

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

IERS Annual Report 2019

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IERS Annual Report 2019

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1 Foreword

Throughout 2019, the IERS focused on our preparations for the International Terrestrial Reference Frame 2020 (ITRF2020). Communications with the Technique Centers has been excellent and while there is still significant work to be done throughout 2020, there are no known obstacles to completing either the inputs to the new TRF nor the combination itself. Finishing out the ITRF2014, IERS Technical Note 40 "Description and evaluation of DTRF2014, JTRF2014 and ITRF2014" was published in early 2020.

The 2019 Unified Analysis Workshop (UAW) was held on 2 – 4 October 2019 in Paris. The UAW is a joint meeting co-sponsored by the International Association of Geodesy (IAG), the Global Geodetic Observing System (GGOS), and the IERS. The final report provides a thorough summary of the workshop as well as conclusions and recommendations from the discussions.

The IERS Conventions Center provides the standard constants and models to be used to ensure consistent IERS data sets. In 2019, Chapter 4 was re-written to be consistent with ITRF2014. It was also decided to create a new printed version of the Conventions in 2022. This version will incorporate a new style so that the main document is greatly reduced in length, which will hopefully improve the usability of the conventions for the general practitioner. For the latest information on the IERS Conventions, please see the IERS Conventions web sites.

The IERS Rapid Service/Predict Center (RS/PC) and the USNO component of the IERS Conventions web and ftp sites were taken offline as they undergo modernization. These services are estimated to be returned to service no earlier than autumn of 2020. To mitigate the loss of these sites, the RS/PC and Conventions Center have found alternate sites to host this information.

The IERS Directing Board (DB) continued to evolve in 2019. Nick Stamatakis replaced Christian Bizouard on 1 January 2019 as the IERS Directing Board (DB) member from the IERS Convention Center as part of the rotating co-directorship. Sigrid Böhm replaced Guangli Wang as the International VLBI Service (IVS) representative. Tom Herring replaced Axel Nothnagel as the International Association of Geodesy (IAG)/International Union of Geodesy and Geophysics (IUGG) Representative. Robert Heinkelmann replaced Tom Herring as the IERS Analysis Coordinator on 1 January 2019. As always, we thank all of the representatives and we wish them the best in their future endeavors. As a volunteer organization, we are dependent on the efforts of all of our participants.

*Brian Luzum
Chair, IERS Directing Board, 2019*

2 The IERS

2.1 Structure

From 2019 to the mid-2023, 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 2018 and 1 July 2023. For reports of components see [Chapter 3](#).

Analysis Coordinator Robert Heinkelmann

Central Bureau *Director:* Daniela Thaller

Technique Centres **International DORIS Service (IDS)**

IDS representatives to the IERS Directing Board:

Jérôme Saunier, Hugues Capdeville (until 31 Dec. 2022),

Petr Štěpánek (since 1 Jan. 2023)

IERS Representative to the IDS Governing Board:

Brian Luzum (until 31 Dec. 2020),

Tonie van Dam (since 1 Jan. 2021)

International GNSS Service (IGS)

IGS Representatives to the IERS Directing Board:

Rolf Dach, Chuck Meertens (until 31 Dec. 2020),

Elisabetta D'Anastasio (since 1 Jan. 2021)

IERS Representative to the IGS Governing Board:

Richard Gross

International Laser Ranging Service (ILRS)

ILRS Representatives to the IERS Directing Board:

Erricos C. Pavlis (until 31 Dec. 2022),

Jean-Marie Torre (until 31 Dec. 2022),

Mathis Bloßfeld (since 1 Jan. 2023),

Clément Courde (since 1 Jan. 2023)

IERS Representative to the ILRS Directing Board: Daniela Thaller

International VLBI Service for Geodesy and Astrometry (IVS)

IVS Representatives to the IERS Directing Board:

Rüdiger Haas, Guanli Wang (until Feb. 2019),

Sigrid Böhm (since 21 March 2019)

IERS Representative to the IVS Directing Board:

Rüdiger Haas

Product Centres Earth Orientation Centre

Primary scientist and representative to the IERS Directing Board:
Christian Bizouard

Rapid Service/Prediction Centre

Primary scientist and representative to the IERS Directing Board:
Christine Hackman (until 4 Dec. 2020),
Nick Stamatakos (since Dec. 2020)
Production director and lead project scientist:
Nick Stamatakos (until Dec. 2020), Sharyl Byram (since Dec. 2020)

Conventions Centre

Primary scientists: Nick Stamatakos, Christian Bizouard
Current representative to the IERS Directing Board:
Nick Stamatakos (until 31 Dec. 2021),
Christian Bizouard (since 1 Jan. 2022)

ICRS Centre

Primary scientists: Bryan Dorland, Jean Souchay
Current representative to the IERS Directing Board:
Jean Souchay (until 31 Dec. 2020),
Bryan Dorland (1 Jan. 2021 to 31 July 2023), N.N.

ITRS Centre

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

Global Geophysical Fluids Centre

Head and representative to the IERS Directing Board:
Jean-Paul Boy
Co-Chair: Tonie van Dam

Special Bureau for the Oceans

Chair: Richard S. Gross (until 31 Dec. 2020),
Henryk Dobslaw (since 1 Jan. 2021)

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 (until 31 Dec. 2019),

Ryan Hippenstiel (since 1 Jan. 2020)

Co-Chair: John Dawson (until 31 Dec. 2019),

Sten Bergstrand (since 1 Jan. 2020)

Working Group on SINEX Format*Chair:* Daniela Thaller**Working Group on Site Coordinate Time Series Format (until 13 May 2020)***Chair:* Laurent Soudarin**IAG/IAU/IERS Joint Working Group on the Consistent Realization of TRF, CRF, and EOP (established as IERS WG in May 2020)***Chair:* Robert Heinkelmann (since 13 May 2020)*Co-Chair:* Manuela Seitz (since 13 May 2020)**Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign (established in March 2021)***Chair:* Jolanta Nastula (since 9 March 2021)*Co-Chair:* Henryk Dobslaw (since 9 March 2021)*(Status as of 1 August 2023)*

2.2 Directing Board

From 2019 to mid-2023, the IERS Directing Board had the following members (for addresses see [Appendix 2](#)):

Chair	Brian Luzum (until 31 Dec. 2020), Tonie van Dam (since 1 Jan. 2021)
Analysis Coordinator	Robert Heinkelmann
<i>Product Centres Representatives</i>	
Earth Orientation Centre	Christian Bizouard
Rapid Service/Prediction Centre	Christine Hackman (until 4 Dec. 2020), Nick Stamatakos (since Dec. 2020)
Conventions Centre	Nick Stamatakos (until 31 Dec. 2021), Christian Bizouard (since 1 Jan. 2022)
ICRS Centre	Jean Souchay (until 31 Dec. 2020), Bryan Dorland (1 Jan. 2021 to 31 July 2023), N.N.
ITRS Centre	Zuheir Altamimi
Global Geophysical Fluids Centre	Jean-Paul Boy
Central Bureau	Daniela Thaller
<i>Technique Centers Representatives</i>	
IDS	Jérôme Saunier, Hugues Capdeville (until 31 Dec. 2022), Petr Štěpánek (since 1 Jan. 2023)
IGS	Rolf Dach, Chuck Meertens (until 31 Dec. 2020), Elisabetta D'Anastasio (since 1 Jan. 2021)
ILRS	Erricos C. Pavlis (until 31 Dec. 2022), Jean-Marie Torre (until 31 Dec. 2022), Mathis Bloßfeld (since 1 Jan. 2023), Clément Courde (since 1 Jan. 2023))
IVS	Rüdiger Haas, Guanli Wang (until Feb. 2019), Sigrid Böhm (since 21 March 2019)

Union Representatives

IAU

Aleksander Brzezinski

IAG / IUGG

Axel Nothnagel (until 6 Dec. 2019),
Thomas Herring (since 7 Dec. 2019)

GGOS

Richard S. Gross

2.3 Associate Members

Abbondanza, Claudio	Ignatenko, Igor
Angermann, Detlef	Ipatov, Alexander
Arias, Elisa Felicitas	Jäggi, Adrian
Balidakis, Kyriakos	König, Rolf
Behrend, Dirk	Kopeikin, Sergei
Bergstrand, Sten	Lambert, Sébastien
Bianco, Giuseppe	Le Bail, Karine
Boucher, Claude	Lemoine, Frank
Bradke, Markus	Lemoine, Jean-Michel
Brunini, Claudio	Lestrade, Jean-François
Bruyninx, Carine	Luceri, Vincenza
Capdeville, Hugues	Ma, Chopo
Capitaine, Nicole	Männel, Benjamin
Chabe, Julien	McCallum, Lucia
Chanard, Kristel	McCarthy, Dennis D.
Chen, Jianli	Meertens, Charles
Chin, Mike	Merkowitz, Stephen
Collilieux, Xavier	Métivier, Laurent
Combrinck, Ludwig	Moore, Angelyn W.
Courde, Clement	Moore, Michael
Craddock, Allison	Müller, Jürgen
Craymer, Michael	Nastula, Jolanta
Davis, Maria	Noomen, Ron
Dieck, Chris	Nothnagel, Axel
Dobslaw, Henryk	O’Gara, Daniel J.
Elger, Kirsten	Pavlis, Erricos C.
Exertier, Pierre	Pavlov, Dmitry
Fisher, Steven	Pearlman, Michael R.
Gambis, Daniel	Perosanz, Felix
Garayt, Bruno	Petit, Gérard
Gaume, Ralph A.	Ray, Jim
Geng, Jianghui	Rebischung, Paul
Gipson, John	Reigber, Christoph
Hackman, Christine	Ries, John
Hase, Hayo	Rodriguez, Jose Carlos
Heflin, Mike	Rothacher, Markus
Heki, Kosuke	Salstein, David
Hippenstiel, Ryan	Schildknecht, Thomas
Huang, Cheng-li	Schreiber, Ulrich
Hugentobler, Urs	Seitz, Manuela

Shelus, Peter J.	Weber, Robert
Souchay, Jean	Willis, Pascal
Soudarin, Laurent	Wilson, Clark
Springer, Tim	Yatskiv, Yaroslav S.
Torre, Jean-Marie	Zhang, Haifeng
Turyshchev, Slava	Zhang, Jie
Villiger, Arturo	Zhang, Zhongping
Vondrák, Jan	Zubko, Nataliya
Wang, Guanli	

Ex officio Associate Members:

IAG Secretary General: Thaller, Daniela
 IAU General Secretary: Rodriguez Espinosa, José Miguel
 IUGG General Secretary: Rudloff, Alexander
 President of IAG Commission 1: Hugentobler, Urs
 Chair of IAG Subcommittee 1.1: Hugentobler, Urs
 Chair of IAG Subcommittee 1.2: Collilieux, Xavier
 Chair of IAG Subcommittee 1.4: Malkin, Zinovy
 President of IAG Commission 3: Steffen, Rebekka
 Chair of IAG Subcommittee 3.1: Braitenberg, Carla
 Chair of IAG Subcommittee 3.3: Chen, Jianli
 President of IAU Division A: Hestroffer, Daniel
 President of IAU Commission A1: Jacobs, Christopher S.
 President of IAU Commission A2: Malkin, Zinovy M.
 President of IAU Commission A3: Stewart, Susan Gessner

(Status as of 1 August 2023)

3 Reports of IERS components

3.1 Directing Board

The IERS Directing Board (DB) met twice in the course of the year 2019. Summaries of these meetings are given below.

Meeting No. 68 April 07, 2019, Technical University of Vienna, Gusshausstr. 27, Vienna, Austria

Introduction and approval of agenda Brian Luzum welcomed the guests and the members of the IERS Directing Board. The agenda was accepted. There were no additional comments.

IERS Technical Notes on ITRF2014 Technical Note 2: ITRF-CCs, Input and evaluation by the Technique Services and others; agreement on editors of IERS Technical Note No. 40: on the evaluation of the three solutions: ITRF, DTRF and JTRF

- 4 contributions so far received at ITRS CC
- A final deadline: End of March 2019 is now passed.
- Proposal: Publication with received contributions after the EGU

Technical Note 3: C04 series aligned to ITRF2014 (replaces TN planned for 08 C04 series)

- No news. Paper on 14C04 was published in the Journal of Geodesy.

Decisions Z. Altamimi will send the contributions that he received to the IERS CB. A joint editing by IERS CB and Z. Altamimi was agreed. Include a list all the authors that contributed to the TN. DGFI: send contributions to Z. Altamimi. Update in two months.

New Action Items #68.01 Provide (hidden) directory to collect the contributions to the Technical Notes.
#68.02 Provide LaTeX template for IERS Technical Notes.
#68.03 Update the metadata reference on the website.
#68.04 Update the text file of C04 on the ftp server.

**Current activities at the ITRS
Combination Centers
Report from ITRS Combination
Centre at JPL**

The report from IDS was given by Richard Gross.

SREF development (Chin et al.)

- Status
 - Time variable, square-root information filter with full process noise matrix
 - Optionally estimates radio source positions for joint TRF/EOP/CRF determination
 - TRF and joint TRF/EOP/CRF test solutions being analyzed
- Plans
 - Reproduce JTRF2014 with SREF
 - Include EOP dynamics, postseismic displacement model
 - Will use SREF to determine JTRF2020

Joint TRF/EOP/CRF determination (Soja et al.)

- Using SREF to jointly determine TRF/EOP/CRF
 - Geodesy Division Outstanding Early Career Scientist Award Lecture by B. Soja: Chasing Consistency: Joint Determination of Terrestrial and Celestial Reference Frames (Session G2.6, Tuesday April 9, 15:30–15:45, Room D2)

JTRF2014 analysis (Abbondanza et al.)

- Submitted article to Comptes Rendus Geoscience
 - A Sequential Estimation Approach to Terrestrial Reference Frame Determination by Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, and X. Wu
 - Invited for special issue on Space-Time Reference Frames
 - Reviews JPL's approach to determining TRFs, comparing it to other approaches

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

The report from IDS was given by D. Angermann.

Publications on the ITRS realizations 2014

- IERS Technical Note on ITRF2014 – TN2:
 - DGFI-TUM submitted in November two contributions to the IERS CB: (1) DTRF2014: DGFI-TUM realization of the International Terrestrial Reference System (ITRS) and (2) Comparison of the latest ITRS realizations: ITRF2014, JTRF2014 and DTRF2014
- Contributions to TN2 already submitted:
 - JPL already submitted a paper on the JTRF2014 solution

- Moreaux G. et al: A comparison of the DTRF2014, ITRF2014, and JTRF2014 solutions using DORIS
- Rodriguez J.: comparison of ITRF2014 and DTRF2014 based on SLR
- Paper on DTRF2014 (Seitz et al., 2019?): DTRF2014: The new ITRS realization of DGFI-TUM considering non-tidal station loading
 - Is close to be submitted to JoG
 - New computation strategy: consideration of non-tidal loading models
 - Extended solution:
 - DTRF2014 solution (SINEX)
 - * non-tidal loading corrections per station (time series)
 - * time series of translations
 - * station position residual time series
 - * allows for a reconstruction of the real station positions

→ All publications on the realizations and their validation should be published soon to make it possible to discuss and if necessary further study important outcomes before ITRS2020 realization.

Effect of non-tidal loading on ITRS realizations

- Atmospheric and hydrological loading model corrections already applied for DTRF2014 (model data provided by Tonie van Dam)
 - Applied on NEQ level
 - Effect of NT-L loading corrections on TRF solutions analyzed for DTRF2014 and for IVS contribution of DGFI-TUM IVS AC:
 - * Improvement of standard deviations
 - * Improvement of WRMS of station position and datum parameter time series
 - * Improvement of the accuracy of the estimated positions and velocities in case of short observation time spans
 - * Large effect on datum parameter time series: annual signals disappear.
- Improvements due to NT-load:
 - Standard deviations (ITPI decreases)
 - WRMS of station position and datum parameter time series
 - Accuracy of position and velocity in case of short observation time spans
 - Datum parameter time series: annual signals disappear

- Additional investigations on the gravitational effect on the SLR satellites lead also to a slight improvement of SLR solution

→ It is recommended to consider NT-loading on observation level for future ITRF solutions

Tidal frequencies in LOD and Δ UT1 series

- Difference time series w.r.t. IERS 14 C04:
 - GNSS and SLR also show periodic signals w.r.t. IERS 08 C04, but $\text{Ampl} < 9 \mu\text{s}$
 - DTRF2014 LOD: $\text{Ampl} = 3 \mu\text{s}$

→ The systematics are relevant w.r.t. the combination of the EOP (all IERS EOP products) and w.r.t. the consistent realization of CRF, TRF and EOP. This should be clarified in preparation of ITRF2020!

Local tie re-measurements

- Started to be discussed during the last IERS Directing Board meeting
 - Local ties with equal vector components (equal length) are not forwarded/reported to the ITRS Centre?
 - Identically measured Local ties at different epochs also strongly improve the TRF stability!
 - Could we get significantly more Local tie measurements for ITRF2020?

DOGS software development

- Software unification and extension
 - A new format was developed for observation equations, normal equations and solutions, which allows for:
 - * a higher temporal resolution of parameters
 - * the entrainment of metadata from input SINEX file → DOGS-CS → SINEX file of the combined solution

→ full SINEX file can be directly written from DOGS-CS without any additional files

Discussion

- Tidal frequencies in LOD and Δ UT1 → problem in C04 series? No systematics in JPL solution
- ITRF2020: consistency of models; local tie issue AI: ZA: CfP via IERS Message addressing also local ties at co-location sites (stations should send updated local tie measurements)
- DOGS software development

Report from ITRS Center The report was given by Zuheir Altamimi.

Status ISO Standard on ITRS

- After the release of the draft document at the stage of DIS (Draft International Standard), and vote by ISO member countries:
 - P-members in favour: 25 (5 with comments)
 - P-members voting against: 0
 - P-members abstaining: 11
- The DIS ballot stage started on March 26 & will end June 18, 2019.
 - All certification organizations are invited to vote and/or formulate comments on the Draft Document.

Update of Chapter 4 of the IERS Conventions

- Update of Chapter 4: Terrestrial reference systems and frames
 - Include ITRF2014 information
 - * Post-Seismic Deformation
 - * Transformation parameters ITRF2014 → Past ITRFs
 - First version submitted to the CC on Feb 08, 2019
 - Review by D. McCarthy received on Feb 21
 - Revised version submitted Feb 28, 2019
 - Published at the IERS Conventions website: April 1

Activities of UN-GGIM Subcommittee on Geodesy

- Proposal under discussion: Adoption of the ITRS and its numerical realization, the ITRF by the UN-GGIM Committee of Experts as the standard reference for geospatial and scientific positioning applications
 - France (Z. Altamimi) is chairing the Infrastructure WG:
 - * Review the membership & add other experts
 - * Review the list of actions following the recommendations of the GA resolution & roadmap
 - * Will ask the UN-GGIM Committee of Experts to provide feedback on GGRF recommendations
 - * Articulate the Infrastructure needs in terms of attributes of a governance mechanism
 - * Will solicit the Techniques to establish a list of urgent needs for Core sites
- TN40: IERS Technical Note on the evaluation of the three solutions: ITRF, DTRF and JTRF → see (TOP 2).

Specific investigations:

- Seasonal signals, geocenter motion
 - Evaluate and understand technique differences at co-location sites
 - To provide a coherent annual geocenter motion model compatible with ITRF2014
 - Investigate SLR to VLBI scale offset using new TEST solutions from VLBI (GSFC) and SLR (ASI)

Revisit the scale offset between SLR & VLBI

Roadmap for ITRF2020?

