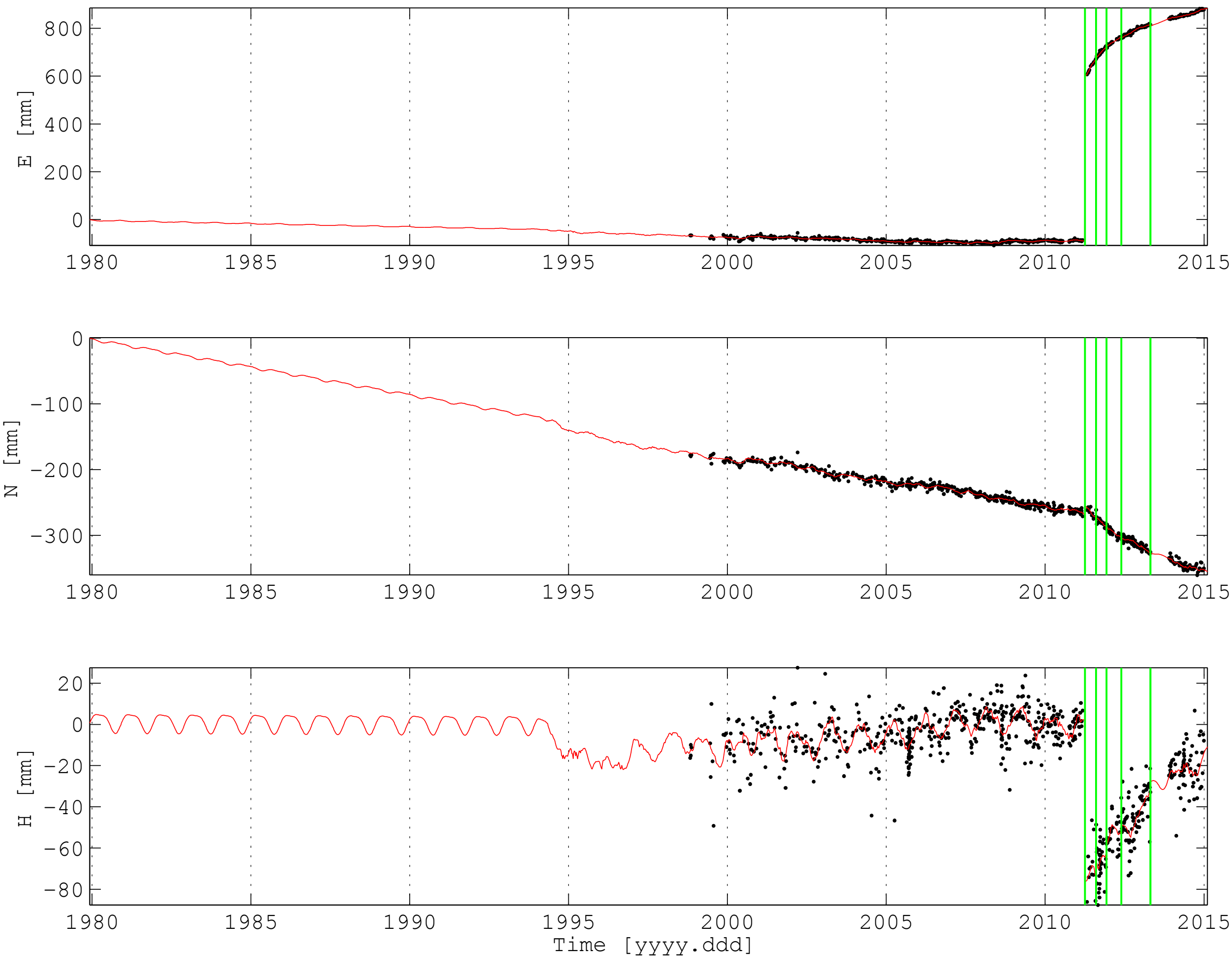


*Fig. 1: Observed (black dots) and Kalman-smoothed, interpolated, and extrapolated (red line) position of the VLBI station at Tsukuba, Japan. The vertical green lines indicate the epochs of discontinuities in the observed position of the station. The east, north, and height (or up) component of the station's position are shown in the top, middle, and bottom panels, respectively.*

determined from a weighted average of SLR and VLBI data with the weights derived from the weights applied to the SLR and VLBI station position data.

Finally, since stations located near each other can be expected to exhibit the same motion, stations of different techniques that are co-located at the same site were constrained to move together.

## JTRF2014

The resulting reference frame, JTRF2014, consists of a set of time series of the positions, but not velocities, of 972 stations spanning November 28, 1979 to February 11, 2015 at weekly intervals along with daily EOPs. As an example of one of the station position time series included in JTRF2014, Figure 1 shows the result for the VLBI station at Tsukuba, Japan. The black dots are the observed positions of the station, the red line is the Kalman-estimated position of the station from JTRF2014, and the vertical green lines indicate the epochs of the discontinuities in the observed station positions at which the process noise was reset. The coseismic displacement of this station caused by the Tohoku, Japan earthquake of March 11, 2011 is readily apparent, especially in the east (top panel) and up (bottom panel) components. By resetting the process noise to a large value at the epoch of the earthquake, the Kalman-estimated position of the station is able to follow the station's coseismic displacement (red line). Between discontinuities, the nominal value of the process noise at this station causes the Kalman-estimated position to be a smoothed version of the observed position. The deterministic model of the process noise is used to both interpolate across gaps in the observations (such as the gap near 2014) and to extrapolate the position of the station to epochs before the station started observing (such as before 1994) or after the station stopped observing (not shown). Since the VLBI station at Tsukuba is co-located with a GNSS station that started observing before it, and because of the co-motion constraint applied to co-located stations, the Kalman-estimated position of the GNSS station is transferred to the VLBI station at those epochs when the VLBI station was not observing but the GNSS station was. This is most evidently seen in the up component (bottom panel) during 1995 to 1998.

Table 2 compares JTRF2014 to ITRF2014 (Altamimi et al., 2016). The entries in Table 2 are the coefficients of a linear fit to a time series of weekly Helmert transformation parameters that map ITRF2014 to JTRF2014. The ITRF2014 station positions were evaluated at the weekly epoch of the JTRF2014 station positions using the linear velocities reported with ITRF2014. No stations affected by earthquakes were included when computing the Helmert transformation parameters using the projected ITRF2014 station positions. The uncertainties given in parentheses in Table 2 are the 1-sigma formal errors of the linear fit to the weekly Helmert transformation parameters and are hence overly optimistic. The translation (*T*) and rotation (*R*) parameters are all less than 0.8 mm except for $T_z$. Plots of the weekly $T_z$ Helmert transformation parameter (not shown) indicate greater variability during 1984–1990 which is adversely affecting the linear fit. The scale (*D*) parameter is also larger, but this is to be expected because the JTRF2014 scale comes from a weighted average of the VLBI and SLR data,

*Table 2: Helmert transformation parameters mapping ITRF2014 to JTRF2014*

| | $T_x$ | $T_y$ | $T_z$ | $D$ | $R_x$ | $R_y$ | $R_z$ |
|---|---|---|---|---|---|---|---|
| O | -0.57 (0.03) | -0.03 (0.03) | -1.48 (0.04) | -1.64 (0.06) | 0.57 (0.02) | 0. 75 (0.02) | 0.25 (0.02) |
| T | -0.12 (0.01) | -0.04 (0.01) | 0.19 (0.01) | 0.20 (0.01) | 0.11 (0.00) | -0.09 (0.00) | -0.17 (0.00) |

Units are mm for the offset (O) and mm/yr for the trend (T). The reference epoch for the trend is January 1, 2005. The values in parentheses are the 1-sigma formal errors.

whereas the ITRF2014 scale comes from a simple average of this data. All rate parameters are at most 0.2 mm/yr. Thus, except in scale, JTRF2014 is highly consistent with ITRF2014.

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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, Xiaoping Wu*

# 3.7 IERS Working Groups
## 3.7.1 Working Group on Site Survey and Co-location

The work towards a more general output and methodology of the work related to co-location and local ties continued. The first step towards a common nomenclature between techniques was reached with the resolution submitted to the REFAG proceedings, which is available through the IERS home page.

Due to different national surveying procedures, local constraints etc., a detailed plan, handbook or instruction for how to perform a local survey has previously been disregarded. However, for the benefit of future surveying work the operational entity of IGN is working on local survey guidelines. The thorough work of producing and reviewing these guidelines is ongoing.

### Co-location status within the different services

#### International DORIS Service, IDS

IDS has adapted the generalized nomenclature, which clarified internal relations between different features of the antennas and its surroundings. Co-location is a permanent objective throughout the DORIS network deployment and evolution. A further development under consideration is monitoring of the DORIS monument stabilities. The current status of the 57 stations in the DORIS network is that 45 are co-located with GNSS, 9 with SLR, and 6 with VLBI. In addition to the geometrical relations between the stations on a site, several DORIS/VLBI radio frequency (RF) compatibility tests were performed by BKG and CNES at Wettzell. The different aspects and requirements for co-location are thus becoming clearer. Future co-locations with DORIS in the coming years are expected in San Juan, Katherine, Ny-Ålesund, Changchun (TBC), and Papenoo (Tahiti).

#### International GNSS Service, IGS

In IGS, the effort to assess individual antenna setup constellations continues. The future antenna phase center model igs14.atx will contain about a dozen of additional robot calibrations that will allow improving the modeling of the phase center position of affected stations. The corresponding antenna/radome combinations have not been calibrated previously; alternatively converted field calibration values have been used. However, the effort applies to many individual stations and only a small number of co-located sites will benefit directly. The model has been compiled, but is not yet in operation.

#### International Laser Ranging Service, ILRS

The ILRS is maintaining a Site information section under its Network heading on the ILRS home page. In this section, links to ILRS Station Survey reports with available survey data are being kept. 24 links to ILRS applicable survey reports, as well as a historical list of surveys performed from the mid-sixties and onwards are available.

**International VLBI Service, IVS**

The European Metrology Research Program (EMRP) joint research project “Metrology for long distance surveying” contributed to the IVS development of local ties. During the EUR137 and T2105 experiments (2015-09-07 and 2015-08-25, respectively) VLBI/GNSS/local tie campaigns were undertaken on the Onsala-Metsähovi baseline. The measurements simultaneously monitored the VLBI telescopes, the IGS antennas, schedule-generated terrestrial ties with the HEIMDALL system, and telescope-mounted GNSS ties during the whole experiments. Although the data have not been fully analyzed yet, the measurements as such were successful. Hence, whatever the results turn out to be, the concept of continual and automated local ties has been proven for the VLBI/GNSS combination without restrictions during two normal experiments. In addition to this, terrestrial laser scanning of radio telescopes (Onsala) and refinement of TLS deformation analysis were made. This aids the detection of focal length variations with respect to elevation, and comparisons with local gain optimization parameters.