- Call for Participation posted at the ITRF Website

Specific investigations in preparation for ITRF2020:

- seasonal signal & geocenter motion; investigate VLBI and SLR test solution

Discussion

- Re-establish a Working Group on Geocenter motion (as WG IERS and IAG Comm. 1)? No objections from the IERS DB.
- Input test solution GSFC VLBI (session-wise) vs ASI SLR (weekly)

Decisions Re-establish Working Group on Geocenter motion in conjunction with IAG Commission 1 (after new IAG structure has been established)

New Action Items #68.05 Send out a CfP via IERS Message addressing local ties at co-location sites (stations should send updated local tie measurements).
#68.06 Send out message to ask for contributions/volunteers to chair the WG on Geocenter motion (after re-organization).

**Reports from the Technique
Centers
IDS Report**

The report from IDS was given by Hugues Capdeville.

DORIS constellation status (current and future missions)

- current missions (Sentinal-3A and 3B, Jason-2 and 3, SARAL, HY-2A, Cryosat2)
- 7 future missions (Sentinel-3C and 3D, HY-2C and 2D, Jason-CSA and CSB, SWOT)

Network operational status

- 60 permanent stations of which: 9 beacons are out of order and 3 are decommissioned, 48 co-locations out of 59 DORIS sites.

Tie vectors available at: ftp://ftp.ids-doris.org/pub/ids/stations/DORIS_ext_ties.txt

Network evolution

- 2 stations pending replacement: Yuzhno-Sakhalinsk, Russia; Port-Moresby, Papua New Guinea; 3 ongoing projects (in order of progress): Changchun (China); Easter (Chile); Katherine (Australia)

IDS reprocessing for next ITRF

- Adopt and evaluate the new standards/models recommended by IERS
 - Implement new linear mean pole model
 - Implement HF (diurnal-subdiurnal) tidal EOP model recommended by IERS after evaluation by the IERS working group lead by J. Gipson
 - Adopt Time-Variable Gravity (TVG) model based on GRACE data + GOCE data + SLR data coherent with new mean pole convention (C(2,1) / S(2,1) coefficients) new EIGEN-GRGS.RL04.MEAN-FIELD is available for download: <https://grace.obs-mip.fr/variable-models-grace-lageos/mean-fields/release-04/>
 - Ocean tide model: FES2014-c soon available on AVISO website
 - Others models/standards from IERS?
- Implement RINEX DORIS processing (crucial topic to take into account the DORIS data of the latest satellites Jason-3, Sentinel-3A and Sentinel-3B)
 - Necessary to use the same format for the same satellite
- Modelling improvement
- Attempt to mitigate the non-conservative force model error on satellites (draconitic signals): use quaternions when available, SRP coefficients and macromodels
- South Atlantic Anomaly compensation → mitigate the SAA effect on DORIS USOs for Spot-5 and Jason series
- Scale, elevation cut off and data downweighting
 - For all IDS ACs: adopt the same elevation cut-off and downweighting law for low elevation data?
- Preparation of individual ACs

- Analysis Coordinators will send to ACs a roadmap to follow in preparation for the next ITRF reprocessing. From April to the next AWG scheduled end Sept. 2019, ACs will work on the 5 topics presented above. During the first day of the AWG: presentation and discussion on the tests done by ACs and the CC. During the second day: final definition of the IDS processing configuration. After this AWG: ACs could start the IDS reprocessing for the ITRF.
- IDS reprocessing
 - We could divide the IDS reprocessing in 4 periods: [1992-2001], +sp5 +env +ja1 [2002-2008], +ja2 [2008-2015], +ja3 +s3a +s3b [2016-2020]
 - ACs could start their reprocessing end 2019 for the first period [1992-2001]
 - IDS Combination Center could start its combination of the first period at the beginning of the year 2020.
 - IDS ACs could continue at the beginning of year 2020 their reprocessing with the second period and provide their solution to IDS CC, ...
 - IDS CC propose to deliver to IERS the final SINEX (until 2020) in February–March 2020.

IDS News

- Passing of Richard Biancale: a tribute to Richard in IDS Newsletter #6
- IDS Newsletter #6 (February 2019)
- IDS Meetings in 2019: IDS AWG April, 2019 at DGFI, Munich; next IDS AWG 30 Sept. – 1 Oct., 2019 at CNES, Paris (TBC)
- IDS Elections: Two positions renewed within the Governing Board for the term, 2019–2022: Analysis Coordinator: New tandem: Hugues Capdeville (CLS, France) & Petr Stepanek (GOP, Czech Republic); Member-at-large: Claudio Abbondanza (NASA, US) succeeds to Marek Ziebart (UCL, UK)

Discussion:

- Gravity field model (#4) vs. ILRS field gravity model #6: discuss within IDS rather to use the same model as the ILRS does or/and to specify the differences between the two versions.

IGS Report The report from IGS was presented by Rolf Dach.

Governing Board

- New vice-chair Felix Perosanz from CNES (who will become chair afterwards), Gary Johnston elected for two more years as chair.

Three complete constellations

- 24 active satellites, Beidou: 3 satellites in space, only one year the data receivable
- Multi-GNSS data files available

IGS AC workshop in 2 weeks in Potsdam with the following topics:

- orbit modelling
- taken for lower satellites for DORIS and SLR (tbd)
- Inclusion of Galileo in re-processing and/or legacy products: not decided yet, but progress is on the way (deficiencies with E5 antenna calibration).
- Antenna calibration: the IGS WG is co-operating with Bonn for chamber calibrations; also geo++ made a presentation on robot calibration.

Galileo

- Fully calibrated satellites and receivers, which will allow to contribute to the scale.

Next IGS workshop will be held in Boulder, USA, on August 12–16, 2020.

Start reprocessing for ITRF2020 this summer.

Discussion

- Ask John Gipson when the high-frequency pole model will be available (agreed that no empirical model) → decide on the model.

Questions:

- Nick Stamatakis: Does the model need to go through the IERS Conventions Center?

Answer: Decide after decision on the model.

ILRS Report The report from ILRS was given by Erricos Pavlis.

ILRS status and activities

- Governing Board Elections for the 18 elected members were completed; and two additional members will be appointed by the new GB: Ulrich Schreiber and Krzysztof Sośnica
- Infrastructure
 - Testing new formats for Data (CRD) and Tracking Predictions (CPF)
 - Web-based station site log archive and maintenance operational
 - Harmonized data screening & QC between EDC and NASA Operations Centers (OCs) is ongoing
- Routine submission of all full-rate data to OCs and DCs from 32 out of the currently active stations (39). We continue to press the rest to confirm ASAP.
- Etalon Campaign Project: dedicated tracking campaign for Etalon 1 & 2 in progress (February 15 to May 15):

https://ilrs.cddis.eosdis.nasa.gov/science/awg/awgActivities/trackingEtalon1_and_2_Feb2019.html

- Increased scrutiny in selecting new missions to track
- Discussions with the IGS and the ICG on tracking GNSS s/c: meeting with stakeholders on Monday afternoon 3:00-5:30 (TUW)
- Issues:
 - Network gaps in Latin America, Africa, and Oceania, and mix of new and old technologies are the primary issues of concern now
- Site log update lapses cause trouble with analysis/products; delinquent sites/agencies are reminded often

ILRS Network Status

- BKG AGGO setup at La Plata Observatory (Argentina)
- New stations underway:
 - Russia: Ensenada (Mexico), Java (Indonesia), Gran Canaria (Spain)
 - NASA/NASA affiliated: McDonald, Haleakala (USA), and Ny-Ålesund (NMA, Norway)
 - Others: Metsahovi (Finland), Mt. Abu and Ponmudi (India), and Yebes (Spain)

- Upgrades underway at some stations
- First co-locations of Russia and NASA SLR laser systems established at Hartebeesthoek (South Africa); Two Russian SLR at Mendeleevo

Mission News & Support

- Network routinely tracked 100+ satellites in 2018
- New, approved missions included: S-NET, Sentinel-3B, GRACE-FO, Tiangong-2, Beidou-3M, PAZ, ICESat-2, Astrocast Precursor, GNSS
- Future missions:
 - Additional GNSS: BeiDou/Compass, Galileo, etc.
 - LightSail-2, COSMIC-2, GY-2C, SWOT, NISAR

ILRS ASC – Analysis Activities

- Preparations for contributing to the development of ITRF2020 are on schedule.
- New operational approach in handling error sources was adopted at the last ASC meeting (Canberra, November 2018):
 - Allowance for estimation of systematic errors simultaneously with all other parameters to eliminate biases in station positions/velocities (in progress)
 - Correction of identified serious shortcomings in the current model for the target signature (also known as “CoM correction”) for all types of ground systems (implemented)
 - Correction of such errors alone can affect the SLR-VLBI scale difference at the 0.25 ppb level.
 - Adopted the new CoM model which was recently released (November 2018) by NSGF, (implemented)
 - SSEM Pilot Project on station systematics completed the next phase and we are awaiting the final submission from all ACs to complete the combination product and the tabular form of the new model
 - The result will be used as the basis for the development of the ILRS product that will be contributed to ITRF2020.
 - We have added estimation/handling of Time Biases:
 - * Time biases are now modeled based on T2L2 results.
 - * Additional time biases from T2L2 until the end of 2017 were added.

- We will include applied RB & TB in SINEX file for next contribution to ITRF with their constraint information in each SINEX combined product.
 - * The SINEX will contain the RB & TB values & σ applied to each station and the applied CoM offsets for that weekly product.
- Next PP will deliver low-degree gravity coefficients as a weekly product and introduce LARES as a 5th target for ITRF product support (by end of 2019).

Status of Special Issue of the Journal of Geodesy

- 12 articles accepted and 12 additional articles currently under review

Recent & Future Meetings Schedule

- The 21st International Workshop on Laser Ranging (IWLR) was hosted by SERC in Canberra, Australia from November 4 to 9, 2018. The ASC meeting was held on Sunday, Nov. 3, 2018. Website of 21st IWLR: <http://www.iwlr2018.serc.org.au>. Abstracts, Presentations and Papers are available from the CDDIS-based site: <https://cddis.nasa.gov/lw21>.
- A Technical Workshop will take place in Stuttgart, Germany: 21–25 October 2019, “Laser ranging: To improve economy, performance, and adoption for new applications”.
- The 22nd International Workshop on Laser Ranging will be held in Kunming, PRC (date TBD in 2020).

Discussion

- ITRF2020 preparation will start by end of the year 2019 (high-frequency model needs to be available; after finishing the Etalon project).

IVS Report The report from ILRS was presented by Rüdiger Haas.

Past and upcoming meetings

- Past meetings: March 2019: 3rd IVS VLBI training school and 24th EVGA working meeting in Las Palmas, Gran Canaria
- May 2019: TOW at Haystack (including a workshop on VGOS correlation)
- March 2020: 11th IVS GM in Annapolis, USA

IVS was celebrating its 20th anniversary at EVGA 2019.

IVS DB elections

- New members since elections in Nov. 2018: Network Representative: Hayo Hase (BKG, La Plata), Analysis and Data Center Representative: James Anderson (GFZ Potsdam), Technology Development Representative: Chet Ruszczyk (MIT/Haystack), Correlator Representative: Laura la Porta (MPIfR Bonn correlator)
- At Large Member: Evgeny Nosov (IAA, St. Petersburg), Aletha de Witt (HartRAO), and Jingling Li (Shanghai Observatory)

CONT17

- Two legacy and one VGOS network.
- Data are correlated and released.
- Analysis results have been presented on EVGA2016.
- A Journal of Geodesy special issue on CONT17 is planned.
- Generally, the baseline length repeatability has been found to be better for VGOS than for the legacy network (see presentation for details).

VGOS development

- VGOS Test (VT) 24 h sessions every 2nd week:
 - Network with up to 7 stations: Wf-Gs-K2-Ws-Yj-Oe/Ow-Is
 - Data correlated at Haystack (e-transfer + disk shipping)
 - Regular production of VGOS-databases since January 2019
 - VT-sessions will continue with this setup at least until April 2019.
 - VGOS-correlation workshop in May 2019 at Haystack
- EU-VGOS 4 h sessions
 - Three European sites (Yj-Ws-Oe/Ow)
 - Study of polarization conversion (HH+VV) $\rightarrow$ (RCP+LCP)
 - Study of impact of radio source structure
- Japanese VGOS tests (1 GHz wide frequency bands)
- Upcoming VGOS partner stations
 - Hobart, Katherine, Yarragadee (all Australia), broadband upgrade
 - McDonald (Texas, USA), under construction
 - Ny-Ålesund twins (Svalbard, Norway), waiting for broadband receivers
 - Metsähovi (Finland), waiting for broadband receiver

- Shanghai siblings (China), first fringes
- Zelenchukskaya, Badary, Svetloe (all Russia), need broadband upgrade

IVS preparations for TRF2020

- Using ICRF3, including galactic aberration
- Using new pole tide model
- New high-frequency EOP model: work is not finalized (annual signal?)
- Important topics to work on:
 - Local-ties at VGOS-legacy co-location stations
 - Thermal and gravitational deformation of telescopes (see presentation for details)

Questions

- Christine Hackman asked about the broadband receivers. Rüdiger Haas explained that these are digital backends.
- Detlef Angermann proposed that other Services should also introduce such a school as the IVS school. Daniela Thaller mentioned that there is a South American SIRGAS training course.
- Robert Heinkelmann asked about local ties. Gravitational deformation will not be available for all stations (some do not exist any longer).

New Action Item #68.07 Send request to John Gipson asking on the availability of the high-frequency EOP model.

Roadmap for next ITRF generation (ITRF2020)

Presentation by IERS Chair

Brian Luzum presented the “Process for Transitions to new ITRF”

- Includes a testing phase of up to 3 months for the ITRS Combination Centers and Technique Centers and a documentation describing with the new ITRF.
- IERS DB finally adopts the new ITRF.
- External evaluation of all combined TRFs foreseen (2 years after IERS DB adoption) to identify areas of concern and areas for improvement.
- Review areas of concern at UAW (within 2 years of IERS DB adoption): UAW provides recommendations as appropriate and IERS addresses recommendations and takes action to resolve concerns.

Presentation by ITRS Centre

Zuheir Altamimi presented the “Roadmap for ITRF2020”:

Recall of the Background/History

- Consultation was sent to the technique ACCs and GGFC on January 24, 2018 => ITRF2020.
- An inventory (list) of all effects and model updates to be considered by all and individual techniques in the reprocessing effort.

Current status per Technique Center

- IVS: high-frequency EOP model to be recommended by the WG; Atmospheric Loading model (ATML) will be applied
- ILRS: Gravity field model, compatible with linear pole model; high-frequency EOP: waiting for a “consensus” model; Will not include a loading model; Reprocessing may start end 2019, beginning 2020
- IDS: high-frequency EOP: waiting for a “consensus” model; A number of DORIS-specific effects will be addressed; Start of processing: beginning of 2020, but maybe earlier
- IGS: Adopt post EGM2008 model: Not all ACs are convinced this has a significant impact on GNSS; high-frequency EOP: waiting for a “consensus” model; Most ACs not in favor of applying a loading model; Start reprocessing probably June 2019

ITRF2020: Call for Participation

- Draft circulated among IERS DB Thursday, Dec 06, 2018 with a list of suitable model updates in the annex
- Comments were welcome until January 10, 2019, but no comments received
- The CfP is now final & posted at the ITRF website: http://itrf.ign.fr/doc_ITRF/CFP-ITRF2020.pdf

ITRF2020 Inputs by TCs: specific model updates are strongly requested

- All techniques waiting for the consensus high-frequency EOP model
- IVS: modeling the gravitational deformation for as many antennas as possible, possibly refine the thermal expansion modeling
- ILRS: SLR range biases to be estimated/applied
- IGS: up to date GNSS force models to be used
- IDS: Improve analysis strategy, DORIS-specific model updates: SRP & SAA

Schedule and time-line

<i>Date</i>	<i>Action</i>
January 10, 2019	Dissemination of the Call for Participation
February 10, 2021	Deadline for solution submissions by Technique Centers. Earlier submissions are welcome
April 2021	First and early results to be shared and discussed with the TCs
Until end of May, 2021	Inter comparisons of the ITRF CCs solutions
~June, 2021	Preliminary ITRF2020 solution available for evaluation by TCs
Sep-Oct, 2021	Final ITRF2020 solution released by the ITRS Center

Discussion

- Richard Gross explained that the JTRF2020 will be one combination solution and one experimental solution for combination at the observation level.
- Robert Heinkelmann asked about the consistency with ICRF. This needs to be evaluated by the IVS first. Therefore, radio sources will not be part of ITRF2020.
- The Word document by Brian Luzum related to the transition process should be put to the internal area of IERS DB members.

Decisions Radio sources will not be part of the ITRF2020

New Action Items #68.08 Contact John Gipson concerning the NT-AL and providing it in SINEX files.
#68.09 Distribute CfP via IERS Message and put on website (ITRF and IERS-CB).
#68.10 Put word document on ITRF transition process to internal area for IERS DB members

IERS Conventions This report was given by N. Stamatakis.

Status report on the update process

Overview of Changes to IERS Conventions

- Major update to Chapter 4 to be consistent with ITRF2014 (cf. report of ITRS Center above)

- Emails to be sent to IERS Chapter Editors-in-Chief and Technical Experts (CETEs): Review ITRF2020 Call for Participation and become familiar with needed / requested items. Identify sections of their associated chapters which could move to a reference section or to Additional Supporting Material section on the Conventions web site.

Access to the Conventions Update v1.3.0

- One method to access the latest update of the Conventions is to use the new Quick Links feature which includes a link to the most “Updated” Conventions (see presentation for details).
- Another method to access the latest update of the Conventions is Conventions Versions link

IERS CC Configuration Management Training / Discussion on using GitLab

- Configuration management for IERS CC is a major challenge. Many organizations use GitLab or other configuration management tools
- All involved in meeting and telecon download latest canonical version before meeting / telecon starts (Slack instant messaging and email can be backup for those rare times when someone cannot access the repository because of internet or other problems.)
- Planned training seminar for GitLab / discussion tentative date and location: on afternoon of 9 October 2019. Location is probably Paris Observatory (in conjunction with Journées 2019).

Preliminary schedule of IERS Conventions Major re-write: final editing by September 2022 (see table on next page)

<i>Actions / Milestones</i>	<i>Response requested by</i>
Chapter Editors and Technical Experts (CETEs) provided Call for Participation in ITRF2020. Conventions Centre asked CETEs to be prepared for the actions in the Call for Participation.	Early 2019
CETEs asked to identify sections that could be shortened.	August 2019
CETEs to be asked to identify sections that might need technical updates.	September 2019
CETEs to be asked to review UAW workshop 2019 direction and plan accordingly.	End of October 2019
1/2 day workshop on GIT (Conventions config management) training at end of Journées 2019.	Early October 2019
Ask for status from CETEs each quarter after April 2019. Slack instant messaging will be proposed to increase communication among CETEs and Conventions Centre.	Each quarter and when needed
Various communications TBD ...	Between end of October 2019 and mid 2021
ITRF 2020 released.	Sept, Oct 2021
CETEs should have rewrites submitted to IERS CC staff. (May slide if ITRF 2020 release is delayed).	June 2022
Allow 3 months of final editing and approvals to be obtained for final draft of re-write.	Sept 2022

Discussion on models agreed for the next ITRF

- Robert Heinkelmann asked about a strategy to fill gaps with people willing to contribute to the Conventions. Nick Stamatakos will ask people directly or propose possible people.
- Zuheir Altamimi asked about the need for updating the geopotential/gravity field chapter.
- Central Bureau: There is an inconsistency with Love number.
- Daniela Thaller mentioned that the ITRF reprocessing clearly name the Conventions and the version number. Therefore, there is a need to put all updates into one version to be used for ITRF2020 analysis.
- Zuheir Altamimi asked about other models that need to be considered for next ITRF2020.
- List important model updates on the website. List all models for the next ITRF release so Technique Centers can refer to the updated model through the website.
- Detlef Angermann pointed out that Chapter 1 is on general definitions and numerical standards and that someone from gravity group needs to be found → Contact IGFS to nominate someone to review that section.
- Zuheir Altamimi noted that if new numbers are introduced in Chapter 1, one needs to be sure that they have no impact on other chapters.

Decisions

Clearly name the conventions and the version number and put all updates into one version to be used for ITRF2020 analysis.

List important model updates on the website. List all models for the next ITRF release so Technique Centers can refer to the updated model through the website.

New Action Item

#68.11 Contact IGFS to ask for nominations to review Chapter 1.

GGOS report

R. Gross provided the following report:

Coordinating Office

- Host of Coordinating Office: Bundesamt für Eich- und Vermessungswesen (BEV)
- Director of Coordinating Office Matthias Madzak resigned effective 31 October 2018; New Director of Coordinating Office is Helmut

Titz effective 17 December 2018, Martin Sehnal will continue to assist.

GGOS Focus area on Sea Level

- Lead of Focus Area: Tilo Schöne resigned effective September 30, 2018.
- Currently discussing options for continuation:
 - Continue current focus and liaise with sea level community, or
 - Redirect focus as incubator for International Altimetry Service

GGOS Affiliates

- National or regional organization, that coordinates space-geodetic activities there
- Established to increase participation in GGOS, particularly from under-represented areas like Africa, Asia, South and Central America
- Is a component of GGOS with representation on Consortium and Coordinating Board. Each GGOS Affiliate has 1 representative to Consortium and collectively they have 2 representatives to Coordinating Board
- First GGOS Affiliate is GGOS Japan, which was established in 2013; Chair: Toshi Otsubo of Hitotsubashi University, Japan. It provides a forum for multi-technique, space-geodetic discussions within Japan, and strives to improve quality of observations & encourage collaboration in Japan
- Encourage others to become GGOS Affiliates
- Held discussions to encourage new GGOS Affiliates

Essential Geodetic Variables

- Observed variables are crucial to characterizing geodetic properties of Earth and are key to sustainable geodetic observations, EOPs
- Assign requirements to each EGV like accuracy, spatial and temporal resolution, latency, stability, ...
- Derive requirements on EGV-dependent products (TRF, CRF, ...) and on infrastructure (observing systems)
- Can be used to update GGOS2020 book

- Established Committee within GGOS BPS to create list of EGVs, assign requirements to them, etc. including representatives of the IAG Services, Commissions, Intercommission Committees, GGOS Focus Areas
- IERS Rep is Tom Herring, but he is no longer IERS AC. A replacement and eventually a second IERS Rep is needed.

DOIs for geodetic Data

- Digital Object Identifiers (DOIs) for publications are widely used by publishers and provide a unique identifier of publication. DOI system managed by International DOI Foundation (IDF)
- DOIs for data sets provide benefits to users and benefits to data providers
- Establish a Working Group with representatives of Services, and data centers. Establish procedures for assigning DOIs to geodetic data sets. Helmut Titz agreed to chair the WG asking for representatives from data centers.

GGOS Representation

- Group on Earth Observations (GEO):
 - IAG is Participating Organization & member of Program Board
 - Program Board manages GEO Work Program, IAG/GGOS participates in Sub-Groups on Sendai & Sustainable Earth Observation
 - GEO Week 2018: 29 October 2018 to 02 November 2018; Kyoto, Japan (IAG/GGOS delegation: R. Gross)
- Committee on Earth Observation Satellites:
 - GGOS is an Associate Member.
 - 32nd CEOS Plenary takes place 16–18 October 2018; Brussels, Belgium. GGOS delegation: R. Gross who gave a presentation on geodetic observations and importance of TRF to Earth observations.

GGOS at Conferences

- European Geosciences Union, Vienna, Austria; 07–12 April 2019 with GGOS Session
- No Bureau meetings this year; instead, they will be held in conjunction with the IUGG
- PLATO Working Group Meeting at Technical University Vienna; Room SEM 124; 08 April 2019; 13:30–15:00. Chairs: Daniela Thaller and Benjamin Männel

- American Geophysical Union in San Francisco, CA; 09–13 December 2019 with a GGOS Session

IUGG 2019

- Venue : Palais des Congrès, Montréal, Canada 08–18 July 2019
- GGOS Symposium G06
- GGOS Coordinating Board meeting on transition from old GGOS CB to new GGOS CB: Tuesday, 16 July 2019; 12:00–13:30 (to be confirmed)
- GGOS Bureau meetings not yet scheduled

UAW2019

- Venue Institut de physique du globe de Paris (IPGP), Paris 02–04 October 2019 (by invitation only)
- Program (tentative)
 - Topics specific to each technique: systematic errors and biases in each technique and status of next generation observing systems
 - Topics common to all techniques: Reference systems and frames (including preparation for ITRF2020), Model improvements, Site surveys, Co-location of techniques (including with gravity, unified height system), Standards, conventions and formats, DOIs for geodetic data sets, Essential Geodetic Variables

Journées 2019

- Venue , Paris 7–9 October 2019

GGOS Days 2019

- Venue: to be held in parallel with SIRGAS2019 Symposium, but 1 day will be joint with SIRGAS2019 in Rio de Janeiro, Brazil; 11–14 November 2019

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

Ch. Bizouard provided the following overview:

Main changes/novelty since December 2018

- March 2019: Update of the interactive tool “Geophysical Analysis” now including atmospheric – ECMWF, oceanic – MPIOP, land water, sea level excitations derived at GFZ
- Filtered mean pole: updated the first day of each month
- Towards an operational multi-technique EOP series GNSS+VLBI from GINS/DYNAMO treatments (COMB OPA).

Earth rotation monitoring

1. The Chandler wobble amplitude decreased down to 40 mas with a tremendous phase change since 2012 – Situation similar to the period 1925–1930.
2. The Earth rotation has strongly accelerated since 2016.

Inconsistencies were found when EOP series were aligned to ITRF2014.

X-pole differs from GNSS series by about 40–50 micro-as since about December 2017. The reason is still unclear, but needs to be figured out.

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

This report was given by C. Hackman.

Preliminary estimates of 2018 accuracy

- Summary: Better than 2017? Agree same w/C04, JPL except in UT1: more like JPL
- PM, estimated: 2018: 57 μ as, 2017: 74 μ as
- PM, 1-d pred: 2018: 274 μ as, 2017: 304 μ as
- UT1, estimated: 2018: 50-76 μ s, 2017: 63 μ s
- UT1, 1-d pred: 2018: 70-89 μ s, 2017: 88 μ s
- 29 Mar 2018 Δ s: re-alignment to C04, CPO $\rightarrow$ dX/dY paradigm, UTGPS deweighted

Status update on various items

- Combination/prediction algorithm improvements: contract about to start!
- Still in progress:
 - R&D on UTGPS repairs
 - Completion of RS/PC email migration: waiting on another departments technical development; ser7@maia.usno.navy.mil not blocked by major spam blockers; Bulletin A inquiries: please use usn.ncr.navobsydc.mbx.eopcp@mail.mil; Transition to new network (USNO DC, NOFS).
- Ongoing research: prediction improvements thru use of OAM/AAM data

IERS RS/PC staff presentations, activities

- Presentations since DB Meeting # 67

- EGU GA 2019 Poster Session G3.1 (Thu 11 Apr 2019): N. Stamatakos, D. McCarthy, D. Salstein, Investigating Possible Combinations of Atmospheric, Ocean, and other Geophysical Angular Momentum Data to Improve Operational Earth Orientation Information
- 24th EVGA Meeting (17–19 Mar 2019; Gran Canaria, ES) oral presentation O303: M. Davis, M.S. Carter, C. Dieck, The IERS Rapid Service / Prediction Center UT1–UTC Combined Solution: Present and Future Contributions
- Unified Analysis Workshop (2–4 Oct 2019; Paris, FR): Stamatakos to represent IERS, deliver RS/PC presentation
- Journées 2019 (7–9 Oct 2019; Paris, FR): Stamatakos, Davis to attend, conduct IERS Conventions workshop after European VLBI Group for Geodesy and Astrometry

The IERS RS/PC team (besides C. Hackman):

- Mr. Nick Stamatakos, RS/PC Production Director & Lead Project Scientist
- Ms. Merri Sue Carter
- Mr. Nathan Shumate
- Ms. Maria Davis

Notes

Nick Stamatakos mentioned that the transition of website from http to https was made (redirection should be happen automatically). An IERS Message should be sent out when the transition takes place.

Working Group on IERS Product Distribution

R. Heinkelmann presented the draft charter of the new IERS Working Group on “Possible improvements related to the distribution of the IERS products” (accordingly to IERS DB decision #65.03)

Draft Charter

- Proposed goals
- Questions to be addressed:
 - What is the current situation of data distribution and is the current situation satisfying the user needs?
 - Who are the users of the IERS products?
 - What are the requirements / preferences of the users in terms of data distribution?
 - Has the actual user need / requirement in terms of distribution been assessed?

– What are the potential proposals for improvements?

- Proposed structure of the group: tbd
- Working plan including schedule / deadline: tbd

Candidate for a chairperson

- Chair (suggested as of 2017-12-09): IERS AC: Heinkelmann, R.

Initial list of members

- Members (suggested as of 2017-12-09): CB: Thaller, D.; Earth Orientation Center: Bizouard, C.; ICRS Center: Souchay, J.; ITRS Center: Altamimi, Z.; ITRS CC DGFI: Seitz, M.; ITRS CC IGN: Altamimi, Z.; ITRS CC JPL: Gross, R.; Rapid Service / Prediction Center: Hackman, C.

Term

- Two years with a possible one-time re-appointment

Charter of the WG has to be defined.

Discussion

- Christian Bizouard proposed to ask Leonid Petrov if he is willing to join the WG.
- Zuheir Altamimi proposed to add the Technique Centers since they are using the data.
- Detlef Angermann pointed out that an interaction with GGOS BPS will be necessary and proposed to add the GGOS BPS to the member list.

EOP comparison UT1–UTC

R. Heinkelmann presented the report.

Current conventional products

- Realization of ITRS: ITRF2014
- Realization of ICRS: ICRF3
- Realization of GCRS ↔ ITRS transformation: IERS EOP 14 C04

Problem statement

- The products are of high quality but determined independently of each other. For ITRF20xx, DORIS, GNSS, SLR, VLBI and local ties are used, but CPO and CRF are not explicitly considered. Analysis approach 1, includes data up to 20xx
- ICRFi: VLBI, no other techniques involved, analysis approach 2, includes data up to yyyy EOP xx C04

- dX, dY, and UT1 are treated independently of x, y
- IVS combined solution considers non-tidal atmospheric loading, ITRF2014 not

Assessment approach by VLBI

- VLBI solution using IVS data between 1984-Jan-24 and 2018-Apr-1 (in common with ICRF3)
- 5992 sessions with about 13.25×10^6 observations
- NNR w.r.t. 303 defining sources (ICRF3) / NNR + NNT w.r.t. 31 stations (ITRF2014)
- EOP are determined together with the global coordinates!

Results and Conclusions (TRF and CRF)

- We realized a consistent set of TRF, CRF, and EOP from a single VLBI solution.
- The GFZ-TRF (VLBI) shows a scale bias w.r.t. ITRF2014 (VLBI + SLR) of about 7 mm.
- The choice of terrestrial datum stations is important and at the same time it becomes increasingly difficult as more and more VLBI stations are affected by seismic events.
- Conclusion: precise co- and post-seismic deformation modeling becomes important.
- Presumption: with the upcoming new generation VGOS ground stations, it will be a big challenge to maintain the VLBI terrestrial frame stability.
- The GFZ-CRF shows small rotations, deformations and a declination bias w.r.t. ICRF3 but within the GGOS goals.
- The VLBI-determined EOP disagree with the IERS EOP 14 C04 on a level exceeding the GGOS goals.
- The EOP prior to about 1992–1993 are much less precise and show large variations. At this time, the VLBA (and other stations) joined the IVS.
- Conclusion: For detail Earth rotation studies that require high-precision EOP, VLBI prior to 1992 could be omitted.
- Hydrostatic mass loading deformation introduces quasi-annual signals in the pole coordinates.

Final conclusions

- With our VLBI-only approach, we cannot fully assess the consistency between TRF, CRF and EOP.
- For the EOP and for VLBI it is important to work with consistent TRF and CRF.
- If highest consistency is aimed for, the TRF, CRF and EOP need to be determined in a single solution involving the four space geodetic techniques (and local ties).

New Action Items

#68.12 Send out IERS Message when transition to https website has been done (2–3 weeks).

#68.13 Ask Leonid Petrov, the Techniques, and the GGOS BPS to participate in WG on IERS Product Distribution.

ICRS/ICRF report
Status of ICRF-3 and next
steps for the IERS

R. Gross presented the report.

ICRF3 adopted by IAU on 1 Jan 2019

- Key accomplishments:
 - Multi-wavelength (S/X, K, X/Ka)
 - Majority of sources much more accurate (>3x improvement)
 - Approximately 30% more sources
 - Available now via IERS ICRS Centre website

Plans

- ICRF3 is now in “maintenance” phase
 - Focus is on improving current positions, source quality
 - Looking at position shifts between frequencies
- ICRF3 team is working with Gaia team towards defining an integrated radio/optical reference frame
 - Likely to be proposed as a working group to IAU
- USNO, Paris Observatory are collaborating on AGN monitoring program (FRAMEx) for reference frame sources

Discussion

- Daniela Thaller asked if there are any ideas to have a better link to the IERS this time. Reply: No ideas so far.

IAU Report R. Gross reported:

100 anniversary of IAU

- During Journées 2019 an IAU centennial session is planned with presentations of the history of IAU Comm. 19 and the Earth rotation over the last 100 years.
- A proposal was sent to have an Earth rotation session at the last Symposium in August, but the IAU did not support it either.
- Plans to publish a history of the commission in a journal article; Zinoviy Malkin is writing the part on polar motion.

Other reports
WG on Site Survey and
Co-location

R. Haas presented the following report:

Terms of Reference

- Ultimate objective: improving the accuracy of tie vectors as well as the consistency of space geodetic solutions.
- Provide authoritative source of surveying methodology advice, promote technical discussion, a forum for the evaluation of existing and new procedures and analysis strategies.
- Support new survey activities with advice and advocate for re-survey where necessary.

Background

- Local ties between different techniques differ from results from geodetic analysis at a level of several millimeters.
- Standard surveying equipment better by a factor of 10
- Industrial grade instruments better by factor 100 → Systematic errors in space geodetic techniques

What has been done in the WG?

- Focus has been directed towards deformation studies of VLBI reflectors
- These studies have been able to separate the internal deformation parameters of the VLBI telescopes, aliasing as several millimeters movements of the telescope in previous and current analysis (undetected in “classic” local tie measurements).
- More telescopes need to be measured – of particular urgency are those telescopes about to be decommissioned.
- Maintenance issue for the telescope operators and the geodetic society as a whole, and a requirement to fulfill the GGOS/VGOS objectives. If this task is not fully embraced by the geodetic community, I fear the GGOS objectives will inevitably fail.

Focus on VLBI

- Structural deformation of reflector alters the internal raypath (non-issue in astronomy)
- Not detected with local tie measurements
- Application of photogrammetric methods (snapshots, equally accurate, non-loading)
- Effects detected at several mm

UAW 2017 Recommendations

- VLBI: 2) Gravitational deformation of VLBI antennas. It is recommended that as many VLBI antennae as possible be measured to determine their gravitational deformation.
- Site survey
 1. Optimize a local network setup combination [...] based on instrument specification.
 2. Development of an in situ GNSS antenna calibration method is a high priority; and especially important to commission at GNSS sites with long history.
 3. In a choice [...] sites without local ties should be prioritized.
 4. For IDS, IGS, ILRS, and IVS specifically (i.e. comment directed to the services):
 - (a) Examine ITRF2014 tie and space geodesy discrepancies available at http://itrf.ensg.ign.fr/ITRF_solutions/2014/ to look for indications of systematic errors.
 - (b) Choose sites with poor consistency between local ties and space geodetic solutions to identify and address problems.

What is the intention of the space geodetic community in this aspect?

- Equipment maintenance to provide best possible data for analysis
- Measurement teams are not deployed at space geodetic sites
- Travel needed for surveying teams
- Measurement data analysis required ⇒ Station operators need to pay ... (!)

Discussion

- Christine Hackman asked about the costs of drone measurements. Those costs are unclear, but Zuheir Altamimi said that a local survey is about 50,000 Euros.

- Zuheir Altamimi proposed to draft a list of co-location sites with highest priority and to support institutions doing local surveys.
- Mike Pearlman notes that the WG in GGOS supports deformation issues in VLBI. He asked if the WG does what IERS expects.
- Zuheir Altamimi responds that local ties of stations are more valuable than the work of the WG. The WG is giving advice to the stations how to do the local survey. This might not be the right frame to solve the discrepancies between terrestrial local-ties and measured coordinate differences by the space techniques.
- Rüdiger Haas notes that the WG is giving advice on doing local survey, but the local surveyors are not following these advice.
- Erricos Pavlis asked if someone is keeping track of the surveys that have been done.
- Zuheir Altamimi proposed to set up a website and asking the sites to make the surveys/reports available.

New Action Item #68.14 How to proceed with the Working Group on Site Survey?

Annual Report 2018 The call for the Annual Report 2018 was sent out 3 weeks ago. The Central Bureau started to print the previous Annual Report 2017.

Next DB meeting (#69) Zuheir Altamimi asked to move the meeting to Sunday morning starting at 8 a.m. for a half-day meeting, because the IAG Executive Committee meeting is normally the whole day on Saturday before AGU.

Decision:

The next DB meeting (half-day meeting) will take place on Sunday, December 8, 2019, before the AGU in San Francisco.

Decisions Organize IERS DB Meeting on Sunday morning.

New Action Item #68.16 Prepare IERS DB meeting No. 69

Meeting No. 69 December 8, 2019, Park Central Hotel, 50 Third Street, San Francisco, California, USA

Introduction and approval of agenda Brian Luzum welcomed the guests and the members of the IERS Directing Board. The agenda was accepted. There were no additional comments.

**Changes in IERS personnel
since last DB meeting**

- IAG / IUGG representative since 7 Dec. 2019: Tom Herring (Thanks to Axel Nothnagel, IAG rep. 2015–2019)
- Richard Gross will continue as GGOS representative to the IERS DB (representative since 2017)
- Detlef Angermann will continue as IERS representative to IAG Commission 1 (Reference Frames) Steering Committee (representative since 2016)
- New IERS representative to IAG Commission 3 (Earth Rotation and Geodynamics) Steering Committee since 8 Aug. 2019: Robert Heinkelmann (Thanks to Brian Luzum, representative 2011–2019)

Deceased IERS officers:

- George A. Wilkins (1929 – Dec. 2018), UK (IAU Representative to the DB, 1 Jan. 1988 – Aug. 1988; Chair of the DB, 1 Jan. 1988 – Aug. 1988)
- Richard Biancale (1952 – Feb. 2019), France (Primary scientist of the CRC at Groupe de Recherches de Géodésie Spatiale (GRGS), 1 Jan. 2001 – 31 Dec. 2008; Chair of the Working Group on Combination at the Observation Level, Oct. 2009 – Apr. 2016)
- William G. Melbourne (1930 – Sep. 2019), USA (Head of the GPS Coordinating Centre, 1990? – 31 Dec. 2000; GPS Coordinating Centre Representative to the DB, 1989? – 31 Dec. 2000)

Associate Members

The updated list of the IERS Associate Members was sent out in advance.