## Recent surveying activities

The Frankfurt team performed local survey campaigns at Onsala space observatory to connect the IVS and IGS reference points in August and September 2015.

Geoscience Australia has continued to undertake monitoring surveys at the Australian sites: Katherine VLBI Observatory (VLBI, GNSS), Mt Stromlo Observatory (VLBI, GNSS, DORIS) and Kiribati (GNSS, DORIS) in 2015.

IGN carried out 36 high precision local tie surveys over the 6 last years (through its involvement in DORIS, REGINA, SONEL).

The US National Geodetic Survey conducted an IERS local site survey of the Mauna Kea, Hawaii ITRF site during 2015. There are two techniques co-located at this site (GNSS and VLBI). A report and SINEX file were provided to the IERS at the conclusion of the survey. NGS is currently developing field procedures and data analysis strategies for using an absolute laser tracking system (Leica AT402) to conduct local tie surveys. If all works out, NGS will use this system to conduct future surveys at a higher level of precision and with increased efficiency.

## Publications

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Pearlman M., G. Appleby, D. Behrend, S. Bergstrand, H. Donovan, C. Emerson, J. Esper, H. Hase , J. Long, C. Ma, D. McCormick, C. Noll, E. Pavlis, P. Ferrage, J. Saunier, D. Stowers , S. Wetzel: GGOS Requirements for Core Sites (Revision 2) Draft 3.4, <https://cddis.nasa.gov/docs/2015/SiteRecDoc_Rev2_D3.4.pdf>

Bergstrand S., X. Collilieux, J. Dawson, R. Haas, J. Long, E.C. Pavlis, J. Saunier, R. Schmid, A. Nothnagel: Resolution on the nomenclature of space geodetic reference points and local tie measurements, <https://www.iers.org/SharedDocs/Publikationen/EN/IERS/WorkingGroups/SiteSurvey/Bergstrand_etal_REFAG2014_TieResolution.pdf>

Metrology for long distance surveying, <https://www.ptb.de/emrp/sib60-home.html>

ILRS Station Survey Reports, <https://ilrs.cddis.eosdis.nasa.gov/network/site_information/survey_reports.html>

ITRF co-location survey: online reports, <http://itrf.ign.fr/local_surveys.php>

*Sten Bergstrand*

## 3.7.2 Working Group on Combination at the Observation Level

The IERS WG COL has contributed to the ITRF2014 realization by combination of the geodetic techniques (DORIS, GNSS, SLR, VLBI) at the Normal Equation level. Twelve years of daily Normal Equations (NEQs) from 2002 to 2013 has been processed for each technique (Tab. 1). The combined Normal Equations at weekly bases in SINEX format has been produced and transferred to the IGN in order to have comparison of the Earth orientation parameters solutions (EOP) and station positions with the new referential frame ITRF2014.

A concluding report about the COL activities has been presented during the last meeting at the BKG in Frankfurt, February 19th, 2016.

The memory stacking for Normal Equations from different Analysis Centres have been defined. For DORIS the arc length is 3.5d for each satellite available during 2002–2013, their Normal Equations contain orbit and geodetic parameters not used for this combination products but interesting for further studies. The list of stations to be estimated and compared with ITRF2014 has been produced. The year 2009 is chosen to test the intra and inter technics combination. Discontinuities of stations positions have been also considered in order to be compatible with Dynamo software.

### Normal Equation pre-processing per technique

- NEQ reduction: keeping parameters are EOP, station coordinates, quasar coordinates, tropospheric zenithal delay for all techniques (Tab. 2). For DORIS orbital elements and non-gravitational parameters are kept for further studies. Laser measurements from DORIS satellites such as Topex, Jason 1 & 2, Envisat, Cryosat, Hy2a are also considered and weekly Doris-Laser NEQ are generated to contribute in this combination.
- Stacking the weighted daily NEQs at weekly bases, synchronous to the GPS week: for DORIS satellites is applied the Helmert weighting algorithm using EOP as common parameters, for SLR satellites using stations as common parameters, for GNSS satellites the daily NEQ stacking is unitary weighted, for VLBI R1 & R4 sessions are weekly stacked with unitary weighting.
- Tropospheric parameters bias & gradients are synchronized every 2h interval (01h, 03h, …, 23h) for selected collocated GNSS, VLBI and DORIS stations. Their estimated positions are tested over one year (2009) when the common tropospheric parameters are mutualized (see IERS Annual Report 2014).

- For satellite techniques, the UT parameter at the beginning of each week is forced to the C04 a priori to estimate the LOD parameter, not applied for combination.
- Introduction of stations constraints to cancel the systematic technique effects: application of transformation parameters (origin & scale for satellite techniques, scale for VLBI technique) by the transformation equation:

$$X_{Tech} = X_{Tech\_ITRF} + A.\Theta_{Tech}$$

- where $X_{Tech\_ITRF}$ are the station parameters of each technique expressed in the ITRF2008 referential frame, $X_{Tech}$ the station parameters which are reduced from the normal equation at the next step, and $\Theta_{Tech}$ the systematic effects, which are kept for estimation.
- Introduction of polar motion constraint to cancel the diurnal retrograde oscillation for sub-daily EOP (for DORIS, SLR and VLBI techniques which have EOP at 6h interval, not apply to GNSS technique for which EOP are 1 point per day).

### Normal Equation combination processing strategy

- At the weekly bases, DORIS, DORIS-Laser, SLR and VLBI NEQs are weighted (Helmert algorithm).
- Orbital parameters and non-gravitational parameters are reduced.
- Elimination of EOP outside the GPS week by forcing them with their a priori values.
- Whitening technique's identifiers from tropospheric parameters to stack their equations for collocated stations.
- Daily linear constraints on 6h interval EOP corrections are applied. Option is considering to reduce or not EOP at 0h, 6h, 18h, 24h for keeping only daily EOP at 12h. The weekly global DORIS, DORIS-Laser, SLR and VLBI NEQ is generated.
- Stacking at the weekly bases the DORIS, DORIS-Laser, SLR, VLBI global NEQ with GNSS weekly NEQ using the Helmert weighting algorithm.
- Mutualizing the diurnal retrograde oscillation parameters for all techniques.
- Application of Non Rotation on the set of quasars (NNR).
- The global weekly NEQ DORIS, DORIS-Laser, GNSS, SLR and VLBI is generated.

### Inversion

The weekly global NEQ DORIS, DORIS-Laser, GNSS, SLR and VLBI is inverted with added constraints:

- Minimal constraints with the seven Helmert parameters are applied on the DORIS, GPS, SLR and VLBI core stations and forced to zero with ±0.01mm.

- Diurnal retrograde oscillation correction parameters variation are forced to ±1frd interval.
- Variations on Non rotation correction parameters for quasar ensemble are constrained to ±100nrd interval.
- Stabilization constraint on zenithal tropospheric parameters of ±1m and quasar correction of ±100nrd.
- Weekly solutions: EOP, station coordinates and for some of them with the zenith tropospheric bias or clock bias, quasar coordinates and centre of mass for DORIS satellites.

**Normal Equation delivered for the ITRF2014 comparison campaign: period 2002–2013**

The parameters and delivered Normal Equations from each GRGS analysis centre are shown in Tables 1–2.

*Table 1: Parameters to estimate for comparison with ITRF2014 and added parameters for further studies*

| ***Parameters*** | ***Estimated Parameters*** | ***Initial Values*** |
|---|---|---|
| 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 |
| <u>*Supplementary Parameters non used for ITRF2014 comparison*</u> | | |
| Zénithal Tropospheric Delay wet component<br>&<br>Horizontal Gradients | **TROWET** @ {01, 03, 05, … 23} Hr: Estimation of wet component versus tropospheric model<br>&<br>**TGETOT**, **TGNTOT** 1 pt/d @ 00Hr | GPT2/GMF1 Model for radioelectric waves & Mendes-Pavlis for SLR/LLR<br>+ tropospheric gradient per station North & East directions |

## Results

We present herewith some results obtained by this combination strategy. Figure 1 shows the adjustment of the quasar coordinates w.r.t. ICRF2 celestial reference frame along the 2002–2013 period. Table 3 resumes the mean and RMS values of these corrections and Table 4 the rotation parameters estimated between the ensemble of quasars coordinates and the ICRF2 referential.

Concerning the pole and UT parameters Figure 2 shows the adjustment values w.r.t. C04 series over the 12 years of processing that presents an annual effect. This effect is observed on GNSS pole and affects the combination solution at the same amplitude. Table 5 resumes the statistics on pole and UT solutions.

*Table 2: Techniques used for combination, delivered GRGS Normal Equations (NEQs)*