New Action Item

#69.01 Ask all IERS components to update.

**IERS Technical Notes on
ITRF2014**

TN 40: IERS Technical Note on the evaluation of the three solutions: ITRF, DTRF and JTRF

- Nearly ready
- 4 contributions by the ITRS Centre and the ITRS Combination Centres
- 3 contributions by the IERS Technique Centres (IDS, ILRS, IVS)

Decisions

- TN 40 to be published at the beginning of 2020.

TN xx: C04 series aligned to ITRF2014 (replaces TN planned for 08 C04 series)

- No news. Paper on 14C04 was published in the Journal of Geodesy.

Decisions: TN 40 to be published at the beginning of 2020.

New Action Items #69.02 Publish TN on ITRF, DTRF and JTRF.
#69.03 Report on TN related to C04

**Current activities at the ITRS
Combination Centres
Report from ITRS Combination
Centre at JPL**

Richard Gross reported on the following activities:

SREF development (Chin et al.)

- Status
 - Time variable, square-root information filter with full process noise matrix
 - Optionally estimates radio source positions for joint TRF / EOP / CRF determination
 - TRF and joint TRF/EOP/CRF test solutions being analyzed
- Plans
 - Reproduce JTRF2014 with SREF
 - Include EOP dynamics, postseismic displacement model
 - Will use SREF to determine JTRF2020

JTRF2014 analysis (Abbondanza et al.)

- Article accepted by Advances in Space Research (A Sequential Estimation Approach to Terrestrial Reference Frame Determination, by Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, and X. Wu)
- Reviews JPL's approach to determining TRFs, comparing it to other approaches

Vector spherical harmonics (Soja et al.)

- Used to intercompare CRFs
 - Allows higher order differences between frames (warping) to be evaluated
- Used here to intercompare TRFs

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

Mathis Bloßfeld presented this report.

Non-tidal loading corrections in DTRF2014 and DTRF2020

- NT-L loading corrections at NEQ level are performed accordingly to OBS level.

- In DTRF2014, NT atmospheric (NCEP) and hydrological loading (GLDAS) was considered (provided by GGFC).
- In DTRF2020, also NT oceanic loading should be considered (TUGO-m + ERA5?).
- NT-L correction: effect on station positions (DTRF2014)
 - Change of station position and velocities depends on observation interval.
 - In particular GNSS station coordinates are changed (many short obs. intervals).
 - From additionally applied OCN loading, stations at the coast (colocation with tide gauges for referencing sea level rise) will benefit!
 - In particular GNSS station heights benefit from NT-L corrections (lowest scatter).
 - Horizontal components do not benefit. Model deficiencies? Level of application?
- NT-L correction: effect on datum parameters (DTRF2014)
 - The characteristic annual signal vanishes when NT-L corrections are applied.
- NT-L correction: VLBI analysis at DGFI-TUM
 - NT-L corrections are performed on NEQ and OBS level.
 - NT atmospheric, hydrological and oceanic loading corrections are applied (single components and combined loading signal)
 - In case of VLBI station networks, in particular the correction for the hydrological component of NT-L leads to a strong reduction of the annual signal!
- NT-L correction on the NEQ level: summary
 - Is in accordance with the definition of the ITRF as a conventional reference frame (IERS conventions) → corrections are applied by a reduction of the original observations.
 - NT-L corrections are fully geophysical (compared to sine/cosine signals).
 - Station heights and datum parameters benefit clearly.
 - But: horizontal station positions do not benefit (also for GNSS with a low scatter of time series and many well distributed stations).
 - Improved in ITRS realization 2020
 - * Full effect on orbit (OBS level) will be applied.

- * Full effect on station positions (NEQ level) will be applied.
- * Level of application for station position corrections and temporal resolution of corrections?
- For future ITRS realizations, the application of NT-L corrections at OBS level should be investigated!

Consistency of applied loading models

- Both, non-tidal atmosphere and ocean circulation products require high temporal resolution (at least 3 h) → problems with application at NEQ level?
- Gravity coefficients and loading should be always derived from identical mass distributions.
- Consistency of NT-L models (example: ILRS)
 - TV Gravity field and NT loading products must be consistent (as e.g., the products from GFZ).
 - They can be combined with all modern ocean and atmospheric tidal loading models.
 - ILRS will use the given AOD models?
 - IDS will apply other AOD products?
- GGFC must be informed about decisions!
- Finally, consistent NT loading models for station corrections must be used!

Scale of ITRS realizations 2020: many model changes related to the scale

- Many model changes will have an impact on the ITRS scale realization.
- For many models the impact of the scale is not well investigated yet.
- ITRS scale realization in 2020 will be a challenge (no consistency with ITRS realizations of 2014).
- A careful step-by-step analysis of the individual contributions is necessary to understand the scale of the ITRS realizations in 2020!

Summary

- NT-L corrections on the NEQ level
 - Station heights, origin and scale benefit.
 - NT-L corrections should be applied with all three components.

- Investigations on how to improve the impact on horizontal station components (model deficiencies, inconsistencies, level of application) is still necessary.
- NT-L models should be consistent for ITRS 2020 realizations
- ITRS 2020 scale realization
 - Many model changes in the individual technique-analyses will have an impact on the scale.
 - ITRS scale realization will become challenging.
 - Investigations of the IERS Technique Services on the impact of the different model changes are very important and will help to validate the new ITRF scale.

Discussion

Jean-Paul Boy added that the GGFC will release a fully new and consistent model based in ERA-5. The latter's latency is thought to be reduced. A consistent hydrology model is also available. Loading and time-variable gravity will be provided. Models from GFZ including predictions are also suitable. A comparison with GFZ models is planned.

Report from ITRS Center

The report was presented by Zuheir Altamimi.

Status ISO Standard on ITRS

- The final document is now under publication
- Translation of the standard in French
- Final publication is expected soon, or January 2020
- Former Resolutions/Agreements on ITRS & ITRF:
 - IUGG2007: adopted the ITRS as the preferred Geocentric Terrestrial Reference System (GTRS) for scientific and technical applications
 - CGPM2011: recommends that the ITRS, as defined by the IUGG and realized by IERS, be adopted as the unique international reference system for terrestrial reference frames for all metrological applications
 - ICG: recommendation to align GNSS-specific reference frames (WGS84, PZ-90, GTRF, CGCS2000, JGS) to the ITRF
 - IUGG2019: recommend to the user community that the ITRF be the standard for positioning, satellite navigation and Earth Science applications, . . .
 - UN-GGIM-2019: adoption of the ITRS and the ITRF as the standard for scientific, geospatial and operational geodetic applications

Activities of UN-GGIM Subcommittee on Geodesy

- Participation in the UN-GGIM 9th Session
- Adoption of the ITRS and its numerical realization, the ITRF by the UN-GGIM Committee of Experts as the standard reference for scientific geospatial and operational geodesy applications
- Towards the creation of a Global Geodetic Center of Excellence (GGCE):
 - Mission & modalities still to be defined/articulated
 - Consultations are ongoing
 - 1st draft will be presented at the UN-GGIM HLF in Windsor, UK, April 2020
- Questionnaire on Geodetic Infrastructure
 - Sent to the IAG Services, including the IERS
 - IERS: Need to agree who should respond?
 - The Central Bureau, with contributions from IERS DB and Components

IERS Technical Note 40: evaluation & inter-comparisons of the three solutions: ITRF, DTRF and JTRF 2014

- Under publication: 7 contributions
- Many thanks to IERS Central Bureau: Wolfgang Dick, Sonja Geist and Sandra Schneider-Leck
- Editors: ITRS Center & IERS CB: Zuheir Altamimi and Wolfgang Dick

Towards ITRF2020

- The CfP was adopted and finalized
- Roadmap and schedule discussed and agreed in past DB meetings
- The ball is in the Technique courts now and hope they will respect the initial time line with no delays
- The ITRS Center is willing to evaluate any test solutions at any time
- UAW2019-RF-Recommendations
 - The IGS is urged to preserve the alignment of its operational products (orbit, clocks, ERP) to the ITRF2014 until the ITRF2020 is published

- The IVS is urged to provide the ATML corrections (if applied) to the right-hand side of the normal equation in the SINEX files
- The ILRS is urged to provide the Range Biases estimates with covariance in their weekly SINEX files
- The IDS is encouraged to mitigate IDS-specific systematic errors that impact the TRF parameters (origin & scale)
- The GGFC is invited to provide a unified loading model including all contributions (Atmosphere, Hydrology & Ocean) for all ITRF2020 sites

ITRF2020: Schedule & time-line

January 10, 2019	Dissemination of the Call for Participation
February 10, 2021	Deadline for solution submissions by Technique Centers. Earlier submissions are welcome
April 2021	First and early results to be shared and discussed with the TCs.
Until end of May, 2021	Inter comparisons of the ITRF CCs solutions
~June, 2021	Preliminary ITRF2020 solution available for evaluation by TCs
Sep-Oct, 2021	Final ITRF2020 solution released by the ITRS Center

IAG Commission 1 and IERS joint Working Groups

- Colocations & Local ties → Renamed to “Methodology for surveying geodetic instrument reference points”
 - Chair: Ryan Hippenstiel (NGS/NOAA)
- Geocenter Motion: “Toward reconciling Geocenter Motion estimates”
 - Chair: Kristel Chanard (IPGP-IGN)
- Consistent realization of TRF, CRF and EOP
 - Chair: R. Heinkelmann (GFZ)
- The three WGs were approved by the IAG EC.
- Need to be approved by the IERS DB.

- New Action Items**
- #69.04 Provide test data set
 - #69.05 Provide station list, especially VLBI and SLR
 - #69.06 Put list of resolutions/agreements on ITRS & ITRF on IERS website
 - #69.07 Coordinate IERS's answers to Questionnaire on Geodetic Infrastructure

**Reports from the Technique
Centers
IDS Report**

The report was presented by Guilhem Moreaux. DORIS constellation status (current and future missions)

- 6 current missions (Sentinal-3A and 3B, Jason-3, SARAL, HY-2A, Cryosat2)
- 7 future missions (Sentinel-3C and 3D, HY-2C and 2D, Jason-CSA and CSB, SWOT)
- 1 proposed mission (MOBILE, proposed to ESA, for gravimetry and geodesy)

Current DORIS Network

- 47 co-located sites out of 58 DORIS stations
- Rate of operating stations over the past year 80%
- Currently out of order: Badary, Krasnoyarsk, Betio, Santa-Cruz, Crozet, Tristan, Ny-Alesund

Network Evolution

- Recent Network Events
 - Jun. 2019: start of the deployment of the 4th generation DORIS beacon at St-John's, Canada.
 - Jul. 2019: 4th generation beacon installation at Ponta-Delgada, Azores, Portugal.
 - Sep. 2019: re-installation at Santa-Cruz, Galapagos, Ecuador after 10-yr outage.
 - Nov. 2019: 4th generation beacon installation at St-Helena, South Atlantic, UK.
- Short Term (2020)
 - La Réunion, France: antenna relocating and 4th generation beacon installation.
 - Crozet, France: 4th generation beacon installation.
 - Male, Maldives: antenna relocating and 4th generation beacon installation.
 - Reykjavik, Iceland: relocating at Höfn (co-location with IGS station "HOFN").

- Changchun, CN: new station installation in place of Yuzhno-Sakhalinsk – TBC.
- Easter Island, Chile: relocating (hosting migration).
- Longer Term
 - Dionysos, Greece: relocating before site closure.
 - Katherine, AS: new station installation in place of Port-Moresby (3 techniques site).
 - Papenoo, Tahiti, FR: new 4 techniques site (TBC).

POD Results: The POE-F DORIS-only orbital radial performance approaches the GPS-based orbits, especially for satellites with smaller Surface/Mass ratio.

DORIS Scale: The IDS contribution to the ITRF2014 shows a scale increase early 2012. The IDS identified the reasons for these patterns:

- Wrong CoM-CoP vector for HY-2A.
- Dependency on the validity standards from the data provider.

As demonstrated by the latest GRG multi-satellite solution, we can now achieve a stable scale from 1993.0 to 2018.0.

IDS reprocessing for next ITRF

- Time Span
 - 1993.0-2021.0
- DORIS Constellation
 - Cryosat-2, Envisat, HY-2A, Jason-1/2/3, Saral, Sentinel-3A/B, SPOT-2/3/4/5, TOPEX
- DORIS Data Format (DORIS 2.2 / RINEX)
 - IDS recommends to the ACs to have one format per mission.
- Satellite Modelling

Attempt to mitigate the non-conservative force model error on satellites (draconitic signals):

 - Use quaternions (for bus and solar panels) when available.
 - Revisit SRP coefficients and macromodels.
- SAA Mitigation Strategies
 - Jason-1: recommendation of the data correction model already used for ITRF2014.
 - Jason-2: TBD.
 - Jason-3: TBD.
 - SPOT-5: recommendation of the data correction model already used for ITRF2014.

- DORIS Antennas
 - Alcatel, STAREC-B/C + associated phase laws.
- Data Elevation
 - IDS encourage the ACs to adopt an elevation cut-off below 10°
 - IDS strongly recommends to downweight low elevation data.
- New standards/models recommended by IERS and IDS
 - New linear mean pole model.
 - Desai & Sibois HF (diurnal-subdiurnal) tidal EOP model recommended by IERS
 - Time-Variable Gravity (TVG) model (based on GRACE data + GOCE data + SLR data coherent with new mean pole convention (C(2,1) / S(2,1) coefficients)
 - Oceanic tidal model (ex: FES2014-b)
 - “Dealiasing products” (atmospheric, ocean -ex: AOD1B-RL06).
- Site Observation Time
 - No more minimum duration (2.5 yrs for ITRF2014).
- Time Schedule (TBC)
 - 2020, April 30th: AC delivery of 1993.0–2002.3 (Until start of Envisat – First DORIS 2G receiver).
 - 2020, June 30th: AC delivery of 2002.3–2011.8 (Until start of HY-2A).
 - 2020, Sept. 30th: AC delivery of 2011.8–2020.0.
 - 2021, Feb; 10th: First delivery of the IDS combined solution to the IERS (1993.0–2020.0).
 - 2021, Feb. 14th: AC delivery of 2020.
 - 2021, Mar. 15th: Complete delivery to the IERS of the IDS combined solution.

IDS Combination Center

- Position and velocity cumulative solution (ids19d04)
 - Based on new IDS combined solution.
 - From 1993.0 to 2019.0.
 - Aligned to ITRF2014.
 - Includes 193 DORIS stations at 84 sites.
 - Available in both SINEX and text formats at CDDIS & IGN ftp sites.
- DPOD2014 version 4.0

- Based on ids19d04.
- Includes 205 DORIS stations at 89 sites.
- Available in both SINEX and text formats at CDDIS & IGN ftp sites. → Update of the SINEX Master file available at IDS CB ftp site.
- DORIS discontinuities
 - Review of the station position and velocity discontinuity → Less unknown breaks.
 - Not used in the DPOD2014 version 4.
- Coordinate Time Series Plots
 - New version of the plots delivered to CDDIS and IGN.
 - Indicate date(s) and origin(s) of the discontinuities (geophysical, technical, unknown) for a better understanding by the users.

IDS News

- IDS Meetings
 - In 2019
 - * IDS AWG, April 4th, at DGFI, Munich.
 - * IDS AWG, Sept. 30th–Oct. 1st, at CNES, Paris.
 - In 2020
 - * IDS AWG, Spring, place TBD.
 - * IDS Workshop, Oct. 19–21, at Venice.
- IDS Newsletter
 - Newsletter #7 will be issued in December 2019.
 - All issues are available at <https://ids-doris.org/ids/reports-mails/newsletter.html>
- IDS Life
 - DORIS will turn 30 in 2020.
 - DGFI-TUM is the 4th Associated Analysis Center.
 - Jason-2/3: DORIS RINEX and DIODE orbit may be soon available in NRT (Followed a request from the IDS NRT DORIS Data WG chaired by D. Dettmering).
 - Creation of an IDS Working Group on Geocenter.
 - Elaboration of first IDS strategic plan.
- IDS Strategic Plan
 - Output of the first IDS retreat
 - Nearly 20 recommendations
 - * To grow the community.

- * To improve the technology, the infrastructure and the processings.
- * To extend DORIS applications.

- First Realizations:
 - Organization of a “DORIS day” prior to EGU 2020 to promote the use of the IDS products.
 - Free access to DORIS POD software to lower the barrier to entry: GINS from CNES/GRGS and GEODYN from NASA may be soon available.

IGS Report The report was presented by Tom Herring.

- Administrative:
 - The current chair Gary Johnston will hand over the business to his vice-chair Felix Perosanz, likely during the workshop in August.
- Workshops:
 - The next IGS workshop is scheduled for August 10 to 14, 2020 in Boulder, Co. It will be organized by UNAVCO and UCAR. The theme is “Science from Earth to Space”
 - The program was developed by F. Blume (UNAVCO) and will be discussed at the IGS GB meeting this afternoon.
- Regarding the processing:
 - Putting the MGEX products in the context of the legacy product chains we can state:
 - * GPS has the best quality
 - * Galileo comes (closely) behind GPS
 - * GLONASS is the third
 - * BeiDou is far away
 - * QZSS is in a quite good shape but as a regional system of a lower interest for global solutions.
 - Galileo starts to enter the legacy product chains:
 - * The repro for ITRF2020 will contain Galileo from a number of ACs (not only the MGEX-ACs made this announcement); will enter the final products after the repro
 - * First AC started to add Galileo to the rapid and ultra-rapid products (not relevant for the reference frame)
 - * The critical point is the receiver antenna correction model (see below)
- Repro for ITRF2020:
 - After the last IERS DB meeting in May 2019 several milestones have been passed.

- In the week after the EGU, a IGS AC workshop was carried out at GFZ facilities from April 15 to 17.
 - * Arturo Villiger (chair Antenna WG) has shown based on chamber calibrations that together with the satellite antenna calibrations (provided for Galileo from GSA) can be used to provide scale information from GNSS for the ITRF generation.
 - * At the workshop Geo++ has shown for the first time a multi-GNSS calibration including the Galileo frequencies. Because of this opportunity, the schedule was revised in a way that these calibrations can be considered as well for the repro.
 - * Apart from this discussion on the antenna calibrations, it was decided to include Galileo (in addition to GPS and GLONASS in the previous repro); recommendations for the satellite orbit modelling have been established (expecting an improvement wrt. to the previous repro); and numerous other models have been agreed.
- According to the new schedule, a preliminary table of antenna corrections was established for a test solution over two years. This test campaign has been processed during the summer by four of the ACs and confirmed the general suitability of these corrections. For some selected antennas further updates have been carried out based on this experience.
- By the 10th September a telecon of all ACs was organized to discuss the results from the test campaign. The use of the new ANTEX corrections was agreed. The ACs have further agreed to process the year 2014 following the standards of the repro for ITRF2020 and check the consistency of these submissions. This is planned for an AC splinter meeting during the AGU.
- It is planned that the solutions are available until summer 2020 for combination.
- Final remark:
 - All updates of the antenna models have been accomplished by updates of the IGS realization of the ITRF14 (big work by Paul Rebischung)

ILRS Report The report was presented by Erricos Pavlis.