| GNSS: CNES-CLS Toulouse | DORIS: CNES-CLS Toulouse | SLR: IMCCE GRGS Paris | VLBI: OB LAB Bordeaux |
|---|---|---|---|
| **4372** daily NEQ,<br>Period January 1st 2002 to December 30th 2013<br>GPS week **1147** to **1773,**<br>GPS – Glonass Constellations,<br>between 23 and 55 GNSS satellites | Weekly NEQ per 3,5d arc length & per satellite:<br>**Doris Doppler**:<br>**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<br>**Doris Laser:**<br>**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 per 9d arc length & satellites<br>**628 LAGEOS-1**,<br>**628 LAGEOS-2**,<br>**628 ETALON-1**,<br>**628 ETALON-2** | Session R1 & R4,<br>**621** NEQ R1 session<br>**621** NEQ R4 session |
| **Pole:** PX, PY 1pt/d @12:00<br>**Pole Rates:** PXR, PYR 1pt/d @12:00<br>**LOD** 1pt/d @12:00<br>**Stations** coordinates<br>SX, SY, SZ 1pt/d | **Pole**: PX, PY, **UT1-TAI** 4pt/d @ 00,06,12,18:00<br>**Nutation** NX, NY 2pt/d @ 00, 12:00<br>**Stations** SX, SY, SZ 1p/week @ 12:00<br>**Tropospheric MZB** (Zenith Tropospheric Delay) 12pt/d @ 02h<br>**MGE, MGN** East & North Gradients 1pt/d<br>--------------------------------------------------------<br>***CDX,CDY,CDZ** Center of mass correction on satellites 1/sat/week<br>***Global station bias** SXC, SXS, SXD, SXT, SXB 1pt/arc<br>***Doppler frequency offset** MFO @ 02h.<br>***Orbital elements** EX, EY, EZ, EXP, EYP, EZP 1pt /arc<br>***Atmospheric** drag and lift FD<br>***Radiation Solar pressure** FS 1pt/arc.<br>***Orbit Biases** BT, BN<br>***Radiation forces**, 1 to 8:<br>-specular reflectivity of panel RRS<br>-diffuse reflectivity of panel RRD<br>***Emissivity of panel** 1 à 8 per arc RE, RF<br>***Gravity field coefficients** normalized: GCN cosinus, GSN sinus 0 up to 40 degree | **Pole** : PX, PY 4pt/d @ 00,06,12,18h:00<br>**UT1-TAI** : PT 4pt/d @ 00,06,12,18:00<br>**Nutation** NX, NY 2pt/d @ 00:00, 12:00<br>**Stations**: SX, SY, SZ 1pt/week @12:00<br>**Station range Bias** MRB 1/w/station<br>--------------------------------------<br>***Orbital elements** EX, EY, EZ, EXP, EYP, EZP 1pt /arc<br>***Radiation Solar pressure** 1pt/week/sat<br>***Orbit Biases** 1pt/week/sat<br>***Gravity field coefficients** normalized: GCN cosinus, GSN sinus degree 0 to 40<br>***Oceanic tides coefficients** normalized OCN, OSN | **Pole** : PX, PY 4pt/d @ 00,06,12,18:00<br>**UT1-TAI** : PT 4pt/d @ 00,06,12,18:00<br>**Nutation** : NX, NY 4pt/d @ 00,06,12,18:00<br>**Stations** : SX,SY,SZ 1pt/week @12:00<br>**Quasars** : QRA, QDE 1pt/week<br>**Tropospheric zenithal delays MZB** 12pt/d @ 02h (01,03,05,07,09,11,13,15,17,19, 21,23)<br>--------------------------------------------<br>***Clock error MTB** for VLBI stations @01:00h |

* Added parameters for further studies which are reduced or eliminated for this step of development

Nutation parameters plotted in Figure 3 show large discrepancies compared to the C04 corrections series w.r.t. IAU200A/2006 model mainly due to GRGS VLBI NEQ where these parameters are not suitably processed. Investigation is in progress to perfect this nutation parameter estimation by GRGS-VLBI processing. Table 6 resumes the means and RMS values for the set of dX and dY estimated by GRGS combination over the 2002–2013 period.

Station positions were estimated. The Wettzell site with GPS, SLR and VLBI collocated stations have represented in X, Y, Z corrections w.r.t. ITRF2008 a priori in Figure 4. It shows an annual oscillation due to the atmospheric loading effect, this model is not included during the process. Tables 7–8 give some statistical values showing the consistency between GPS, SLR and VLBI solutions.

The systematic effects are estimated on this 2002–2013 period. Figure 5 shows the X, Y, Z translations for satellite techniques and scale factor for satellite and VLBI techniques. Table 9 resumes the means and RMS values of these systematic effects. We note high discrepancies on VLBI scale factor from 2008 year and great annual oscillation on GNSS Z-translation ±25mm in opposite sign comparing from DORIS, DORIS-Laser and SLR variations. In this

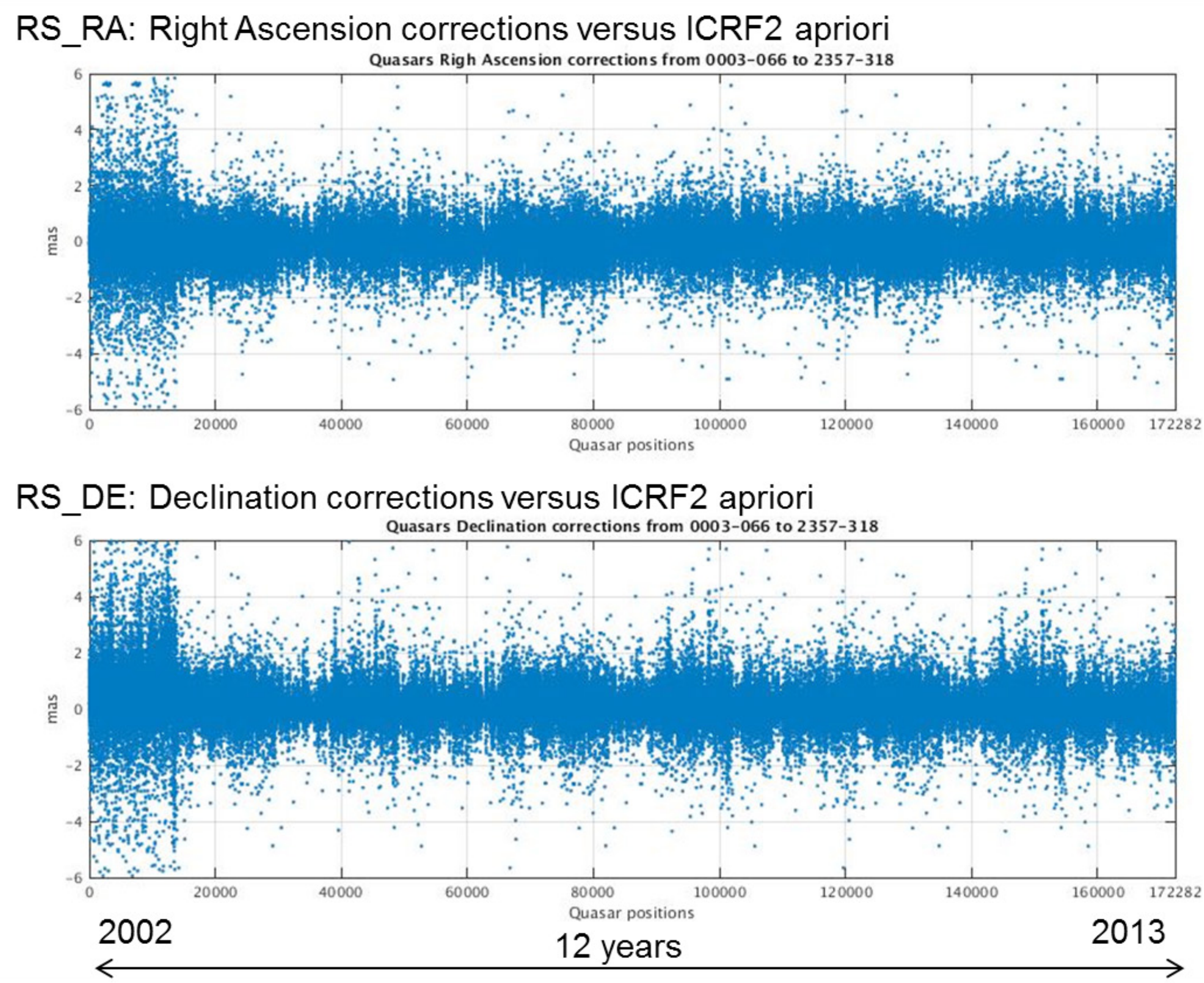


*Fig. 1: Radio source corrections w.r.t. ICRF2*

*Table 3: Means & RMS of quasar corrections w.r.t. ICRF2*

| | Mean (mas) | RMS (mas) |
|---|---|---|
| Right ascension RS_RA | –0.0343 | 0.7221 |
| Declination RS_DE | 0.1334 | 0.7907 |

*Table 4: Rotation parameters w.r.t. ICRF2*

| | R1 (mas) | R2 (mas) | R3 (mas) |
|---|---|---|---|
| Mean | 0.0982 | 0.0198 | 0.1537 |
| Uncertainty | 212.720 | 186.267 | 154.292 |

*Table 5: Pole & UT1, mean & RMS w.r.t. C04*

| | xp (mas) | yp (mas) | UT1–UTC (μs) |
|---|---|---|---|
| Mean | –0.0294 | –0.0042 | –2.0 |
| RMS | 0.0512 | 0.0373 | 26.4 |