ILRS Network Activities

- Station closings:

- MLRS, McDonald, TX: lightening strike; to be replaced by SGSLR (ca. 2021)
- Upgraded stations:
 - Simosato (Japan): kHz operations since late 2018
 - Wuhan (China): submitting data (validated, operational)
 - San Fernando, Spain (validated, operational)
 - Tanegashima, Japan (irregular data submission)
 - San Juan (Argentina): kHz operations planned for 2020
 - BKG AGGO (Argentina): setup at La Plata Observatory; (TIGO relocation)
- Quarantined stations:
 - Zelenchukyska, Russia
 - Tahiti, French Polynesia
 - NRL/Stafford, Virginia
 - Geochang, Korea (new station; no data yet)
 - Stuttgart, Germany (new station; no data yet)

Mission News & Support

- Missions Standing Committee
 - New chair (Stephen Merkowitz) and co-chair (Toshi Otsubo)
- Tracked 110+ satellites in 2019
- Formulated new GNSS tracking strategy
- Completed 3-month Etalon campaign
- Updated mission support request guidelines, e.g. advance notice of six months (minimum)
- Future missions requesting ILRS support:
 - Astrocass Precursor (2 cubesats/engineering testing)
- Additional GNSS: BeiDou/Compass, Galileo, etc.
 - COSMIC-2, HY-2C, SWOT, NISAR

ILRS Status and Activities

- Infrastructure
 - Testing new formats for Data (CRD) and Tracking Predictions (CPF)
 - Web-based station site log archive and maintenance operational

- Harmonized data screening & QC between EDC and NASA OCs (Implemented)
- Implemented new strategies to “rate” station performance underscoring value to the users and science products (online tool)
- ILRS sets tracking priorities to balance requests and maximize the utility of the network
- Routine submission of all full-rate data to OCs and DCs from most of the currently active stations (40)
 - We continue to press the rest to conform ASAP
- Etalon Campaign Project: dedicated tracking campaign for Etalon 1 & 2 (February 15 to May 15, 2019)
- Published ILRS workshop planning guidelines
- Developed draft MOU between ILRS/GGOS and ROSCOSMOS
- Increased scrutiny in selecting new missions to track
- Adopted plan for tracking GNSS s/c:
 - Each constellation selects 4 satellites for higher priority tracking (3 segments of tracking requested per pass)
- Issues:
 - Network gaps in Latin America, Africa, and Oceania, and mix of new and old technologies are the primary issues of concern now
 - Site log update lapses cause trouble with analysis/products; delinquent sites/agencies are reminded often!
 - Lack of standardization in system hardware and operations
 - Marginal operation at many stations, making little or no contribution to the ILRS data products
 - Addressing data quality issues; still some systematics
 - Continued increase in number of target satellites as new missions use SLR for orbit determination and other applications (110+ satellites)

ILRS ASC – Analysis Activities

- Preparations for contributing to the development of ITRF2020 are on schedule
- New operational approach in handling error sources adopted at the ASC meeting in Canberra, November 2018 implemented:
 - Allowance for estimation of systematic errors simultaneously with all other parameters to eliminate biases in station positions/velocities (in progress);

- Correction of identified serious shortcomings in the current model for the target signature (also known as “CoM correction”) for all types of ground systems (implemented);
- Correction of such errors alone can affect the SLR-VLBI scale difference at the ~ 0.25 ppb level.
- Adopted the new CoM model which was recently released (November 2018 & September 2019) by NSGF (implemented).
- SSEM Pilot Project on station systematics completed the next phase and we received the final submission from ALL (7) ACs to complete the combination product and the tabular form of the new model (TBD);
- The result will be used as the basis for the development of the ILRS product that will be contributed to ITRF2020;
- We have added estimation/handling of Time Biases:
 - Time biases are now modeled based on T2L2 results
 - Additional time biases from T2L2 until the end of 2017 added
 - Review of T2L2 bias from NASA OC in progress
- We will include applied R_B & T_B in SINEX file for next contribution to ITRF with their constraint information in each SINEX combined product
 - The SINEX will contain the R_B & T_B values & σ applied to each station and the applied CoM offsets for that weekly product
- Next PP will deliver low-degree gravity coefficients as a weekly product and introduce LARES as a 5th target for ITRF product support (in early 2020)

Publications

- Special Issue of the Journal of Geodesy, Vol. 93, #11, Twenty articles and the preface, 287 pages
- ILRS 2016–2018 Report in Preparation

Recent & Future Meetings Schedule

- An ILRS Technical Workshop took place in Stuttgart, Germany: 21–25 October 2019, “Laser ranging: To improve economy, performance, and adoption for new applications”
 - The ITWLR Website: http://cddis.nasa.gov/2019_Technical_Workshop
 - We held the first ILRS one-day school on laser ranging with large participation and success; expanding to 2 days seems most appropriate in the future; replies from a survey under evaluation

- An ILRS ASC meeting will take place on the Saturday, May 2, prior to EGU 2020; information and details in early January 2020
- The 22nd International Workshop on Laser Ranging (IWLR) will be held in Kunming, PRC: November 2 – 6, 2020
 - We will probably hold the ASC meeting on Nov. 1, 2020 (TBD)
 - A meeting website will be released soon, early in 2020

IVS Report The report was presented by Johannes Böhm.

The Past and upcoming VLBI meetings

- Past meeting: May 2019: TOW at Haystack, including workshop on VGOS correlation/postprocessing
- March 2020: 11th IVS GM at Annapolis; IVS stakeholder meeting directly before the IVS GM

Legacy S/X

- Continued observing program for the alignment of ICRF3 and Gaia
- R1-2020: every 2nd R1-session with 14+ station network to improve EOP determination (i.e. mimic CONT performance)
- Journal of Geodesy special issue on CONT17 in progress, 16 papers submitted

VGOS

- IVS VGOS test sessions in 2019 with up to 8–9 stations
 - EU: Ws (Wettzell, DE) – Yb (Yebes, ES) – Oe (Onsala, SE), Ow (Onsala, SE),
 - US: Gs (Goddard) – Wf (Westford) – K2 (Kokee) – Mg (MacDonald)
 - JP: Is (Ishioka)
 - Every 2 weeks, 24 h long sessions, correlated at Haystack
 - VG databases available at data centers since January 2019
- EU VGOS sessions with 4 stations
 - Ws (Wettzell, DE) – Yb (Yebes, ES) – Oe (Onsala, SE), Ow (Onsala, SE)
 - Every 2nd week, 4–6 h long sessions, correlated at Bonn
 - Focus: source structure, polarization
- VGOS intensive tests performed: K2 (Kokee) – Ws (Wettzell)
 - Correlation by several correlators for quality control

- To be operational in 2020
- In December 2019 VGOS intensive series Oe (Onsala) – Is (Ish-ioka) will start
- "VGOS operational series" (VO) will run bi-weekly with 8+ stations
- EU-VGOS series continue as well
- VGOS mixed-mode sessions planned for 2020

VGOS development

- Upcoming VGOS partner stations
- US: MacDonald (Texas, USA), quasi operational
- AU: Hobart, Katherine, Yarragadee, broadband upgrade
- EU: Ny-Ålesund twins (Svalbard, Norway), waiting for broadband receivers; Metsähovi (Finland), waiting for broadband receiver; Santa Maria (Azores), broadband upgrade
- CN: Shanghai siblings, first fringes
- RU: Zelenchukskaya, Badary, Svetloe(all Russia), need broadband upgrade
- Thailand
- Tahiti
- 2 additional Chinese "telescopes abroad"

IVS preparations for ITRF2020

- Using ICRF3, including galactic aberration
- Using new pole tide model
- Using new high-frequency EOP model
- Important topics:
 - Local-ties at VGOS-legacy co-location stations
 - * Several short-baseline interferometry sessions, e.g. Kokee, Wettzell, Onsala, to tie legacy and VGOS stations
 - Thermal and gravitational deformation of telescopes

Roadmap for next ITRF generation (ITRF2020)

Zuheir Altamimi reminded about the roadmap for the generation of ITRF2020:

- The time line was agreed, there should be no delays.
- Test solutions are highly welcome.

- Seasonal signals will be in the center-of-mass frame of SLR.

Discussion

- The IERS CB will establish an FTP area to submit solutions.
- Scale issues: The Galileo-based scale by IGS need to be evaluated.

New Action Item #69.08 Establish an FTP area to submit solutions for ITRF2020.

GGOS/IERS Unified Analysis Workshop 2019

69 participants attended this workshop.

Sessions

- Opening Session: Welcome
- DORIS Systematic Errors and Biases
- GNSS Systematic Errors and Biases
- VLBI Systematic Errors and Biases
- SLR Systematic Errors and Biases
- Gravity Models for Precise Orbit Determination
- Global Space Geodesy Infrastructure
- Standards, Conventions, and Formats
- Digital Object Identifiers for Geodetic Data Sets
- Global Unified Height System
- Reference Systems and Frames
- Site Survey and Co-location
- Closing Session: Summary of sessions and discussion of recommendations

DORIS Systematic Errors & Biases

- Recommendations
 - South Atlantic Anomaly
 - * Determine optimal strategy for reprocessing by holding test campaigns
 - During 2007 for Jason-1 and SPOT-5
 - During 2017–2018 for Jason-2 and Jason-3
- Scale
 - Use corrected values of antenna phase center offset (PCO)
 - Downweight low-elevation data

- Non-conservative force modeling
 - Mitigate 117-day signal in DORIS data and products by
 - * Using quaternions for Jason satellites
 - * Adjusting 1Cr/arc
 - Use more recent albedo and infrared models
- Notes: Imperfect thermosphere models remain a limiting factor in determining orbits of DORIS satellites at those altitudes

GNSS Systematic Errors & Biases

- Recommendations
 - Troposphere products
 - Provide results, especially from reprocessing, because of their importance

VLBI Systematic Errors & Biases

- Recommendations
 - Gravitational deformation of antennas: All VLBI antennas should have surveys done in order to determine the effect of gravitational deformation

Global Space Geodesy Infrastructure

- Recommendations
 - Inter-Service communication
 - * Establish regular communication channels among the different techniques, to ensure that issues impacting each other are discussed in a timely manner
 - Sustaining space geodesy enterprise
 - * Great opportunity to participate in analysis and interpretation of geodetic data
 - * Encourage students and young scientists to become involved

Standards, Conventions, & Formats

- Recommendations
 - Inconsistency of tide systems
 - * IAG resolve inconsistency concerning treatment of permanent tide
 - Inconsistency of numerical standards
 - * Clearly document the numerical standards used for all geodetic products
 - * Develop a new Geodetic Reference System (GRS20XX), based on best estimates of ellipsoidal parameters
 - Simplifying IERS Conventions

- * Encourage contributors to follow guiding principles for simplifying Conventions
- Nutation models
 - * Update amplitudes of leading terms of IAU2000
 - * Test shortened series for certain operational purposes
 - * Correct existing inconsistencies in precession-nutation models
 - * Test available FCN models. Consider whether IERS should recommend an FCN model
 - * Prioritize tasks of IAU/IAG JWG on Improving Earth Rotation Theories and Models, in order to obtain results in two years
- High-frequency EOP models
 - * Adopt Desai & Sibois / Egbert TPX08 model

Reference Systems and Frames

- Recommendations
 - IGS
 - * Urge IGS to preserve alignment of products to ITRF2014 until ITRF2020 is published
 - IVS
 - * Urge IVS to provide atmospheric loading corrections to right-hand side of normal equations in SINEX files
 - ILRS
 - * Urge ILRS to provide range bias estimates with covariance in weekly SINEX files
 - IDS
 - * Encourage IDS to mitigate DORIS-specific systematic errors that impact frame parameters (origin, scale)
 - GGFC
 - * Invite GGFC to provide a unified loading model that includes all contributions (atmosphere, hydrology, and ocean) for all ITRF2020 sites

Site Survey and Co-location

- Recommendations
 - IERS Working Group
 - * Continue IERS Working Group on Site Survey and Co-location
 - * Set objectives
 - * Clarify reporting expectations
 - * Engage IAG Services in activities of the Working Group
 - * Hold annual meetings

- * Disseminate knowledge of antenna deformation measurements
- * Issue guidelines
- * Liaise with the tide gauge community
- * Distribute publications related to the activities of the Working Group
- Deflection of vertical
 - * Understand deflection-of-vertical contribution to local tie measurements
- Prioritize site surveys
 - * Survey sites that have never been done before re-surveying those that have

(For a more detailed report, see Section 4 of the IERS Annual Report 2019.)

GGOS report Changes to GGOS Structure

- Chair
 - Basara Miyahara, GSI, Japan
 - * Appointed by IAG Executive Committee following search conducted by GGOS
 - Also known as GGOS President (adopted by IAG EC)
 - * The President of GGOS is the Chair of the GGOS Coordinating Board
 - * The President of GGOS is also known as the Chair of GGOS
- Vice Chair
 - Laura Sánchez, DGFI-TUM, Germany
 - * Selected by GGOS Chair (Basara Miyahara)
 - * Approved by GGOS Coordinating Board
- Consortium
 - Representatives of Services, Commissions, ICCs, Affiliates
 - 36 members in total
 - BIPM no longer represented since it is no longer considered to be an IAG Service
- Coordinating Board
 - Consortium elects
 - * 4 Service representatives, 2 Commission and ICC representatives, 1–2 Affiliate representative(s)
 - * Representatives elected to CB must be members of the Consortium

- * Except for Affiliate representative(s) which must be member(s) of Affiliate(s)
- Coordinating Board elects
 - * 3 members-at-large to increase diversity (geographic, gender, discipline)
- Executive Committee
 - Chair appoints
 - * 2 voting members of CB to be CB representatives to Executive Committee
 - * 1 represents the Services
 - * 1 represents the Commissions
 - Subject to approval by Coordinating Board
- Focus Area on Geohazards
 - Application of geodetic techniques to improve tsunami warning
 - John LaBrecque intends to resign as lead, search for new lead ongoing
- Focus Area on Sea Level
 - Application of geodetic techniques to mitigate or adapt to sea level change hazards
 - Tilo Schöne resigned as lead effective 01 October 2018, search for new lead and/or topic of Focus Area not successful
 - Has been dissolved
- Representatives to other organizations
 - International Earth Rotation and Reference Systems Service
 - * Richard Gross (JPL, USA)
 - IAG Inter-Commission Committee on Theory
 - * Michael Schmidt (DGFI-TUM, Germany)
 - IAG Inter-Commission Committee on Climate Research
 - * Mayra Oyola (JPL, USA)
 - IAG Inter-Commission Committee on Marine Geodesy
 - * Marie Francoise Lalancette-Lequentree (SHOM, Brest, France)
 - * Yusuke Yokota (University of Tokyo, Japan)
 - Committee on Earth Observation Satellites (CEOS)
 - * GGOS is an Associate Member of CEOS
 - * Allison Craddock and Richard Gross are the GGOS representatives to CEOS
 - All representatives approved by GGOS Coordinating Board
 - Group on Earth Observations (GEO)

- * IAG is a Participating Organization in GEO and a member of its Program Board
 - * Allison Craddock and Richard Gross are the IAG representatives to GEO
- Bureau of Products and Standards
 - Working Group on ITRS Standards for ISO TC 211
 - * Will not continue because work has been completed
 - Working Group on the Establishment of the GGRF
 - * Will not continue because work has been completed
 - Working Group “Towards a consistent set of parameters for the definition of a new GRS”
 - * Will be established with Urs Marti as Chair
- Coordinating Office
 - Director
 - * Martin Sehnal replaces Helmut Titz as Director
 - Working Group on DOIs for Geodetic Data Sets
 - * Newly formed
 - * Chaired by Kirsten Elger, GFZ, Germany
 - * From one to four representatives from GGOS, IERS, IGS, IVS, IDS, ILRS, IGFS and four other representatives
 - * 22 members in total
 - * Meeting at AGU: Monday, December 9, 2019

Past Meetings

- Unified Analysis Workshop
 - Jointly organized by GGOS and IERS; 2–4 October 2019; IPGP, Paris, France
- GGOS Days 2019
 - Held in conjunction with SIRGAS Symposium; 12–14 November 2019; IBGE, Rio de Janeiro, Brazil
- American Geophysical Union
 - GGOS session merged with real-time GNSS session
 - * Title: Real-Time High-Accuracy GNSS Positioning: Error Modeling, Applications, and Incubation of New Initiatives
 - * Orals: G13A; Monday, December 9, 2019
 - * Posters: G23B; Tuesday, December 10, 2019

Future Meetings

- European Geosciences Union, 2020
 - GGOS session: The Global Geodetic Observing System: Improving Infrastructure for Future Science
- GGOS Days 2020: 5–9 October 2020; TU Munich (tentative)

IERS Conventions ***Status report on the update process***

The report was presented by Nick Stamatakos.

Review of Changes to IERS Conventions Centre

- A letter sent to the IERS and signed by the Commanding Officer of USNO indicated that the servers `maia.usno.navy.mil` was undergoing modernization and would be offline beginning 24 October 2019.
 - The Conventions web site and ftp sites were hosted at the maia server.
 - Expected completion of work and return to servers is estimated 30 April 2020.
- The site <http://iers-conventions.obspm.fr> remains available for all users to use for conventions related issues.
- USNO is looking at options / suggestions for where to also host the Conventions in the interim between the shutoff date and the new date.
 - Version tar-balls may be soon available at <http://www.usno.navy.mil>. However, it is not feasible to host the entire conventions at this site.

Status of IERS Conventions Centre re-write staff and Chapter numbering

- Michael Efroimsky has generously volunteered to be the Editor-in-Chief of Chapter 10. If there are no objections, then the co-chairs will officially make him the Editor in Chief.
- We need more volunteers for some positions.
- There is a change in the IERS Conventions 2010 and IERS Conventions 2022 Chapter numbering.

IERS Conventions Template and Conventions Rewrite Guidelines

- Proposed Conventions template finished by Maria Davis of IERS Conventions staff.
 - Template is under review but we hope to have an official template for users very soon.
 - A copy of the proposed template is available upon request.
- Proposed Rewrite Guide and Rewrite Example has been approved by IERS Conventions co-chairs on 4 December 2019.
 - Will be emailed to all participants of IERS Conventions rewrite staff in mid December.
 - The rewrite guide and Rewrite Example can be provided upon request to the IERS DB.

- Rewrite Example is a simplified, slimmed down, easier-to-follow version of the latest Chapter 5 from IERS Conventions 2010; it is *not* intended to be a rewrite of Chapter 5 for the IERS Conventions 2022.
- The number of pages in the Rewrite example was about $\frac{1}{2}$ of what it is today.

IERS Conventions Centre Configuration Management Training / Discussions

- Conventions Rewrite Guidelines communication will be via SLACK or other arrangements.
 - Planned training in Oct 2019 was postponed due to lack of travel funding.
 - GitLab training / discussion is being rescheduled to do via netmeeting or internet meeting.
- Conventions rewrite guidelines and communication will be via SLACK instant messaging, phone calls, or netmeetings.
 - If there are questions or concerns with the guidelines, we will certainly discuss issues and concerns with all involved.
- IERS Chapter 5 example re-write details were presented at UAW in Oct 2019.

New Action Items

- #69.09 Provide tar-ball, put this also to IERS website
- #69.10 Provide LaTeX template for TN
- #69.11 Store LaTeX source code of new conventions at IERS CB

EOP Products

Report from Earth Orientation Centre

This report was not presented.