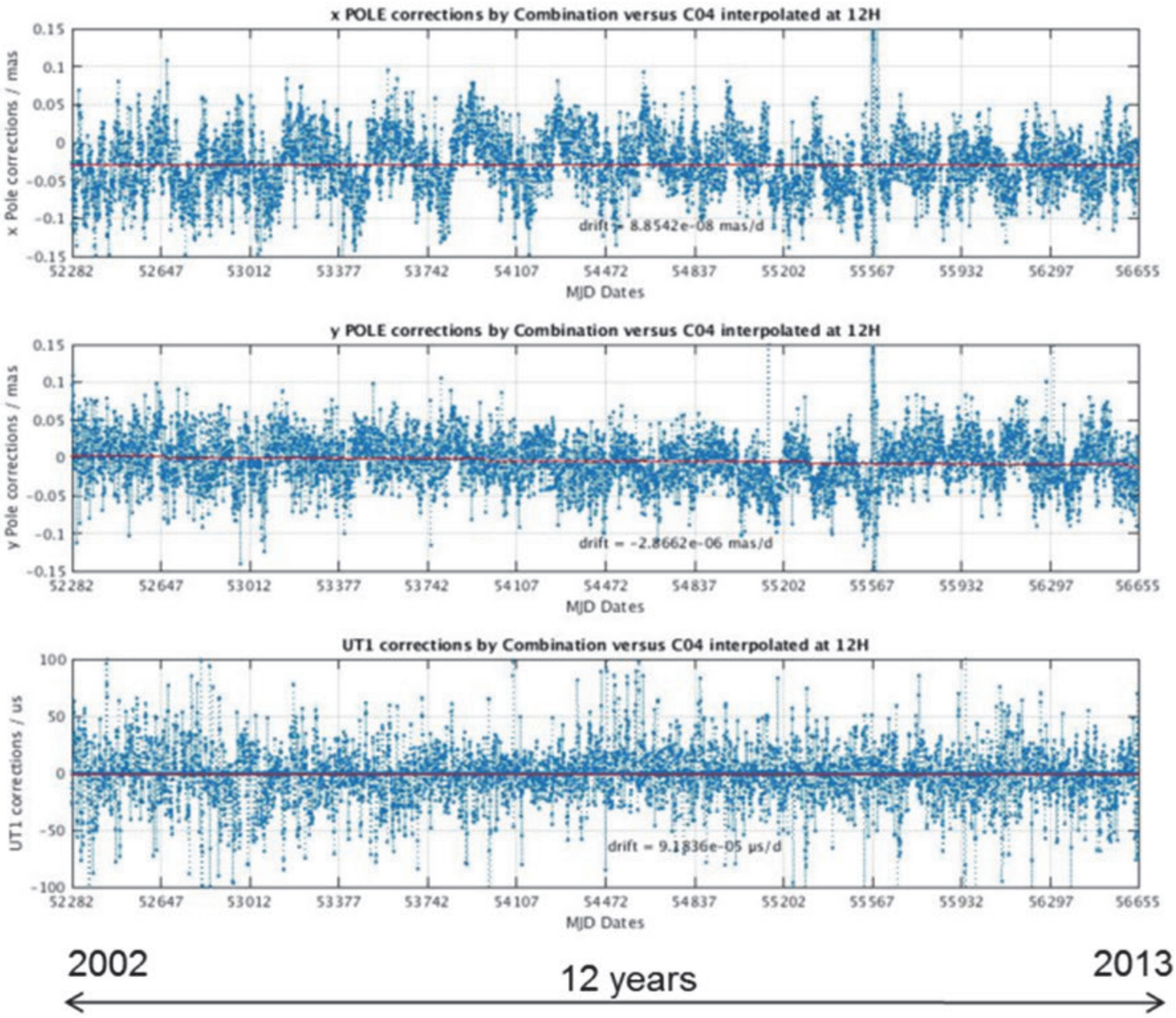


*Fig. 2: Pole and UT corrections w.r.t. C04 series over 2002–2013 period*

*Table 6: Nutation corrections w.r.t. IAU2000A/2006*

| | dX (mas) | dY (mas) |
|---|---|---|
| Mean | 0.0039 | 0.0195 |
| RMS | 0.3670 | 0.3482 |

*Table 7: RMS3D of Wettzell station*

| | RMS 3D (m) |
|---|---|
| GPS | 0.0149 |
| SLR | 0.0464 |
| VLBI | 0.0205 |

*Table 8: Rates of Wettzell station*

| rate | (m/y) | (m/y) | (m/y) |
|---|---|---|---|
| GPS | –0.0171 | 0.0173 | 0,009 |
| SLR | –0.0148 | 0.0169 | 0.105 |
| VLBI | –0.0167 | 0.0176 | 0.0101 |

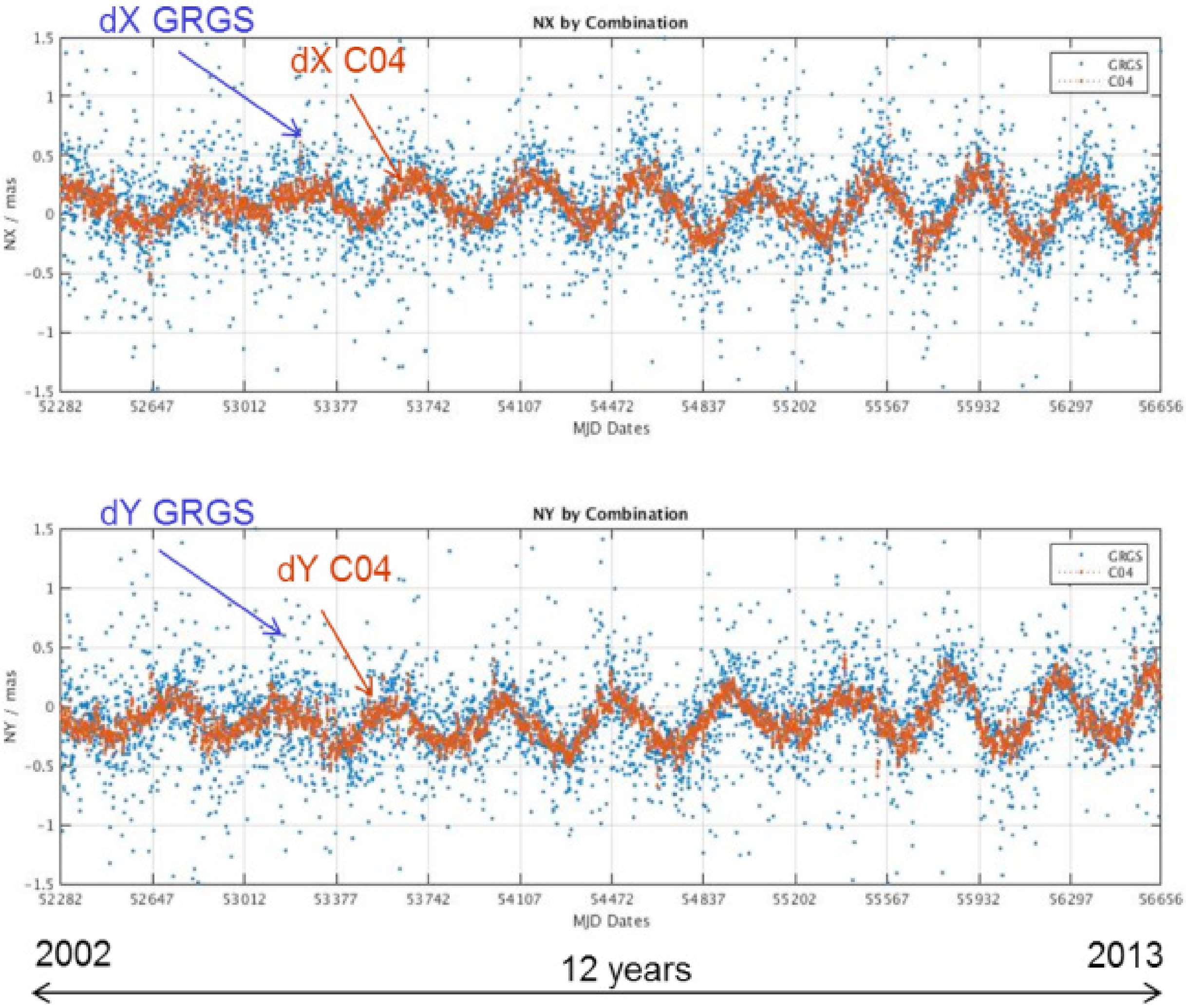


*Fig. 3: Nutation corrections w.r.t. model IAU2000/2006A*

*Table 9: Systematic effects by techniques, means and RMS values for translation and scale factor*

| | DORIS | | SLR on DORIS satellites | | GNSS | | SLR on 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 |

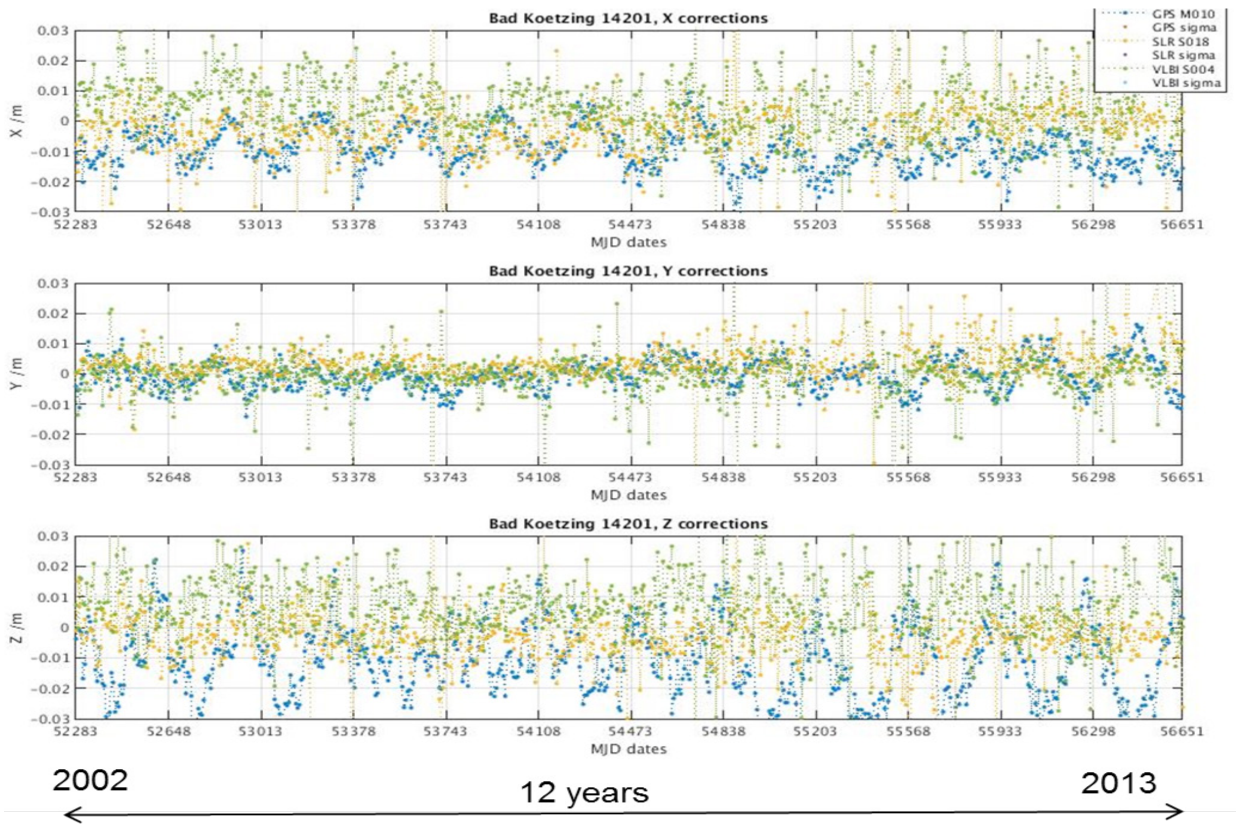


*Fig. 4: Wettzell (Bad Koetzting) station with GPS: 14201M010 SLR: 14201S018 VLBI: 14201S004, corrections in X, Y, Z w.r.t. their ITRF2008 a priori*

process, systematic effects are applied to the whole set of stations with seismic phenomena not excluded. A better estimation of these effects consists to exclude seismic stations from these systematic effects cancellation constraints.

Transformation parameters in three translations, scale and three rotations are weekly estimated. Figure 6 shows these parameters on the 2002–2013 period and Table 10 resumes the means and uncertainties values per techniques. We note the perturbation on translations (5cm) and rotations (5µas) for VLBI during the years 2008–2009 probably due to a badly datum constrained and the annual oscillation on GPS translations (+/-25mm for TZ) due to the atmospheric loading effect model not included.

## Conclusions

In this combination at Normal Equation level performed by the GRGS Combination Centre the COL-WG have shown the possibility to determine simultaneously quasar coordinates, Earth orientation parameters and station coordinates. Algorithms developed to process DORIS GNSS SLR and VLBI techniques are available to perform combination with some modification on systematic effects cancellation and datum selection for minimal constraints applica-

*Table 10: Means and uncertainties for transformation parameters in translation, scale factor and rotations for DORIS, GNSS, SLR and VLBI techniques*

| | TW (mm) | TY (mm) | TZ (mm) | Sc (mm) | RX (µas) | RY (µas) | Rz (µas) |
|---|---|---|---|---|---|---|---|
| DORIS | –2.0±4.6 | 0.0±3.7 | –2.8±7.2 | **–3.2±7.1** | 0.2±2.4 | –1.0±3.0 | 0.0±3.1 |
| GNSS | **–6.3±7.4** | –1.1±4.6 | **–5.5±14.5** | –1.7±2.1 | –0.07±0.3 | –0.4±0.6 | –0.2±0.9 |
| SLR | –1.1±3.3 | –0.2±2.7 | –0.2±5.5 | **4.0±5.6** | 0.7±2.8 | –0.9±2.8 | –0.3±4.2 |
| VLBI | **–4.0±11.7** | **3.8±12.2** | 1.6±5.9 | **3.1±7.8** | **–2.8±10.5** | **–1.7±8.6** | 0.8±5.4 |

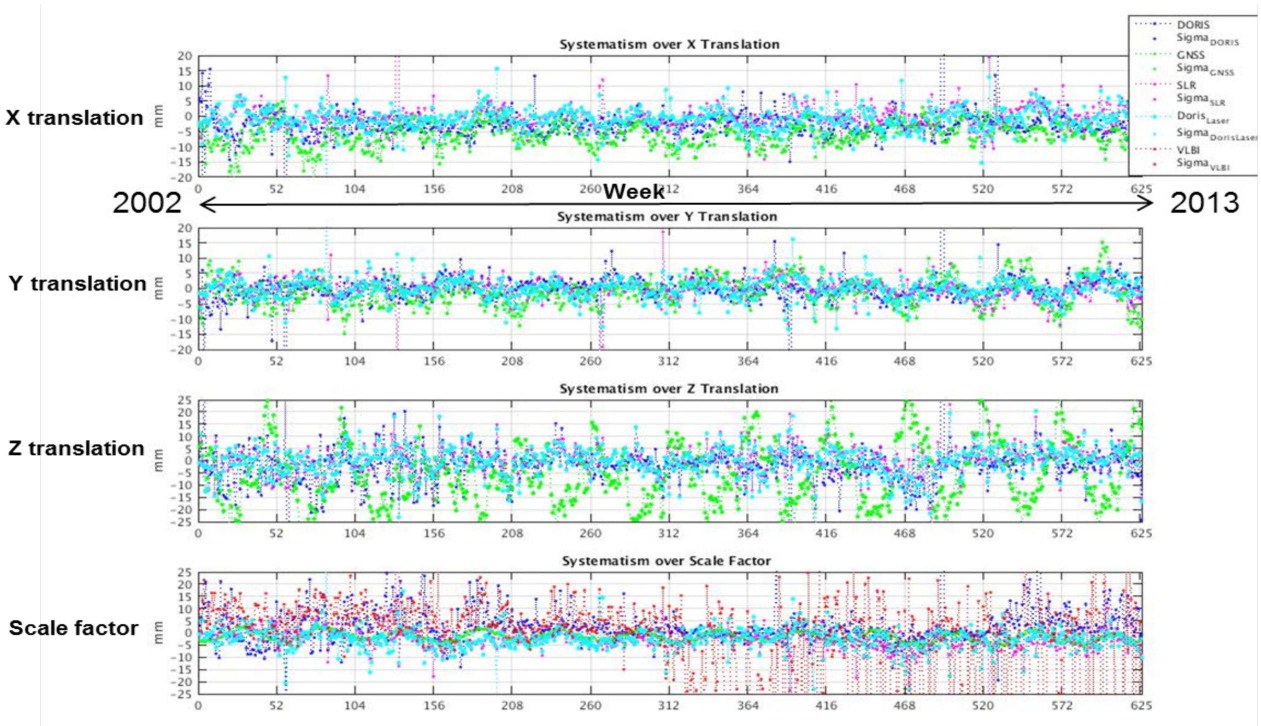


*Fig. 5: Systematic effects in translation and scale factor weekly estimated over the 625 weeks 2002–2013*

tion. This development closes the COL activities presented at the last meeting on 19th February 2016 at BKG Frankfurt am Main.

GRGS Combination Centre pursues this improvement in combination technique and studies the EOP determination by GNSS and VLBI combination from NEQ produced by different analysis centres in SINEX format. EOP solutions will be compared to the C04 series for evaluation and for testing the improvement in their determination.

## References 2015

Richard J.Y., Bellanger A., Biancale R., Bizouard C., Bourda G., Bouquillon S., Coulot D., Deleflie F., Gambis D., Lemoine J.M., Loyer S., Pollet A., Soudarin L., Multi-Techniques Combination for Earth Orientation Parameters, station and quasar coordinates, EGU2015, Vienna, 12th – 19th April 2015

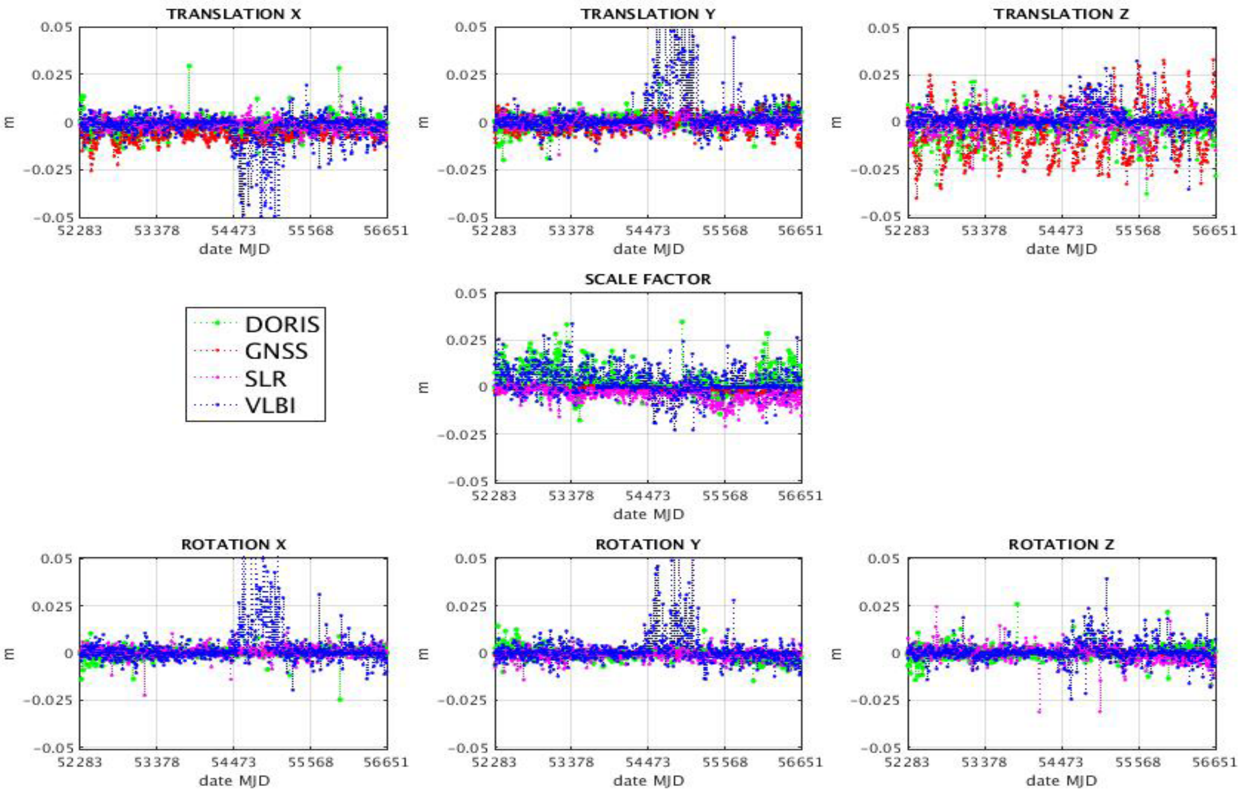


*Fig. 6: Transformation parameters for DORIS, GNSS, SLR and VLBI 1p/week over 2002–2013 period*

## Participants in Working Group activities

D. Gambis, J.-Y. Richard, C. Bizouard, Observatoire de Paris/GRGS
R. Biancale, J.-M. Lemoine, CNES/GRGS
F. Deleflie, IMCCE/GRGS
S. Loyer, L. Soudarin, CLS/GRGS
G. Bourda, Observatoire de Bordeaux
M. Seitz, R. Heinkelmann, M. Gerstl, H. Müller, M. Bloßfeld, DGFI-TUM
R. Schmid, TUM
D. Thaller, BKG (formerly AIUB)
M. Mareyen, S. Bachmann, BKG
R. König, GFZ
D. König, GEST/UMBC (formerly GFZ, now BKG)
T. Springer, D. Svehla, ESA/ESOC
H. Krasna, K. Teke, TUW
C. Sciarretta, ASI/e-GEOS
M. Kudryashova, ORB/IMCCE
F. Lemoine, GFSC

*Jean-Yves Richard, Richard Biancale*

## 3.7.3 Working Group on SINEX Format

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.

During the year 2015 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.

The latest version of the SINEX format is v 2.02. A full format description is available at <http://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html>.

The SINEX format is used by all four space-geodetic techniques to provide their products. In addition, the combined terrestrial reference frame (ITRF) is also provided in SINEX format. To ensure that all technique-specific needs are covered by the SINEX format, representatives from each Technique Service are members of the SINEX Working Group. Additionally, representatives of the IERS ITRF Combination Centres, the IERS Working Group on Co-location and Site Survey, and the IERS Convention Centre 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.

In the framework of generating the next release of an ITRF, i.e. ITRF2014, a new representation of non-linear station motions due to post-seismic movements was implemented in the adjustment process by the ITRS Combination Centre at IGN (Institut National de l'Information Géographique et Forestière). Exponential and logarithmic terms will now represent the station motions together with linear velocities. The ITRS Combination Centre defined how these new parameters will be represented in SINEX. This definition still needs to be included in an updated version of the official SINEX format.