Report from IERS Rapid Service / Prediction Centre

This report was presented by Christine Hackman.

24 October 2019 changes to IERS RS/PC product distribution

- The ftp servers/websites on which USNO distributes IERS products (RS/PC, Conventions) were shut down per US Navy direction 24 Oct 2019
- We advised users (per the above direction) that the estimated return-to-service date was 30 April 2020
- Impacted users are/were advised to fill out a requirements form at <https://www.usno.navy.mil>, or to contact USNO PAO Mr. Geoff Chester at Geoff.chester@navy.mil; +1 (202) 762 1438
- Nick Stamatakis + team have been hard at work developing new distribution channels and handling user requests/comments

- IERS RS/PC products currently available at:
 - CDDIS: daily EOPs, Bulletin A (<ftp://cddis.gsfc.nasa.gov/pub/products/iers>)
 - IERS: daily EOPs, Bulletin A (<ftp://ftp.iers.org/products/eop/rapid/>)
 - Possible: Navy open website
- Future:
 - Official return to stock date: 30 April 2020
 - Advise building margin into that date when planning
 - We will advise when completion date/URLs/etc. finalized
 - Huge thank you to the IERS RS/PC team, CDDIS and IERS CB for assistance in product distribution

IERS RS/PC staff presentations, activities

- Presentations since DB Meeting # 67
- EGU GA 2019 Poster Session G3.1 (Thu 11 Apr 2019): N. Stamatakos, D. McCarthy, D. Salstein, Investigating Possible Combinations of Atmospheric, Ocean, and other Geophysical Angular Momentum Data to Improve Operational Earth Orientation Information
- 24th EVGA Meeting (17–19 Mar 2019; Gran Canaria, ES) oral presentation O303: M. Davis, M.S. Carter, C. Dieck, The IERS Rapid Service / Prediction Center UT1–UTC Combined Solution: Present and Future Contributions
- Unified Analysis Workshop (2–4 Oct 2019; Paris, FR): Stamatakos to represent IERS, deliver RS/PC presentation
- Journées 2019 (7–9 Oct 2019; Paris, FR): Stamatakos, Davis to attend, conduct IERS Conventions workshop after European VLBI Group for Geodesy and Astrometry

The IERS RS/PC team (besides Christine Hackman):

- Mr. Nick Stamatakos, RS/PC Production Director & Lead Project Scientist
- Ms. Merri Sue Carter
- Mr. Nathan Shumate
- Ms. Maria Davis
- Their hard work is gratefully acknowledged.

- New Action Items**
- #69.12 Remove selection of Bulletin A from subscription form at IERS website
 - #69.13 Reconsider the need of email version of Bulletin A

**ICRS/ICRF report
Status of ICRF-3 and next
steps for the IERS**

The report was presented by Bryan Dorland.

ICRF3 Status/Update

- ICRF3 adopted by IAU on 1 January 2019
- Key accomplishments:
 - Multi-wavelength (S/X, K, X/Ka)
 - Majority of sources much more accurate (3x improvement)
 - Approximately 30% more sources
 - Available now via IERS ICRS Centre website
- Plans:
 - ICRF3 is now in “maintenance” phase
 - * Focus is on improving current positions, source quality
 - * Looking at positions shifts between frequencies
 - ICRF3 team is working with Gaia team towards defining an integrated radio/optical reference frame
 - * Likely to be proposed as a working group to IAU
 - USNO, Paris Observatory are collaborating on AGN monitoring program (FRAMEX) for reference frame sources

S/X-band Status

- S/X ICRF3 maintenance work being led by NASA/GSFC + USNO (David Gordon (GSFC), Alan Fey (USNO), Lucas Hunt (USNO))
- USNO VLBA time allocation used for X/S observations of under-observed and weak sources in 3 proposals
 - Made to improve ICRF3 and for ICRF3 maintenance
 - Most target sources too weak to be observed in regular IVS sessions
- Observations:
 - 20 UF001 sessions – 2017
 - 24 UG002 sessions – 2018
 - 24 UG003 sessions – 2019–2020
 - * 14 analyzed to date

K-band Status

- K-band work being led by HartRAO & JPL with USNO VLBA time allocation

- VLBA dual polarization (RCP/LCP) at 4 Gbps operational
- Demonstrated 4 Gbps imaging
- Improving ion calibration from GNSS data
- HartRAO-Hobart observations continue
- HartRAO improving pointing
- Preparing for Italy-South Africa baselines to improve Declinations
- Work in progress to add 50-meter LMT to VLBA sessions
- See DeWitt et al., K-band Roadmap, Journées 2019,
https://syrtte.obspm.fr/astro/journees2019/journees__pdf/SessionIII_1/DE%20WITT_Aletha.pdf

X/Ka-band Status

- X/Ka work being led by JPL
- Observations continue with NASA's DSN at 2Gbps
- ESA's Malargüe Argentina station upgraded:
 - 256 Mbps to 896 Mbps single band to dual band X/Ka
 - GNSS ion calibrations no longer needed for this station
- JAXA is close to completing its 54-meter antenna at Misasa (near Usuda).
- First Ka fringes with JAXA expected 1st half 2020.
- Baseline from Japan to Australia expected to improve Declinations.
- Jacobs et al., Journées, 2019 give more details:
https://syrtte.obspm.fr/astro/journees2019/journees__pdf/SessionIII_1/JACOBS_Christopher.pdf

Optical Reference Frame Status

- Current visible standard: Gaia DR2 (2018)
 - Approx. 1.6 Gsources, mG = ~4.5–20.7
 - 1 mas accuracy for bright to mid-range sources
 - Tied directly to AGN (mid-IR AGN)
 - Next full release: DR3, 2nd half of 2021
- USNO producing bright star catalog m_v5 to supplement Gaia
 - Combination of URAT (SH) + UBAD (NH)
 - April 2020 timeframe
- Future: LSST to produce optical astrometry to mg~27

- 2020-2030 timeframe
- Southern ~60% of sky only
- NIR (J, H, and K bands)
 - VISTA survey (southern hemisphere)
 - UKIRT survey (northern hemisphere)
 - * Expected completion ~2021–22

ICRF-related Research Work

- USNO and Paris Observatory are collaborating on the Fundamental Reference Frame AGN Monitoring Experiment (FRAMEx)
 - Utilize observing assets around the world to observe and monitor reference frame objects to best characterize astrometry and photometry, identify excellent reference frame sources, and better constrain underlying astrophysics
 - Initial observing is utilizing VLBA, USNO telescopes, SWIFT, VLA

Other items

- October 2019, Paris Observatory hosted the 2019 Journées meeting
 - 118 participants from around the world; discussions covered TRF, CRF and EOPs
 - Next meeting will be in St. Petersburg in 2020 and will focus on time
- USNO websites taken offline for major upgrades; expected back online in mid-2020
 - IVS Analysis Center, IVS Source Structure Center, IERS ICRS Center, IAU Double Star Center
- Paris Observatory continues to fully support IERS ICRS needs
- Paris Observatory, USNO and Paris Institute for Astrophysics is hosting a workshop on AGN/Reference Frames in June 2020 at Paris Observatory

Other reports ***IERS WG on Site Survey and*** ***Co-location and relationship*** ***with GGOS BNO***

The report was presented by Mike Pearlman.

Mike Pearlman gave an overview of the work of the GGOS Bureau of Networks and Observations (BNO) and its relations to the IERS Working Group on Site Survey and Co-location. This WG provides a large body of valuable work that is a significant contribution to GGOS.

***Proposed change in IERS
World Data System
membership type***

The report was presented by Christine Hackman.

- C. Hackman became IERS ISC World Data System (WDS) representative Fall 2018. (Formerly B. Richter)
- IERS WDS membership had expired
- Renewal as Regular Member required complex IT certification procedure, entry into which cost 1000 euro, and which needed to be renewed every three years
- Becoming Network Member skips above complex procedure, is free. IVS, IGS are network members.
- Per November 2019 DB polling C. Hackman will apply for Network Membership.
- If you have significant WDS involvement, please let C. Hackman know.

Annual Report 2018

The AR 2017 was printed and distributed in spring. For the AR 2018, 16 contributions have been received and edited, the last 4 contributions are in preparation.

New Action Items

#69.14 Finalize IERS AR 2018.

Next DB meeting (#70)

The next DB meeting (half-day meeting) will take place on Sunday, May 3, 2020, before the EGU in Vienna.

New Action Items

#69.15 Prepare IERS DB meeting #70.

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. 68, April 7, 2019, at Technical University of Vienna, Austria, and No. 69, December 8, 2019, at Park Central Hotel, Washington, DC, 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: ILRS introductory and refresher course on SLR and LLR, European Geosciences Union General Assembly 2019 (including meetings of the ILRS Analysis Standing Committee, the GGOS Coordinating Board, the GGOS Bureau of Networks and Observations, and the GGOS Standing Committee PLATO), 24th Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA) and 20th IVS Analysis Workshop, 27th IUGG General Assembly, Implementation of the GGRF in Latin America, GGOS/IERS Unified Analysis Workshop, SIRGAS Workshop 2019 in Satellite Laser Ranging, and GGOS Days 2019.

IERS components maintain individually about ten 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 2019 the web site was continually updated, several new pages and documents were added. An extended list of meetings related to the work of the IERS was maintained and updated frequently. The CB maintains also the web pages of the IERS working groups. In an internal area, accessible for DB members and IERS Associate Members, all presentations given at IERS DB meetings since 2000 are available, and further documents were added.

The IERS Annual Report 2017 was printed and distributed. The CB edited most parts of the IERS Annual Report 2018 and of the IERS Technical Note No. 40 (Description and evaluation of DTRF2014, JTRF2014 and ITRF2014). Along with the reports of the IERS components, provided by them, the annual reports contain general information on the IERS assembled by the CB. The CB compiled also summaries of DB meetings and its own report. The $\text{\LaTeX}$ template for annual reports was further improved.

A report of IERS activities for the period 2015–2019 was submitted to IAG in May 2019.

During the year 2019, 22 IERS Messages (Nos. 368–389) were edited and distributed. They include news from the IERS and of general type as well as announcements of conferences.

Address and subscription information have regularly been updated in the IERS user database. There were about 2800 users in 2019 with valid addresses who subscribed to IERS publications for e-mail and regular mail distribution.

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

The Director of the CB, Daniela Thaller, chairs the IERS Working Group on SINEX Format and is ex officio member of the other IERS WGs. She also leads, together with Benjamin Männel of GFZ, the GGOS Standing Committee PLATO (Performance Simulations and Architectural Trade-Offs), which is also a Joint Working Group with IAG Sub-Commission 1.1. She represents the IERS in the ILRS Governing Board and represents the IERS within the GGOS WG on implementing DOIs for Data and Products (established in 2019). 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.

International Earth Rotation and Reference Systems Service

Organization Data / Products / Tools Publications Science background News / Meetings Links

Earth orientation data
ICRF
ICRS
ITRF
ITRS
Geophysical fluids data
Conventions
Data analysis tools
IERS Plot Tool
EOP of today
Time scales
EOP reader
Date Converter

IERS > Data / Products / Tools > Data analysis tools > Date Converter

Date Converter

To convert a date choose the input format and enter your data. After submitting the script generates the other formats.

Date type	Date
☐ Day of Year (DOY; YYYY)	317; 2020
☒ Date (YYYY-MM-DD)	2020-11-12
☐ Modified Julian Date (MJD)	59165
☐ GPS Week (Week; DOW)	2131; 4

Convert Date

Fig. 1: User interface of the Date Converter tool, see also <https://www.iers.org/IERS/dateconverter>

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 2019 further developments of the IERS DIS concentrated on the enhancement of the data management system and of the interactive tools to visualize and analyze IERS products. Especially security features were updated to meet current standards.

An improved monitoring system was established for the data management system to ensure a timely and error-free provision of the IERS products on the webpages and ftp server.

A new feature has been implemented in the data management system, which allows the direct upload of USNO earth rotation data to the servers of the of the IERS Central Bureau.

Further improvements of the IERS DIS included the development of a date converter tool (see Fig. 1) and the availability of csv formatted files on the ftp server.

Staff in 2019

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

Presentations

Robert Heinkelmann, Brian Luzum, Daniela Thaller, Wolfgang R. Dick: The International Earth Rotation and Reference Systems Service. Invited paper presented at International workshop for the implementation of the Global Geodetic Reference Frame (GGRF) in Latin America, Buenos Aires, Argentina, Sep. 18, 2019.

Daniela Thaller, Wolfgang R. Dick, Brian Luzum, Robert Heinkelmann: Activities of the International Earth Rotation and Reference Systems Service. Invited paper presented at the joint SIRGAS / GGOS symposia, Rio de Janeiro, Brasil, November 12, 2019

Wolfgang R. Dick, Daniela Thaller, Sonja Geist

3.3 Analysis Coordinator

Introduction

This is my first annual report as IERS Analysis Coordinator and I would like to express my thanks to the former Analysis Coordinator Thomas Herring from MIT EAPS for excellently serving the IERS.

In this annual report, I will address an assessment of the current consistency of IERS EOP products. The transformation between International Celestial Reference System ICRS (Arias et al., 1995) and International Terrestrial Reference System ITRS (IUGG Resolution 2, 2007¹) is important for many scientific and societal applications. It consists of two parts. The more prominent part is referred to as Earth Orientation based on the Earth Orientation Parameters EOP that contribute to the arguments of 3d rotation matrices. The other part contains the geodesic rotations due to the different dynamics of Solar System Barycenter SSB and Geocenter expressed through the Barycentric Celestial Reference System BCRS to Geocentric Celestial Reference System GCRS transformation (IAU Resolution B1.3, 2000²) in a space-time context. If the latter is properly considered, the EOP of Very Long Baseline Interferometry VLBI and of satellite-based space geodetic techniques, such as Global Navigation Satellite Systems GNSS, Satellite Laser Ranging SLR and Doppler Orbitography and Radio Positioning Integrated by Satellite DORIS, coincide. The rotational effects that arise from the BCRS → GCRS transformation are known as geodesic precession and nutation and are considered by the current precession and nutation models of IAU. Therefore, EOP from various space geodetic techniques should be unbiased and thus can be compared and combined. The EOP are a set of five parameters (dX , dY , $ERA \sim UT1$, x_p , y_p) that express the orientational difference of co-located CRS and TRS in terms of spatial rotations. While polar motion PM and ERA are absolute quantities, the celestial pole offsets dX , dY are corrections to the celestial pole coordinates (X , Y) obtained from the IAU precession-nutation models.

The theoretical implications are clear, but the practical realization, i.e. when systems are realized through frames, adds more complexity. The realization of ICRS is currently ICRF2 (IAU Res. B3, 2009³; Fey et al., 2015) and the realization of ITRS is ITRF2014 (Altamimi et al., 2016). Both frames, ICRF2 and ITRF2014, can be directly accessed by VLBI and hence, VLBI is a suitable tool to assess the consistency of the two frames directly and without assumptions. The assessment, however, is of course only as precise as VLBI analyses can deliver.

The axes directions of ICRF2 (at J2000.0 = 2000-01-01 12:00 TT, e_1 is pointing to the vernal equinox, e_3 points to the celestial pole and

¹<http://www.iugg.org/resolutions/perugia07.pdf>

²https://www.iau.org/static/resolutions/IAU2000_French.pdf

³https://www.iau.org/static/resolutions/IAU2009_English.pdf

$e_2 = e_3 \times e_1$) are obtained applying a series of processes. Within the corresponding ICRF2 Working Group the VLBI solution gsf008a was selected. This solution, gsf008a, was obtained with no net rotation NNR condition on ICRF1 involving a number of sources in common with ICRF1 (Ma et al., 1998). Thereafter, the resulting CRF was rotated onto ICRF-Ext.2 (Fey et al., 2004) using 138 radio sources in common with gsf008a-CRF. The result of which became ICRF2 by decision of the IAU General Assembly.

The axes directions of ITRF2014 (at 2010.0, e_1 points to the intersection of the terrestrial equator and the prime meridian of zero longitude, e_3 coincides with the mean pole of the Earth rotation axis and $e_2 = e_3 \times e_1$) were established within a multi-technique combination of data from the space geodetic techniques VLBI, GNSS, SLR and DORIS mentioned before. The orientation was formed by applying NNR on positions (at 2010.0) and velocities of 125 predominantly GNSS sites. In the combination process of the site coordinates, PM offsets were combined across all four techniques, whereas PM rates just involved the two techniques GNSS and VLBI. UT1 and LOD were adjusted as well but from VLBI data only and CPO were not adjusted but fixed to the values that were provided by the intra-technique combined VLBI solution, which also fixed the positions of radio sources to the ICRF2 coordinates.

Comparison of EOP when fixing or adjusting radio source coordinates

In this small study I address the effects of fixing radio source coordinates to ICRF2 (the approach taken for ITRF2014 computation) vs. taking a priori values from ICRF2 plus estimating adjustments to radio source coordinates (common practice of VLBI analyses).

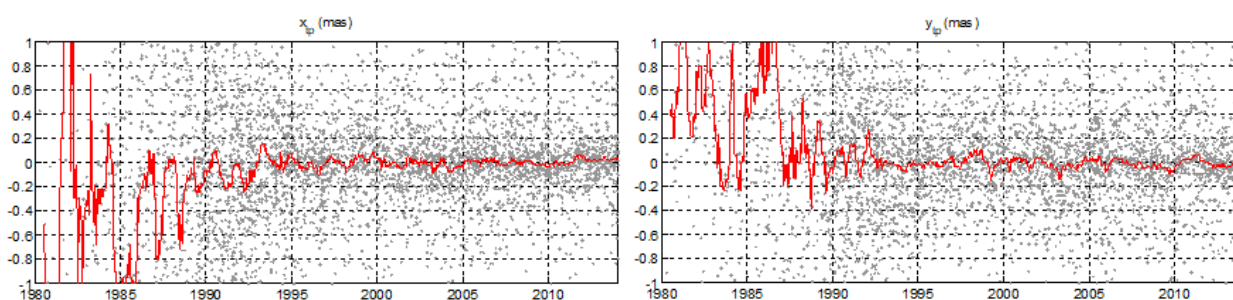


Fig. 1: PM differences of two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated. The grey dots are the session-wise results and the red line shows a moving median.

The values reported in Table 1 are obtained ignoring the data points before 1993.0. About at this time (1993.0) the VLBI technology and scheduling significantly advanced leading to more stable results than before. The shifts and drifts are not exceeding the current quality targets of geodetic VLBI for EOP, which are an accuracy of $33 \mu\text{as}$ and stability

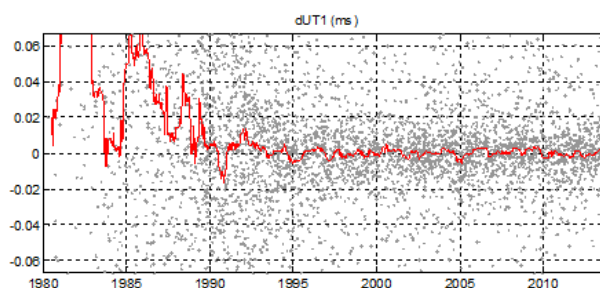


Fig. 2: $dUT1$ differences of two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated.