The IVS community brought up the need to provide more information on radio source positions within the SINEX file. The parameters describing the radio source positions are already defined, however, a detailed information on, e.g., the number of observations per source is not yet available. As this kind of information turned out to be useful for further using the radio sources from SINEX files, there will be a new block defined. The final format description extension is not yet ready.

*Daniela Thaller (on behalf of the WG)*

## 3.7.4 Working Group on Site Coordinate Time Series Format

This Working Group is a unified one, both an IERS WG (<http://iers.org/WGSCTSF>) and IAG WG 1.1.1 (<http://iag.uni.lu/index.php?id=175>) of Sub-Commission 1.1 (Coordination of Space Techniques). The following report summarizes its activities in 2015. For more details on the goals and on previous work see the reports for 2012 to 2014 and the web sites.

### Goals and objectives

- Define a common exchange format for coordinate time series for the geodetic techniques (DORIS, GNSS, SLR, VLBI). The format should provide a user-friendly presentation of coordinate time-series results for a potentially broader community of users.
- Ensure that the format contains the necessary information (data and metadata) to be easily used or converted for the web tools of the IAG Services (GGOS, IERS, IDS, IGS, ILRS, IVS)
- The format must allow the comparisons of time series between GNSS, SLR, VLBI and DORIS, but also with other techniques such as tide gauges records. Some of the issues that should also be addressed are, e.g., reference system, time unit, content description …

### WG Members

In order to have the best possible interaction with the groups working with station coordinate time series, the working group is composed of time series providers and users:

- Thomas Herring (MIT), IERS Analysis Coordinator (ex officio)
- Daniela Thaller, Director of the IERS Central Bureau (ex officio)
- Bernd Richter (BKG), GGOS portal manager
- Xavier Collilieux (IGN), ITRS Combination Center
- Manuela Seitz (DGFI), ITRS Combination Center
- Laurent Soudarin (CLS), IDS representative
- Paul Rebischung (IGN), IGS representative
- Erricos Pavlis (Univ. of Maryland, Baltimore County), ILRS representative
- John Gipson (NASA), IVS representative
- Médéric Gravelle (Univ. La Rochelle), user (SONEL)
- Yehuda Bock (Scripps Institution of Oceanography), user (SOPAC GPS webservice)
- Simon Williams (Proudman Oceanographic Laboratory), user (CATS software)
- Xiaoping Wu (JPL), user

## Timeline of activities

- April 2012 WG established by IERS DB (IAG WG 1.1.1 since 2013)
- Dec. 2012 1st WG meeting in San Francisco
- April 2013 2nd WG meeting in Vienna
- May 2013 Presentation of the WG activity at the IERS Retreat in Paris
- July 2014 Draft document submitted to the WG
- Apr. 2015 3rd WG meeting in Vienna

## WG activity in 2015

A meeting of the WG took place in Vienna, on April 15th, 2015, during the EGU General Assembly week. Based on a non exhaustive list of existing formats at IAG services and GPS time series providers, metadata and data have been examined.

### Summary of previous discussions

#### *File structure and format*

- Metadata and data should be in the same file.
- Easy identification of data block and metadata block should be possible.
- Header should be easy and quickly to read, to get the required information easily.
- Avoid stripping out the data and putting it into user's own format, that might lead to errors.
- To lighten the format, use default values (units ...) and optional fields.

#### *Data*

Epoch, time scales, time tags:

- Time should be as specific as possible.
- It should be easily understood by users (eg. YYYY MM DD HH MM SS.sss), easy to lot (MJD), precise enough for high frequency sampled series.
- Two time scales are probably needed.
- Decimal year is not recommended as it can cause problems because of leap years.
- A certain flexibility of the format is necessary. For daily and weekly sampling, hours, minutes and seconds could be ignored.
- The sampling frequency could be indicated in the metadata.
- Time tag: middle of the span.

Coordinate system:

- XYZ needed to convert to any geographic system

  (We want to plot NEU variations in mm, but XYZ is the basic data)

Accuracy of the series (vs magnitude):

- A precision of 10 to 3 mm may be required.

  However, such a precision is not required for fast event such as glacier (several m/year).

***Metadata***

- Metadata descriptors
  - To be unified
  - To be used by plotting tools
  - Need for a list of descriptor type? (Unified Content Descriptor? Cf. metadata search engine of the GGOS Portal)
- Transformation applied by provider must be indicated (6, 7, … parameters).

***Open issues***

- How many stations per file? More than one raises issues (e.g. ties between stations) and consequences on the format (e.g. block of metadata for each station, station code in data).
- Position and velocity discontinuities (soln in SINEX): desired but a lot of issues.
- Need of correlations between components?
- Exchange format: in text or elaborate language (JSON, XML, YAML …)?
- Substitution character when values non available: «N/A», other? Separation with coma?

**Existing formats at IAG services and GPS time series providers**

**IDS STation Coordinates Difference format (STCD)**

<http://ids-doris.org/documents/report/CB_STCD_format_v1.0.pdf>

**UNAVCO Plate Boundary Observatory (PBO) GPS time series format**

<http://www.unavco.org/projects/major-projects/pbo/lib/docs/gps_timeseries_format.pdf>
<http://pbo.unavco.org/doc/NOTICE%20TO%20UNAVCO%20DATA%20PRODUCT%20USERS%2020130315.pdf>

**Nevada Geodetic Laboratory (NGL) GPS time series formats**
<http://geodesy.unr.edu/gps_timeseries/README_txyz2.txt>
<http://geodesy.unr.edu/gps_timeseries/README_tenv.txt>
<http://geodesy.unr.edu/gps_timeseries/README_tenv3.txt>

**University of La Rochelle (ULR) GPS time series format**
No description

**JPL GPS Time Series and Residual Format**

<http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf>

***Others formats*:**

**Scripps Orbit and Permanent Array Center (SOPAC) XML for Geodesy**

http://sopac.ucsd.edu/xmlGeodesy.shtml

**Virtual Observatory (VO) VOTable Format Definition**

<http://www.ivoa.net/documents/VOTable/>

The content of these formats have been listed and compared, regarding the metadata and the data. The examination allows identifying three types of metadata (file information, site information, and product information) as well as a list of variables forming the data block.

## Future activities

The next step is to define the necessary elements for the time series exchange format (metadata content, data table, mandatory and optional inputs) as well as the units, the coordinate system, the date and time system. Starting from these elements, a draft of format can be proposed.

*Laurent Soudarin, Wolfgang R. Dick*

# 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 parameters 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,

- o 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 Subcommission 1.1
Chair of IAG Subcommission 1.2
Chair of IAG Subcommission 1.4
President of IAG Commission 3
Chair of IAG Subcommission 3.1
Chair of IAG Subcommission 3.2
Chair of IAG Subcommission 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 J. Luzum
(address see below)

**Analysis Coordinator**

Thomas Herring
Massachusetts Institute of Technology
77 Massachusetts Avenue
Building 54-618
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
fax: +33-1-4051-2291
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@usno.navy.mil

**Conventions Centre Representative**

Christian Bizouard
Observatoire de Paris
61, avenue de l'Observatoire
75014 Paris
France
phone: +33-1-4051-2335
fax: +33-1-4051-2291
e-mail: christian.bizouard@obspm.fr

**ICRS Centre Representative**

Jean Souchay
Observatoire de Paris
SYRTE
61, Avenue de l'Observatoire
75014 Paris
France
phone: +33-1-40512322
fax: +33-1-40512291
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: altamimi@ensg.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
67084 Strasbourg Cedex
France
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
fax: +41-31-31-631-3869
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
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 Goddard
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**

Chopo Ma
Planetary Geodynamics Laboratory, Code 698
NASA's Goddard Space Flight Center
Greenbelt, MD 20771, USA
phone: +1-301-614-6101
fax: +1-301-614-6522
e-mail: Chopo.Ma@nasa.gov

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

**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**

Bernd Richter
Bundesamt für Kartographie und Geodäsie
Richard-Strauss-Allee 11
60598 Frankfurt am Main
Germany
phone: +49-69-6333-345
fax: +49-69-6333-441
e-mail: bernd richter@bkg.bund.de

(*Status as of 1 January 2017*)

# Appendix 3: Contact addresses of the IERS components

**Analysis Coordinator**

Thomas Herring
Massachusetts Institute of Technology
77 Massachusetts Avenue, Building 54-618
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)**
IGS Central Bureau
Jet Propulsion Laboratory (JPL)
M/S 238-540, 4800 Oak Grove Drive
Pasadena, CA 91109, USA
phone: +1-818-354-2077
fax: +1-818-393-6686
e-mail: igscb@igscb.jpl.nasa.gov

*IGS Representatives to the IERS Directing Board*:
Rolf Dach, Chuck Meertens
*IERS Representative to the IGS Governing Board*:
Richard Gross

**International Laser Ranging Service (ILRS)**
ILRS Central Bureau
NASA's Goddard Space Flight Center (GSFC), Code 690.5
Greenbelt, MD 20771, USA
phone: +1-301-614-6542
fax: +1-301-614-6099
e-mail: cb@ilrs.gsfc.nasa.gov

*ILRS Representatives to the IERS Directing Board*:
Ludwig Combrinck, Erricos C. Pavlis
*IERS Representative to the ILRS Directing Board*:
Daniela Thaller

**International VLBI Service for Geodesy and Astrometry (IVS)**
IVS Coordinating Center
NASA's Goddard Space Flight Center (GSFC), Code 698.2
Greenbelt, MD 20771, USA
phone: +1-301-614-5939
fax: +1-301-614-6099
e-mail: ivscc@ivscc.gsfc.nasa.gov

*IVS Representatives to the IERS Directing Board*:
Rüdiger Haas, Chopo Ma
*IERS Representative to the IVS Directing Board*: Chopo Ma

**International DORIS Service (IDS)**
IDS Central Bureau
CLS
8-10, rue Hermes, Parc Technologique du Canal
31526 Ramonville CEDEX, France
phone: +33 5 61 39 48 49 / 5 61 39 47 50
fax: +33 5 61 39 48 06
e-mail: Laurent.Soudarin@cls.fr
*IDS representatives to the IERS*:
Hugues Capdeville, Jérôme Saunier
*IERS Representative to the IDS Governing Board*: Brian Luzum

## Product Centres

**Earth Orientation Centre**
Observatoire de Paris
61, Avenue de l'Observatoire
75014 Paris
France
phone: +33-1-4051-2335
fax: +33-1-4051-2291
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**
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@usno.navy.mil

*Primary scientist and representative to the IERS Directing Board*: Christine Hackman