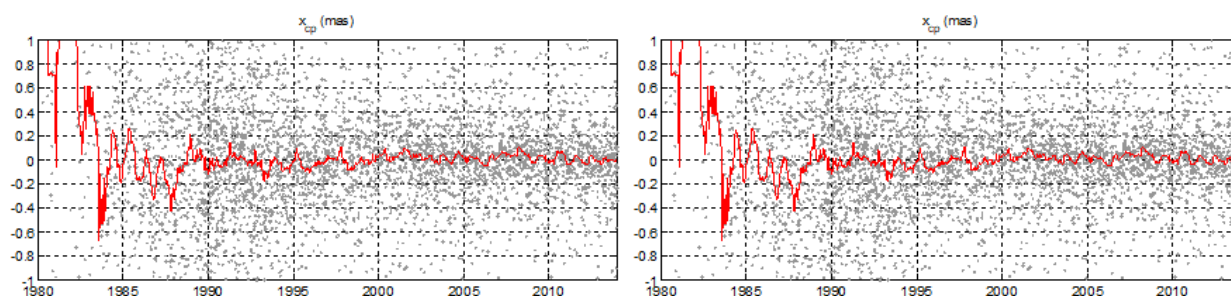


Fig. 3: CPO differences of two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated.

of $3.3 \mu\text{as} \cdot \text{y}^{-1}$. I do not generally recommend to ignore VLBI data prior to 1993.0. With appropriate formal errors, the VLBI data prior to 1993.0 do provide important information about Earth rotation, radio source and point positions during the earlier years before the availability of the GNSS and DORIS techniques. I only discard the data points for the computation of shift and drift, which otherwise would be affected considerably, in particular as these data points are at the edge of the data set.

Table 1: Shift and drift between two VLBI solutions, one with radio source coordinates fixed on ICRF2 and one with a priori values from ICRF2 and radio source coordinates estimated. $dUT1$ is given in μas for better comparison with the other EOP.

parameters	shift (μas)	drift ($\mu\text{as} \cdot \text{y}^{-1}$)	RMS (μas)
x_p	-5.8	1.0	282.6
y_p	-14.7	-0.2	307.0
$dUT1$	-5.8	2.2	269.3
dX	-3.7	0.3	281.3
dY	-8.3	0.0	254.4

Comparison of input data of ITRF2014 and ICRF2

The input data used for the calculation of ITRF2014 were

- session-wise VLBI data of IVS between 1980.0 and 2015.0,
- GNSS data of IGS with daily resolution between 1994.0 and 2015.1,
- SLR data of ILRS with weekly / fortnightly resolution between 1983.0 and 2015.0,
- DORIS data of IDS with weekly resolution between 1993.0 and 2015.0, and
- epochal local tie vectors at co-location sites.

All input data series are intra-technique combined data sets provided by the respective technique combination centers. The pre-combined solutions are based on a variety of VLBI data analysis software. For ICRF2 only session-wise VLBI data of IVS was used between August 1979 and April 2009. The VLBI data input was an individual solution, no combination and hence, a single VLBI data analysis software was used. Accordingly, ITRF2014 and ICRF2 differ very much in terms of input data. EOP that refer to ITRF2014 and ICRF2 link two reference frames to each other that are obtained using very different input data. From the point of view of the input data, ITRF2014 and ICRF2 cannot be consistent. The two frames can still be connected to each other through the set of transformations mentioned above. The procedure with the daily average EOP can still be applied, but these parameters have a limited scientific meaning only as the reference frames that are linked are inconsistent.

In order to assess the effect of the different input data, two VLBI solutions are compared, one solution fixes the station coordinates to ITRF2014 (the inter-technique combined frame), the other solution to VTRF2014 (Bachmann et al., 2016). VTRF2014 is a TRF determined by VLBI data only but from the same input data forwarded to the ITRF2014 combination. Accordingly, VTRF2014 and ITRF2014 most of all differ in terms of geodetic datum. The origin of VTRF2014 is taken over from ITRF because VLBI is insensitive to the exact position of the origin of the coordinate system. The network scale parameters of VTRF2014 and ITRF2014 differ, however, this does not affect rotations. The following figures show the EOP differences between these solutions. When ignoring data points before 1993.0, the differences in the x_p components are small and stable, whereas the y_p components show a linear trend. The linear drift determined by regression indicates this as well (Table. 2).

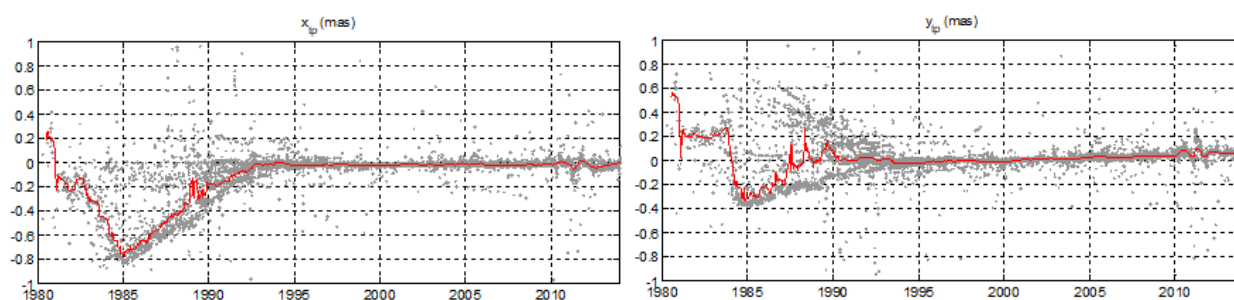


Fig. 4: PM differences of two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014.

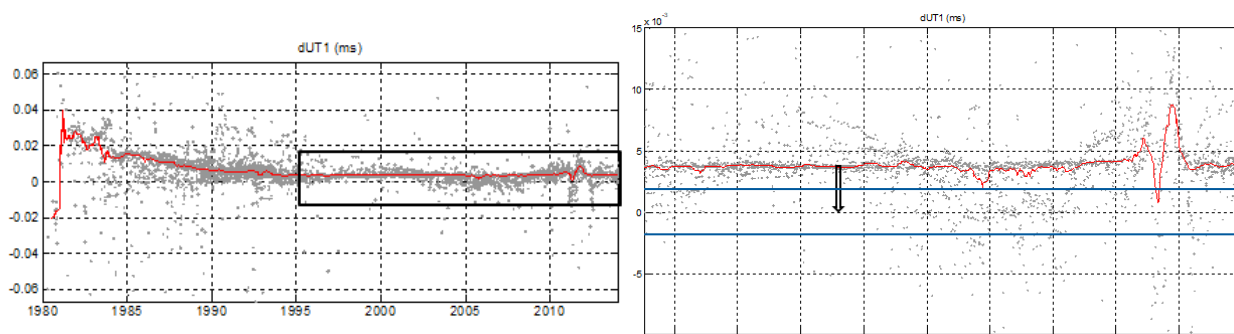


Fig. 5: $dUT1$ differences of two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014. The black rectangle in the left panel indicates the area that is displayed with a zoom factor on the right. The two blue horizontal lines inserted at $\pm 33 \mu as$ visualize the desired quality level w.r.t. a constant shift, which is clearly exceeded (black arrow). The wavelet-like difference around the year 2011 is caused by different modeling of co- and post-seismic effects of the Tōhoku megathrust quake on 2011-03-11. As long as station coordinates are estimated, the differences play no role.

Table 2: Shift and drift between two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014.

parameters	shift (μas)	drift ($\mu as \cdot y^{-1}$)	RMS (μas)
x_p	-16.6	-0.2	67.3
y_p	4.3	3.3	81.3
$dUT1$	57.3	-1.3	85.5
dX	-0.1	-0.0	11.7
dY	-0.2	0.0	8.3

The systematic effects on the CPO are insignificant (Table 2). The CPO RMS ($11.7 \mu as$, $8.3 \mu as$) are also very small at the level of the assumed axes stability of ICRF2 of $10 \mu as$. When applying different terrestrial reference frames, there is no significant effect on CPO, but the $dUT1$ can be distorted. The differences in phase of Earth rotation $dUT1$ are stable around $57.3 \mu as$ an equivalent of almost 2 mm on the Earth surface.

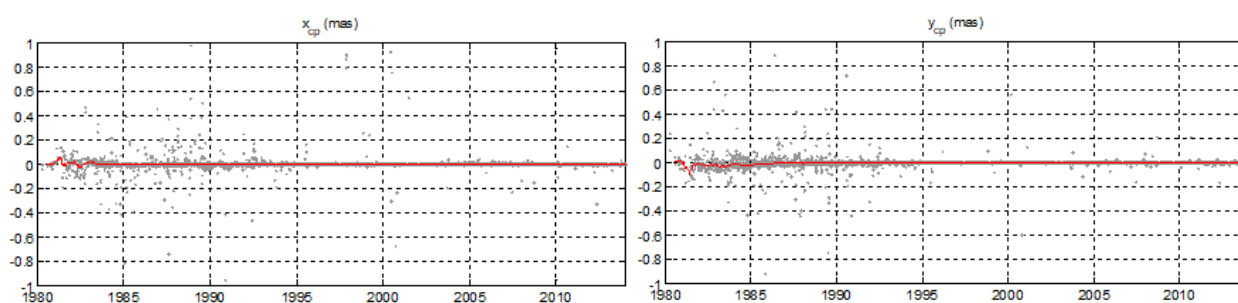


Fig. 6: CPO differences of two VLBI solutions, one with station coordinates fixed on ITRF2014 and one with station coordinates fixed on VTRF2014.

The realization of the reference frame orientation by VLBI (VTRF2014) and by multi-technique combination (for ITRF2014 the orientation is realized mainly through GNSS sites) results in a systematic shift of $dUT1$. The identified $dUT1$ offset could be a consequence of a small rotation of the VLBI subnetwork w.r.t. the NNR datum stations of ITRF. My recommendation to the IERS ITRS combination centers here would be to check whether the choice of common stations used for the no net rotation (NNR) condition for ITRF does also stop the rotation for each of the involved four space geodetic techniques subnetworks precisely and free of bias.

Comparison of analytical models of ITRF2014 and ICRF2

The models used for the data analysis leading to ITRF2014 and ICRF2, respectively, are compared in this chapter.

- IERS Conventions: basically, ITRF2014 applied IERS Conventions 2010 (Petit & Luzum, 2010), whereas ICRF2 adheres to IERS Conventions 2003 (McCarthy & Petit, 2004).
- Atmospheric pressure loading: for ITRF2014 tidal atmospheric loading was used; for ICRF2 tidal and non-tidal.
- Ocean tidal loading: the correction is applied for both reference frames but based on different tide models.
- Ocean pole tide loading: this model was introduced in IERS Conventions 2010. It is applied for ITRF2014 computation, but disregarded for ICRF2.
- Pole tide loading: the correction is applied for both reference frames but based on different mean pole models.
- Ephemerides: for ITRF2014 it is DE 421, whereas for ICRF2 it is DE 405.
- Cut off elevation angle: is not applied for ITRF2014, but for ICRF2 it is applied.

- Tidal variations of Earth rotation: the tidal corrections are applied for both reference frames; for ITRF2014, however, additional long-periodic ocean tidal effects on PM are considered.

Accordingly, ITRF2014 and ICRF2 substantially differ in terms of model application. The differences caused by these individual model choices should be assessed in order to quantify the level of inconsistency between ICRF2 and ITRF2014.

Summary, Conclusions & Outlook

I partly assessed the inconsistency of ICRF2 and ITRF2014 directly by comparing results of VLBI data analyses. The assessment is therefore limited to the quality of the VLBI data analysis. In the tests, CPO were affected insignificantly, whereas Earth Rotation Parameters, PM and $dUT1$, partly show considerable systematics. Prior to 1993.0, VLBI shows larger deviations of ERP likely because of the VLBI networks. The number of stations and radio sources included in earlier sessions is smaller (Fig. 7). The other very likely reason is that the ITRF orientation is mainly based on GNSS stations, what can cause small but significant shifts in comparison to an orientation based on VLBI only, in particular because GNSS data is only included after 1994.0. The offset we found between the VLBI-only and the primarily GNSS-based $dUT1$ should be investigated in more detail, in particular because $dUT1$ is effectively taken over from VLBI into the ITRF computation, what might create inconsistency between the ITRF and $dUT1$.

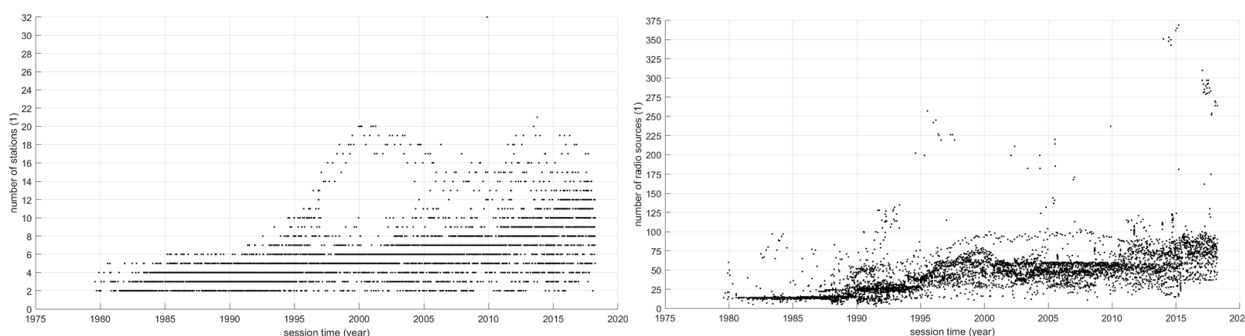


Fig. 7: Number of stations (left panel) and number of radio sources (right panel) that effectively took part in IVS 24h sessions.

Any inconsistencies of the terrestrial and celestial reference frames are inevitably applying to the EOP. The most consistent EOP can thus only be obtained together with TRF and CRF in a single solution based on the same input data and analytical models. Such a solution allows also the stochastic models of terrestrial and celestial parts to interact with each other, leading to consistent and comparable formal errors of station coordinates, radio source coordinates, and EOP.

The inconsistencies between terrestrial and celestial reference frames are assumed small, but they are unavoidable following the currently applied realization procedure. For a user, who is just interested in carrying out the ICRF2 to ITRF2014 transformation or vice versa, they do probably not matter at all. For scientific applications, however, the inconsistency of the two reference frames and the EOP is of very high relevance because it has the potential to affect scientific results and their interpretation. Among the scientific topics that are likely to be affected through reference frame inconsistencies are the interaction of terrestrial and celestial reference frames and EOP interpretation for geoscientific or climate studies. Utilizing inconsistent EOP series for validation purposes is highly questionable as well.

Concluding, more efforts need to be made for the quantification of the inconsistency of the current conventional reference frames and EOP. This will be the mission of the IERS Analysis Coordinator in the upcoming term.

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Robert Heinkelmann

3.4 Technique Centres

3.4.1 International DORIS Service (IDS)

Overview The International DORIS Service was established in 2003 with the primary mission to provide a service to support geodetic and geophysical research activities through DORIS data and derived products. The current report summarizes the different activities held in 2019 by the IDS components. More detailed information can be found in the IDS Report 2019–2020 available for download from the IDS website at <https://ids-doris.org/ids/reports-mails/governing-board.html#activity> (to be published in 2021).

DORIS system

Satellites During this report period (2019), the number of DORIS satellites has decreased to six (see Table 1).

Table 1: *DORIS data available at IDS Data Centers. As of December 2019*

Satellite	Start	End	Mission
SPOT-2	31-MAR-90 04-NOV-92	04-JUL-90 15-JUL-09	Remote sensing
TOPEX/Poseidon	25-SEP-92	01-NOV-04	Altimetry
SPOT-3	01-FEB-94	09-NOV-96	Remote sensing
SPOT-4	01-MAY-98	24-JUN-13	Remote sensing
SPOT-5	11-JUN-02	11-DEC-15	Remote sensing
Jason-1	15-JAN-02	21-JUN-13	Altimetry
ENVISAT	13-JUN-02	08-APR-12	Altimetry, Environment
Jason-2	12-JUL-08	10-OCT-19	Altimetry
Cryosat-2	30-MAY-10	-	Altimetry
HY-2A	1-OCT-11	-	Altimetry
SARAL	14-MAR-13	-	Altimetry
Jason-3	17-JUN-16	-	Altimetry
SENTINEL-3A	16-FEB-16	-	Altimetry
SENTINEL-3B	25-APR-18	-	Altimetry

After more than 11 years in orbit, the Ocean Surface Topography Mission (OSTM) on Jason-2 permanently ceased acquisition of scientific data on October 10, 2019.

Many future missions will guarantee a constellation of DORIS contributor satellites up to 2030 and beyond:

- HY2-C, HY-2D (CNSA/NSOAS) are two Chinese missions flying DORIS, the first launched in September 2020, the second planned for 2021.
- Jason-CS will ensure continuity from Jason-3. Jason-CSA / Sentinel-6A was launched in November 2020; Jason-CSB / Sentinel-6B is planned for 2025. The Jason-CS / Sentinel satellites are part of the Copernicus program and are the result of international cooperation between ESA, Eumetsat, the European Union, NOAA, CNES and NASA/JPL.
- Sentinel-3C and -3D (ESA/Copernicus) are under development and expected for 2024 and 2025.
- SWOT (Surface Water Ocean Topography), a joint project involving NASA, CNES, the Canadian Space Agency and the UK Space Agency, is planned for 2021.

Network The current DORIS network consists of 59 stations including 4 master beacons (Toulouse, Greenbelt, Hartebeesthoek, Kourou), 1 time beacon (Terre-Adelie) and 1 experimental beacon dedicated to IDS for scientific purposes (Wettzell). Mangilao (Guam Island, USA), initially dedicated to IDS, joined the permanent DORIS network in September 2019. (Figure 1)

2019 was a year marked by the start of the deployment of 4th generation DORIS beacon (B4G), a much-awaited development. Indeed, a new architecture built with up-to-date electronic technology and advanced components will allow reliable operation through 2030+ and the addition of a signal amplifier at the foot of the antenna will allow a larger distance between beacon and antenna (50m instead of only 15m) providing better options to satisfy the sky-clearance criterion for new or renovated DORIS sites.

The B4G deployment started from mid-2019 at St-John's, Canada. The deployment strategy consists in replacing gradually the aging equipment and renovating sites for which the relocation of the antenna will enhance the station performance. Four sites were equipped with B4G in 2019: Grasse, St-John's, Ponta-Delgada, and Saint Helena.

Furthermore, we continued deploying the new generation of ground antennae (Starec C type) for which standard uncertainty of the 2GHz phase center in the vertical direction was significantly reduced to im-

prove measurements accuracy. We achieved an antenna replacement of 30% of the network (18 sites) at the end of 2019.

Throughout the network development there has been a continuing effort to co-locate DORIS with other space geodetic techniques and with tide gauges. 48 DORIS stations out of 59 are co-located with at least one other IERS technique: GNSS, SLR, and/or VLBI (Figure 1). All tie vectors at co-located sites with DORIS are available in a maintained file “DORIS_ext_ties.txt” on IDS web and data centers.