**Conventions Centre**
U.S. Naval Observatory, Earth Orientation Department
3450 Massachusetts Avenue, NW, Washington, DC, USA
phone: +1-202-762-0242
fax: +1-202-762-1563
e-mail: brian.luzum@usno.navy.mil

Observatoire de Paris
61, Avenue de l'Observatoire
75014 Paris, France
phone: +33-1-4051-2335
fax: +33-1-4051-2291
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**
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@usno.navy.mil

Observatoire de Paris, SYRTE
61, Avenue de l'Observatoire
75014 Paris, France
phone: +33-1-40512322
fax: +33-1-40512291
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**
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: itrf@ign.fr

*Primary scientist and representative to the IERS Directing Board*: Zuheir Altamimi

**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

***Special Bureau for the Oceans***
Richard S. Gross
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***
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***
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***
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 (DGFI)**
Manuela Seitz
Deutsches Geodätisches Forschungsinstitut an der TUM
Alfons-Goppel-Straße 11
80539 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)**
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: altamimi@ensg.ign.fr

**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 1 January 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 `ser7`

**Monthly earth orientation data**
Web access:
http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins
ftp access: `hpiers.obspm.fr` - directory `iers/bul/bulb_new`

**Long term earth orientation data**
http://hpiers.obspm.fr/eop-pc/index.php?index=eoptable
ftp access: `hpiers.obspm.fr` - directory `iers/eop`

**Leap second announcements**
Web access:
http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins
ftp access: `hpiers.obspm.fr` - directory `iers/bul/bulc`

**Announcements of DUT1**
Web access:
http://hpiers.obspm.fr/eop-pc/index.php?index=bulletins
ftp access: `hpiers.obspm.fr` - directory `iers/bul/buld`

### Conventions

Web access:
IERS Conventions 2010:
http://tai.bipm.org/iers/conv2010/conv2010.html

### International Celestial Reference Frame

Web access: http://hpiers.obspm.fr/icrs-pc/
ftp access: `hpiers.obspm.fr` - directory `iers/icrs-pc`

### International Terrestrial Reference Frame

Web access: http://itrf.ensg.ign.fr/
ftp access: `lareg.ensg.ign.fr` - directory `pub/itrf`

### Geophysical fluids data

Web accesss: http://geophy.uni.lu/

## 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/wws/arc/itrfmail

## IERS Components

**Directing Board**
Web page: http://www.iers.org/DB

**Analysis Coordinator**
Web page: http://www.iers.org/AC

**Central Bureau**
Web page: http://www.iers.org/CB

### Product Centres

**Earth Orientation Centre**
Web site: http://hpiers.obspm.fr/eop-pc/

**Rapid Service/Prediction Centre**
Web site: http://www.usno.navy.mil/USNO/earth-orientation

**Conventions Centre**
Web site: http://tai.bipm.org/iers/

**ICRS Centre**
Web site: http://hpiers.obspm.fr/icrs-pc/

**ITRS Centre**
Web site: http://itrf.ensg.ign.fr/

**Global Geophysical Fluids Centre**
Web site: http://geophy.uni.lu/
***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)**<br>Web site: http://www.igs.org/ |
| | **International Laser Ranging Service (ILRS)**<br>Web site: http://ilrs.gsfc.nasa.gov/ |
| | **International VLBI Service (IVS)**<br>Web site: http://ivscc.gsfc.nasa.gov/ |
| | **International DORIS Service (IDS)**<br>Web site: http://ids-doris.org/ |
| **ITRS Combination Centres** | **Deutsches Geodätisches Forschungsinstitut (DGFI)**<br>Web site: http://www.dgfi.tum.de/en/international-services/itrs-combination-centre/ |
| | **Institut Géographique National (IGN)**<br>Wep site: http://itrf.ensg.ign.fr/ |
| | **Jet Propulsion Laboratory (JPL)**<br>Web page: http://www.iers.org/ITRSCC-JPL |
| **Working Groups** | **Working Group on Site Survey and Co-location**<br>Web site: http://www.iers.org/WGSiteSurvey |
| | **Working Group on SINEX Format**<br>Web site: http://www.iers.org/WGSINEX |
| | **Working Group on Site Coordinate Time Series Format**<br>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>.

| | |
|---|---|
| A&A | Astronomy & Astrophysics |
| AAC | Associated Analysis Centre |
| AAM | Atmospheric Angular Momentum |
| AAS | American Astronautical Society |
| AC | Analysis Centre |
| AC | Analysis Coordinator |
| ACC | [IGS] Analysis Center Coordinator |
| AGGO | Argentinian-German Geodetic Observatory |
| AGN | Active Galactic Nucleus [or Nuclei] |
| AGU | American Geophysical Union |
| AICAS | Astronomical Institute, Academy of Sciences of the Czech Republic |
| AOD | atmospheric and oceanic dealiasing |
| AOV | Asia-Oceania VLBI Group for Geodesy and Astrometry |
| APOD | Atmospheric density Detection and Precise Orbit Determination [satellite] |
| APOLLO | Apache Point Observatory Lunar Laser-ranging Operation |
| APSG | Asia-Pacific Space Geodynamics |
| AR | [IERS] Annual Report |
| AR | autoregressive |
| ASCII | American Standard Code for Information Interchange |
| ASI | Agenzia Spaziale Italiana |
| AUS | = AUSLIG |
| AUSLIG | Australian Surveying and Land Information Group (now: Geoscience Australia ) |
| AWG | Analysis Working Group |
| BACC | Beijing Aerospace [Command and] Control Center |
| BIH | Bureau International de l'Heure |
| BIPM | Bureau International des Poids et Mesures |
| BKG | Bundesamt für Kartographie und Geodäsie |
| BVID | Bordeaux VLBI Image Database |
| CA | California, USA |
| Caltech | California Institute of Technology |
| CATREF | Combination and Analysis of Terrestrial Reference Frames |
| CATS | Create and Analyze Time Series [software] |
| CB | Central Bureau |
| CC | Combination Centre |
| CCD | Charge-Coupled Device |
| CDDIS | NASA Crustal Dynamics Data Information System |
| CDS | Centre de Données astronomiques de Strasbourg |
| CERGA | Centre d'Etudes et de Recherches Géodynamiques et Astronomiques |
| CfA | Harvard-Smithsonian Center for Astrophysics |
| CFHT | Canada-France-Hawaii Telescope |
| CLS | Collecte Localisation Satellites |
| CMP | Conventional Mean Pole |
| CNES | Centre National d'Etude Spatiale |
| CODE | Centre for Orbit Determination in Europe |
| COL | combination at/on the observation level |
| C/P | Combination and Prediction |
| CPC | Climate Prediction Center |
| CRF | Celestial Reference Frame |
| CSR | Center for Space Research, University of Texas |
| CTIO | Cerro Tololo Inter-American Observatory |
| DB | Directing Board |
| DC | District of Columbia, USA |
| Dec, DEC | declination |
| deg | degree |
| DGFI | Deutsches Geodätisches Forschungsinstitut |
| DiFX | Distributed FX |
| DIODE | Détermination Immédiate d'Orbite par Doris Embarqué |
| DIS | IERS Data and Information System |
| DOI, doi | Digital Object Identifier |
| DOMES | Directory Of MERIT Sites (originally; now of more general use) |
| DORIS | Doppler Orbit determination and Radiopositioning Integrated on Satellite |
| DOR-O-T | DORIS Online Tools |

| | |
|---|---|
| DR | Data Release |
| DSS | Digitized Sky Survey |
| DTRF | ITRS realization by DGFI |
| DUT1 | = UT1–UTC |
| E | East [position/coordinate/direction] |
| EAM | Effective Angular Momentum |
| ECCO | Estimating the Circulation and Climate of the Ocean |
| ECMWF | European Center for Medium Range Weather Forecasting |
| EGSG | Extra-Galactic Science with Gaia |
| EGU | European Geosciences Union |
| EMR | Energy, Mines and Resources Canada (replaced by NRCan) |
| EMRP | European Metrology Research Program[me] |
| ENVISAT | Environmental Satellite |
| EO | Earth Orientation |
| EOC | Earth Orientation Centre |
| EOP | Earth Orientation Parameters |
| EOST | École et Observatoire des Science de la Terre |
| ERA | ECMWF Reanalysis Data |
| ERP | Earth Rotation Parameters |
| ESA | European Space Agency |
| ESOC | European Space Operations Center, ESA |
| EUMETSAT | European Organisation for the Exploitation of Meteorological Satellites |
| EVGA | European VLBI [Group] for Geodesy and Astrometry |
| e-VLBI | Electronic transfer VLBI |
| FedEx | Federal Express Corporation Inc. |
| FNMOC | [US Navy] Fleet Numerical Meteorology and Oceanography Center |
| frd | femtorad[ian] |
| FTP, ftp | File Transfer Protocol |
| GA | General Assembly |
| GA | Geoscience Australia |
| GAGNES | Gaia for AGN and Extragalactic Science |
| Gb | gigabyte |
| GB | Governing Board |
| GCRF | Gaia Celestial Reference Frame |
| GDR | Geophysical Data Record |
| GDSCC | Goldstone Deep Space Communications Complex |
| GMES | Global Monitoring of Environment and Security |
| GEST | Goddard Earth Science and Technology Center |
| GFO | GEOSAT Follow-On [satellite] |
| GFZ | GeoForschungsZentrum Potsdam |
| GGAO | Goddard's Geophysical and Astronomical Observatory |
| GGFC | Global Geophysical Fluids Centre |
| GGOS | Global Geodetic Observing System |
| GGRF | Global Geodetic Reference Frame |
| GHz | gigahertz |
| GINS | Geodesy by Simultaneous Digital Integration [software] |
| GIOVE | Galileo In-Orbit Validation Element |
| GIQC | Gaia Initial Quasar Catalog[ue] |
| GLDAS | NASA's Global Land Data Assimilation System |
| GLONASS | GLObal'naya NAvigatisionnay Sputnikovaya Sistema [Global Orbiting Navigation Satellite System, Russia] |
| GLOUP | GLObal Undersea Pressure |
| GNSS | Global Navigation Satellite System |
| GOP | Geodetic Observatory Pecny |
| GPS | Global Positioning System |
| GRACE | Gravity Recovery and Climate Experiment |
| GRASP | Geodetic Reference Antenna in Space |
| GRAIL | Gravity Recovery and Interior Laboratory |
| GRGS | Groupe de Recherches de Géodésie Spatiale |
| GSC | GSFC Analysis Center |
| GSFC | Goddard Space Flight Center |
| GSI | Geospatial Information Authority of Japan |
| HAM | Hydrological Angular Momentum |
| HEIMDALL | High-End Interface for Monitoring and spatial Data Analysis using L2-Norm |
| HEO | High Earth Orbiter |
| hr | hour, hours |
| HY | HaiYan / Haiyang [satellite] |
| IAA | Institute of Applied Astronomy, St. Petersburg |
| IAG | International Association of Geodesy |
| IAU | International Astronomical Union |

| | |
|---|---|
| IB | Inverted Barometer |
| ICRF | International Celestial Reference Frame |
| ICRS | International Celestial Reference System |
| ICSU | International Council for Science |
| IDS | International DORIS Service |
| IERS | International Earth Rotation and Reference Systems Service |
| IfE | Institut für Erdmessung [Institute of Geodesy], University of Hannover |
| IGG, IGGB | Institute of Geodesy and Geoinformation of the University of Bonn |
| iGMAS | International GNSS Monitoring and Assessment System |
| IGN | Institut National de l'Information Géographique et Forestière (formerly: Institut Géographique National) |
| IGR | IGS rapid [products / satellite orbits] |
| IGS | International GNSS Service |
| ILRS | International Laser Ranging Service |
| ILW | International Workshop on Laser Ranging |
| IMCCE | Institut de Mécanique Céleste et de Calcul des Éphémérides |
| INASAN | INstitut AStronomii Rossijskoj Akademii Nauk (Institute of Astronomy of the Russian Academy of Sciences) |
| INFN | Istituto Nazionale di Fisica Nucleare [National Institute for Nuclear Physics] |
| Int. | International |
| INT, Int. | Intensive [VLBI session] |
| IP | Internet Protocol |
| IPGP | Institut de Physique du Globe de Paris |
| IPGS | Institut de Physique du Globe de Strasbourg |
| IRAF | Image Reduction and Analysis Facility |
| IRIS | International Radio Interferometric Surveying |
| IRNSS | Indian Regional Navigation Satellite System |
| ISO | International Organization for Standardization |
| ITRF | International Terrestrial Reference Frame |
| ITRS | International Terrestrial Reference System |
| IUGG | International Union of Geodesy and Geophysics |
| IVOA | International Virtual Observatory Alliance |
| IVS | International VLBI Service for Geodesy and Astrometry |
| JADE | JApanese Dynamic Earth observation by VLBI |
| Jason-CS | Jason Continuity of Service [mission] |
| JMA | Japan Meteorological Agency |
| JPL | Jet Propulsion Laboratory |
| JTRF | ITRS realization by JPL |
| JSON | JavaScript Object Notation |
| KALREF | Kalman filter for Reference frames |
| LAREG | Laboratoire de Recherche en Geodesie |
| LARGE | Laser Ranging to GNSS s/c Experiment |
| lat | latitude |
| LDAS | Land Data Assimilation System |
| LEO | Low Earth Orbit(er) |
| LFOA | Leopold-Figl-Observatorium für Astrophysik |
| LLR | Lunar Laser Ranging |
| LOD | Length of Day |
| lon | longitude |
| LQAC | Large Quasar Astrometric Catalog[ue] |
| LQRF | Large Quasar Reference Frame |
| LRO | Lunar Reconnaissance Orbiter |
| LS | least-squares |
| LSDM | Land Surface Discharge Model |
| MA | Massachusetts, USA |
| mas | milliarcsecond(s) |
| µas | microarcsecond(s) |
| MCC | Russian Mission Control Centre |
| MD | Maryland, USA |
| MeO | Métrologie Optique [Grasse SLR /LLR system] |
| MERIT | Monitoring Earth Rotation and Intercomparison of Techniques |
| MGEX | Multi-GNSS Experiment |
| MIT | Massachusetts Institute of Technology |
| MJD | Modified Julian Day |
| MLRS | McDonald Observatory Laser Ranging Station |
| MOE | Medium Orbit Ephemeris |
| MOG2D | two-dimensional barotropic gravity wave ocean model |

| | |
|---|---|
| MPIfR | Max-Planck-Institut für Radioastronomie / Max Planck Institute for Radio Astronomy |
| ms | millisecond(s) |
| µs | microsecond(s) |
| N | North [position/coordinate/direction] |
| N | number |
| N/A | not available |
| NASA | U.S. National Aeronautics and Space Administration |
| Nat. | National, Nacional |
| NATML | non-tidal atmospheric pressure loading |
| NAVGEM | [U.S.] Navy Global Environmental Model |
| NCEP | U.S. National Centers for Environmental Prediction |
| NEQ | normal equation |
| NEU | North, East, Up [position/coordinates/directions] |
| NGL | Nevada Geodetic Laboratory |
| NIST | [U.S.] National Institute of Standards and Technology |
| NMA | Norwegian Mapping Authority |
| NMC | National Meteorological Center (replaced by NCEP) |
| NNR | No-net-rotation |
| No. | Number |
| NOAA | U.S. National Oceanic and Atmospheric Administration |
| NOFS | [U.S.] Naval Observatory Flagstaff Station |
| NORAD | North American Aerospace Defense Command |
| NP | SLR normal point(s) |
| NRAO | [U.S.] National Radio Astronomy Observatory |
| NRCan | Natural Resources, Canada (formerly: EMR) |
| nrd | nanorad[ian] |
| NTP | Network Time Protocol |
| OAM | Oceanic Angular Momentum |
| OBP | Ocean Bottom Pressure |
| Obs. | Observatory, Observatoire |
| OCARS | Optical Characteristics of Astrometric Radio Sources |
| OHIG | O'Higgins [station] |
| OP, OPA | Observatoire de Paris |
| ORB | Observatoire Royal de Belgique |
| PBO | Plate Boundary Observatory |
| PC | Product Centre |
| PCO | phase center offset |
| PM | Polar Motion |
| POC | point of contact |
| POD | Precise [or Precision] Orbit Determination |
| POLAC | Paris Observatory Lunar Analysis Center |
| PPP | Precise Point Positioning |
| PSD | post-seismic deformation |
| PSF | point spread function |
| PUL | Pulkovo Observatory |
| PZT | Photographic Zenith Tube [*or* Telescope] |
| QSO | Quasi-Stellar Object [*or* quasar] |
| RA | right ascension |
| RAEGE | Red Atlantica de Estaciones Geodinamicas y Espaciales |
| R&D | Research and Development |
| REFAG | [Symposium on] Reference Frames for Applications in Geosciences |
| REGINA | Regional glacial isostatic adjustment and CryoSat elevation rate corrections in Antarctica |
| RINEX | Receiver INdependent EXchange format |
| RMS | Root Mean Square |
| RRFID | USNO Radio Reference Frame Image Database |
| RS/PC | IERS Rapid Service/Prediction Center |
| RF | radio frequency |
| RT | radio telescope |
| RT | real-time |
| RTCM | Radio Technical Commission for Maritime Services |
| RTS | IGS Real-Time Service |
| SAA | South Atlantic Anomaly |
| SARAL | Satellite with ARGOS and ALTIKA |
| SB | Special Bureau |
| SBA | GGFC Special Bureau for the Atmosphere |
| SBCP | GGFC Special Bureau for the Combination Products |

| | |
|---|---|
| SBH | GGFC Special Bureau for Hydrology |
| SBO | GGFC Special Bureau for the Oceans |
| s/c | spacecraft |
| SDSS | Sloan Digital Sky Survey |
| sec | second(s) [of time] |
| SG | space-geodetic |
| SGP | Space Geodesy Project |
| SGSLR | Space Geodesy SLR [system] |
| SHAO | Shanghai Observatory |
| SIC | Satellite Identification Code |
| SINEX | Solution (Software/technique) INdependent EXchange Format |
| SIO | Scripps Institution of Oceanography |
| SLR | Satellite Laser Ranging |
| SNR | signal-to-noise ratio |
| SOFA | Standards Of Fundamental Astronomy |
| SOKENDAI | Graduate University for Advanced Studies |
| SONEL | Système d'Observation du Niveau des Eaux Littorales |
| SOPAC | Scripps Orbit and Permanent Array Center |
| SPOT | Satellite Pour l'Observation de la Terre |
| SSALTO | Segment Sol multi-mission d'ALTimétrie, d'Orbitographie et de localisation précise |
| STCD | STation Coordinates Difference |
| SWOT | Surface Water Ocean Topography [mission] |
| SYRTE | (Laboratoire) Systèmes de Référence Temps-Espace |
| TAI | Temps Atomique International (International Atomic Time) |
| TAROT | Télescopes à Action Rapide pour les Objets Transitoires |
| TB | terabyte |
| TBC | to be confirmed |
| TC | Technique Centre |
| TE | Temps des éphémérides / Ephemeris time |
| TIGO | Transportable Integrated Geodetic Observatory |
| TJO | Telescopi Joan Oró |
| TN | [IERS] Technical Note |
| ToR | Terms of Reference |
| TRF | Terrestrial Reference Frame |
| TT | Terrestrial Time |
| TU | Technical University |
| TUM | Technical University of Munich |
| TUW | Technische Universität Wien (Vienna University of Technology) |
| TV | television |
| TWS | terrestrial water storage |
| UAW | Unified Analysis Workshop |
| UBAD | USNO Bright-Star Astrometric Database |
| UCAC | USNO CCD Astrograph Catalog |
| UCL | University College London |
| UK, U.K. | United Kingdom |
| UKMO | U.K. Meteorological Office |
| ULR | University of La Rochelle |
| UMBC | University of Maryland, Baltimore County |
| UN | United Nations |
| UNB | University of New Brunswick |
| UNAVCO | University Navstar Consortium |
| UN-GGIM | Global Geospatial Information Management Initiative of the UN |
| Uni, Univ. | University |
| URAT | USNO Robotic Astrometric Telescope |
| URL | Uniform Resource Locator |
| US, U.S. | United States |
| USNO | United States Naval Observatory |
| USO | Ultra-Stable Oscillator |
| UT | University of Texas |
| UT, UT0, UT1, UT2R | Universal Time |
| UTAAM | NOAA AAM analysis and forecast data |
| UTC | Coordinated Universal Time |
| VCS | VLBA Calibrator Survey |
| VEX | VLBI Experiment Documentation |
| VGOS | VLBI Global Observing System |
| VLBA | Very Long Baseline Array, NRAO |
| VLBI | Very Long Baseline Interferometry |
| VO | Virtual Observatory |
| WDS | ICSU World Data System |
| WG | working group |
| WRMS | Weighted Root Mean Square |
| XML | eXtensible Markup Language |
| yr | year |