In 2019 the following DORIS sites were visited:

- B4G testing and site survey at Grasse (France)
- Reconnaissance in Reykjavik and Höfn (Iceland)
- Renovation and site survey at St-John’s (Canada)
- B4G installing at Ponta-Delgada (Azores, Portugal)
- Re-installation at Santa-Cruz (Galapagos, Ecuador)
- B4G installing at Saint-Helena (South Atlantic, UK)

In 2020, the overall objectives are:

- Continuation of the deployment of the 4th generation beacon
- Renovation of the DORIS station at La Réunion (France)
- Restarting at Badary and Krasnoyarsk (Russia)
- Relocation of the Icelandic DORIS station in Höfn
- Antenna relocation at Malé (Maldives)
- Installation of new DORIS site at Changchun (China)
- Relocation of the DORIS station at Easter Island (Chile)
- Relocation of the DORIS Greek station

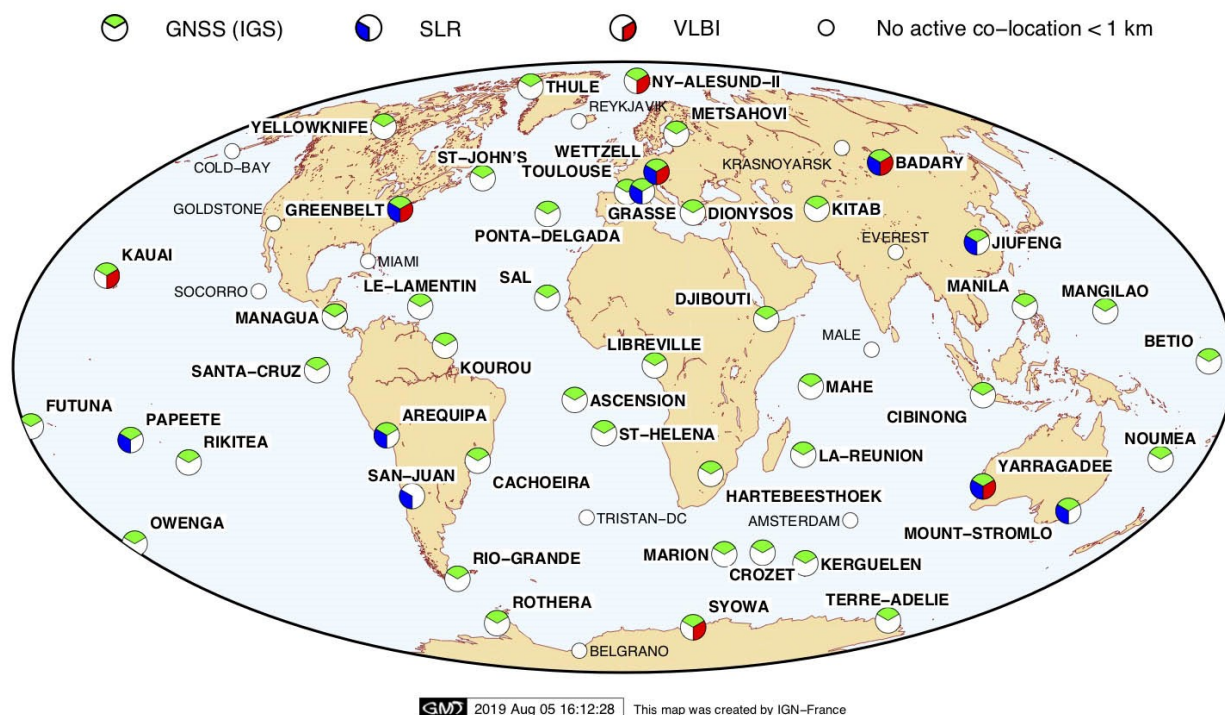


Fig. 1: The permanent DORIS network and co-location with other IERS techniques (as of August 2019).

IDS organization and activities

Governing Board

New members have joined the Governing Board (GB) to serve for the period 2019–2022:

- Hugues Capdeville (CLS, France) and Petr Štěpánek (Geodetic Observatory Pecný, Czech Republic) as the new tandem for the Analysis Coordination, elected by the IDS Associates;
- Claudio Abbondanza (NASA/JPL, USA) as a Member-at-Large, elected by the IDS Associates;
- Ernst Schrama (TU Delft, The Netherlands) appointed by IAG Executive Committee in July 2019 to serve as the new IAG representative.

The current list of members can be seen at the web page <https://ids-doris.org/ids/organization/governing-board.html>.

Meetings

In 2019, IDS organized two meetings of the Analysis Working Group, first on April 4 at DGFI-TUM in Munich (Germany), then at CNES in Paris (France) on September 30 and October 1. All the presentations from these meetings are made available by the Central Bureau on the IDS website at:

<https://ids-doris.org/ids/reports-mails/meeting-presentations/ids-awg-04-2019.html>

<https://ids-doris.org/ids/reports-mails/meeting-presentations/ids-awg-09-2019.html>

These meetings were also an opportunity for the Governing Board to meet.

Associated Analysis Centers

The application of the DGFI-TUM (Munich, Germany) to become an Associate Analysis Center was approved by the IDS Governing Board at its meeting on October 1, 2019. In addition to the six regular Analysis Centers, four Associate Analysis Centers now contribute to the IDS analysis activities.

IDS Strategic Plan

After the IDS Retreat held in June 2018, the IDS GB worked on the development of a strategic plan for the IDS. The main lines of the plan were presented to CNES and IGN in November 2019. In the coming years, IDS will focus on growing the community, extending the DORIS applications, and improving the technology, the infrastructure and the processing.

IDS at GGRF Workshop

Frank Lemoine (chair of the GB) and Laurent Soudarin (director of the Central Bureau) attended the International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America held in Buenos Aires, Argentina, from September 16 to 20, 2019. It was the opportunity to meet the friendly colleagues from the agencies hosting DORIS stations in this part of the world.

The presentations given by IDS during this workshop are available on the IDS website:

- Presentation of the DORIS system and the International DORIS Service

<https://ids-doris.org/documents/report/meetings/GGRFworkshop2019-DORISandIDS-Soudarin.pdf>

- The science contributions of DORIS and synergy with other space geodetic techniques

<https://ids-doris.org/documents/report/meetings/GGRFworkshop2019-ScienceContributionDORIS-Lemoine.pdf>

**Unified Analysis Workshop
(October 2–4, Paris)**

Several IDS/DORIS-related presentations were given for the Unified Analysis Workshop held at IPGP in Paris from October 2 to 4:

- Session "DORIS Systematic Errors and Biases":
 - “South Atlantic Anomaly compensation”
 - “DORIS scale”
 - “Non-conservative force modeling”
- Session “Global Space Geodesy Infrastructure”:
 - “The DORIS Ground Network, Current Status and Future Prospects”
- Session “Reference Systems and Frames”:
 - “Limiting Error Sources Affecting the Geocenter Motion & GM Estimation”
- Session “Site Survey and Co-location”:
 - “IGN Recent and Planned Local Site Survey Activities & Contribution to the EURAMET GeoMetre Project”

The presentations are available on GGOS website (<https://ggos.org/event/uaw-unified-analysis-workshop-2019/>).

**User Service
Data information service**

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

In 2019, the Central Bureau made an inventory of the archived data at CDDIS and IGN in order to ensure the completeness of the datasets required for the DORIS contribution to ITRF2020. It led to the delivery of missing files and the correction of nomenclature anomalies and archiving errors.

The Central Bureau also interfaced with the Combination Center for making available several products:

- DPOD2014 version 4 and new combined solution;
- time series for the webservice;
- new version of the DORIS SINEX master file that contains for each DORIS station geographic positions, station IDs, type and eccentricity of the antennas. See <ftp://ftp.ids-doris.org/pub/ids/stations/ids.snx>

Web and ftp sites Address: <https://ids-doris.org>

In 2019, an improvement has been made to the display tool of the main events that occurred on the DORIS space segment and ground segment (<https://ids-doris.org/doris-system/system-monitoring/table-of-all-events.html>). Sort filters have been added and it is now possible to export the displayed results in CSV format. A tutorial on how to use the tool has also been created.

DOR-O-T, the IDS Webservice Address: <https://ids-doris.org/webservice>

In 2019, a new feature was added to the network viewer (<https://apps.ids-doris.org/apps/map.html>). In addition to the DORIS network and the IGS co-located stations, it is now possible to display the ILRS and IVS co-located stations.

Newsletter IDS Newsletter #6 was published in February 2019. It contains the following articles:

- The synergy of SLR and DORIS as geodetic techniques (F. Lemoine, A. Belli, C. Noll, NASA GSFC)
- The Azores: a key location occupied by DORIS for three decades (J. Saunier, IGN, C. Jayles, CNES, G. Moreaux, CLS, P. Yaya, CLS)
- Ponta Delgada: the host agency in short (R. TF. Marques, CIVISA)
- Tribute to Richard Biancale (F. Lemoine, NASA, L. Soudarin, CLS, JM. Lemoine, CNES, P. Ferrage, CNES, JP. Boy, EOST)

The issues are distributed via email and are also available at <https://ids-doris.org/ids/reports-mails/newsletter.html>.

Data Centers Two data centers currently support the archiving and distribution of data and products for the IDS:

- Crustal Dynamics Data Information System (CDDIS), funded by NASA and located in Greenbelt, Maryland, USA (<ftp://cddis.nasa.gov>)
- l'Institut National de l'Information Géographique et Forestière (IGN) in Marne la Vallée, France (<ftp://doris.ign.fr>) and (<ftp://doris.ensg.eu>)

In 2019, CDDIS warned the user community of the scheduled end of anonymous ftp to CDDIS archives, and strongly recommended to start the transition to the use of https as the preferred method.

Analysis Centers and Coordination

The activities of all the DORIS analysts of the past year 2019 have been dominated by preparation of ITRF2020 reprocessing. Two Analysis Working Group meetings (AWG) were realized, in April (TUM, Munich, Germany) and in September/October (CNES, Paris, France). As the major topics we can highlight ITRF reprocessing schedule and standards, South Atlantic Anomaly (SAA) mitigation, Satellite attitude/orbit modeling and stability of the scale.

All the IDS Analysis Centers (AC) continue the standard routinely processing by taking into account the last DORIS data available. The IDS includes six ACs and four “associate analysis centers (AAC)”, who use eight different software packages. For ITRF 2020 reprocessing, the analysis centers ESA, GOP, GRG and GSC promised full participation, while INA plans a limited contribution processing pure DORIS RINEX data. All other ACs and AACs are encouraged to participate partially. A Geocenter working group was established including ACs (AACs) CNES, GOP, GRG and DGFI-TUM.

IDS standards/recommendations for ITRF2020 reprocessing were defined. The list of major updates with respect to the standards used for ITRF 2014 reprocessing are as follows:

- New satellites Saral, Sentinel-3A and Sentinel-3B involved
- Elevation-dependent observation weighting recommended
- Usage of the measured satellite attitude (quaternions), if available, is strongly recommended
- Up-to-date external models/standards (time-variable gravity field + secular pole, ocean tides, sub-daily pole model)
- Combination of advanced strategies for SAA mitigation
- Avoid a usage of data accessories from the IDS Doppler exchange format, as the center of mass corrections and the observation validity indicator. Use own data preprocessing and satellite attitude modeling instead
- Use DORIS data in the RINEX format, at least for the Sentinels where old Doppler data format is not supported
- Apply updated phase law model for ground antenna Alcatel-type

The ITRF reprocessing schedule has been defined to process the data from 1993.0 to 2021.0 according to the following schedule:

- 2020, March 30: AC delivery of 1993.0–2002.3 (until start of Envisat First DORIS 2G receiver)
- 2020, June 30: AC delivery of 2002.3–2011.8 (until start of HY-2A).

- 2020, Sept. 30: AC delivery of 2011.8–2020.0
- 2021, Feb. 10: First delivery of the IDS combined solution to the IERS (1993.0–2020.0)
- 2021, Feb. 14: AC delivery of 2020
- 2021, Mar. 15: Complete delivery to the IERS of the IDS combined solution (1993.0–2021.0)

Combination Center

In 2019, in addition to the routine evaluation and combination of the IDS AC solutions, the IDS Combination Center delivered to the IDS Data Centers its fourth version of the DPOD2014 (DORIS extension of the ITRF2014 for Precise Orbit Determination) based on the fourth version of the DORIS cumulative position and velocity solutions. The IDS CC conducted also several analyses related to the ITRF2020 and analyzed the ITRF2014 DORIS-to-DORIS tie vector residuals.

Publications

IDS published the 2018 activity report that was broadly distributed to all DORIS participants and relevant services (see <https://ids-doris.org/ids/reports-mails/governing-board.html#activity>).

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

Conclusions

The DORIS constellation lost Jason-2 in 2019, but two new satellites join it in 2020, HY-2C and Sentinel-6A. The year was marked by the start of the deployment of 4th generation DORIS beacon (B4G), a much-awaited development, providing better options to satisfy the sky-clearance criterion for new or renovated DORIS sites.

The composition of the GB has slightly evolved with the departure of some members whom we thank warmly for their involvement and their replacement by new colleagues whom we welcome.

In 2019, DGFI-TUM (Munich, Germany) became the fourth Associate Analysis Center. The group has been contributing for several years to AWG studies and analyses. It thus confirms its participation in IDS.

The year was devoted to the preparation of DORIS data reprocessing for ITRF2020. The Analysis Coordination with the Analysis Centers defined the reprocessing schedule, and a list of recommended standards has been established. Besides, an inventory of the archived data at the Data Centers was performed to ensure the completeness of the datasets.

IDS continues to evolve. In the coming years, the Service will focus on growing the community, extending the DORIS applications, and improving the technology, the infrastructure and the processing.

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

3.4.2 International GNSS Service (IGS)

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

IGS activities and developments in 2019 that are of interest to IERS are summarized within this report. The information was compiled from the 2019 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 2019. It is available for download from the publications section of the IGS website www.IGS.org.

Routine Operational Activities

IGS network stations are maintained and operated globally by many institutions. This global network makes tracking data openly available at different latencies – from daily RINEX files to real-time streams – for public use. These data contain either the legacy GPS and GLONASS observations in RINEX 2 format, or the full set of potential signals/measurements for all available GNSS in RINEX 3 format. IGS tracking data, which is held by each of the five global Data Centers on permanently accessible servers, increased in volume from 2 TB to 11 TB (135 million files) over the last 5 years, supported by significant additional storage capabilities and resilient redundancy provided by IGS Regional Data Centers.

The IGS Analysis Centers and Associate Analysis Centers utilize tracking data from between 70 to more than 350 stations to generate and control the quality of highest-precision products up to four times per day. Product Coordinators combine these contributions into official IGS products on an operational basis including a quality control procedure. Nearly 3.5 GB of IGS Final, Rapid, and Ultra-rapid product files (GPS and GLONASS) as well 28 MB of IGS real-time and 225 MB of for IGS MGEX products are made available weekly. Additionally, ionosphere (5 MB per day) and daily troposphere files (3.2 MB per day) for more than 300 stations are produced.

The level of interest of users in IGS products is best exemplified by the download statistics, indicating typically over 1.7 billion files (170 TB)

downloads during the year (according to the Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center, an IGS Global Data Center). The Central Bureau assumes responsibility for day-to-day management of the service, interaction with station operators, and answering from users on a regular basis. These activities are performed all year and day-by-day, with high redundancy and reliability, through the pooled resources of 142 self-funding organizations from 45 countries worldwide.

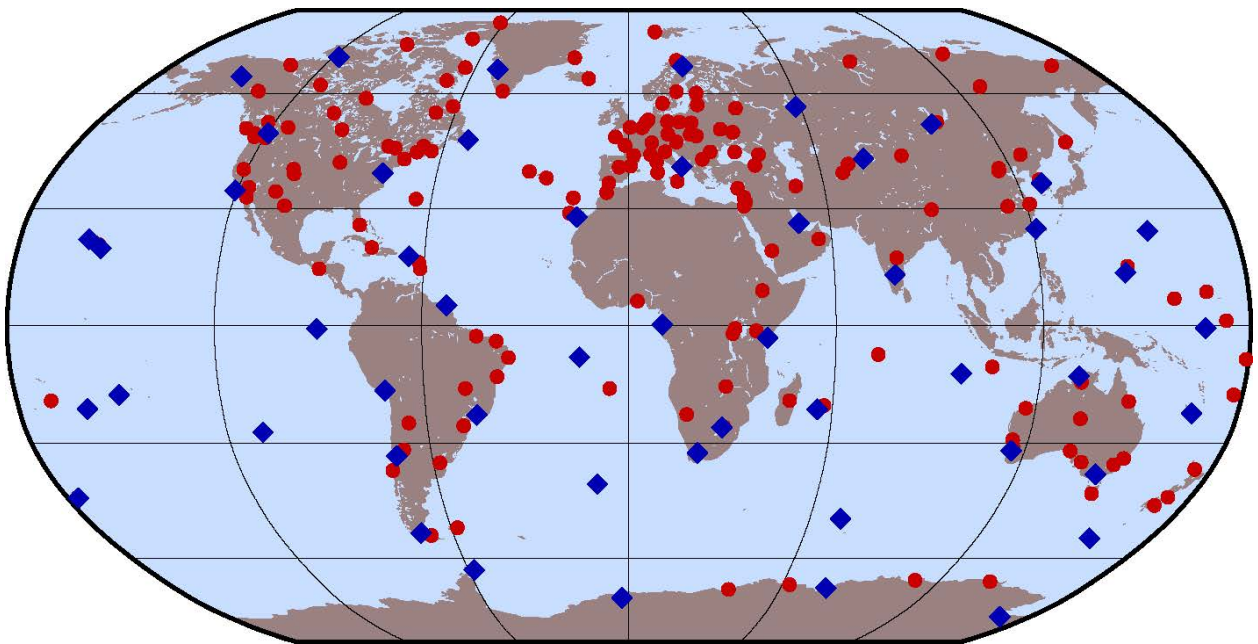


Fig. 1: Geographical distribution of the stations with given coordinates and velocities in IGS14 realization of the ITRF2014 reference frame. The blue diamonds indicate the location of the 51 core stations that are used for the datum definition when generating the IGS products.

Network Status

The Central Bureau monitors a globally distributed network of 507 select GNSS tracking stations that operate according to the IGS guidelines. More than one third of them are providing an extended set of observations for the new GNSS constellations. Approximately 221 IGS stations provide real-time data streams to support the IGS real time activities.

Since GPS week 1934 (29 January 2016), the IGS has been using the IGS14 realization of the ITRF2014 reference frame. It contains the coordinates and velocities for 252 stations, where only a globally well distributed subset of 51 stations are used as so-called core sites for the datum definition when generating the IGS products. For 113 of them the coordinates are affected by the change of the related antenna phase center model why it was decided to update the realization to IGS14 in early 2020. The geographical distribution of the stations is shown in Figure 1.

Analysis and Core Product Generation

The IGS core products have continued to be operationally combined and delivered to users in a timely manner through 2019. 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 <http://acc.igs.org>. The ACC also coordinates the ACs to assimilate changes made by them and to ensure that the best analysis models and procedures are used, along with coordination among the other relevant IGS Components, preparation of component reports, and so forth.

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

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

Real-time Service

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

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

Multi-GNSS Extension

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

It was decided at the IGS 2014 workshop in Pasadena, California, USA, that the related dataflow of RINEX 3 files with an extended set of observations be integrated into the legacy dataflow. This activity was coordinated by the Infrastructure Committee and did involve all relevant components of the IGS (station manager, data and analysis centers, and several working groups). Currently about 60% of the IGS stations deliver their data in RINEX 3 format using the new longer station IDs, as foreseen in the RINEX 3 format description.

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

Formats and Standards

The joint IGS/RTCM RINEX Working Group is responsible for maintenance of the RINEX format. The latest adapted version is RINEX 3.04. While tracking data from GNSS-capable equipment shall be solely available in RINEX 3 after a target date to be specified, tracking data from legacy receivers will continue to be available in RINEX 2 for the foreseeable future.

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

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

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

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

Governance

After Allison Craddock became the Director of the IGS Central Bureau in 2018, Mayra Oyola was appointed in February 2019 to fill the role of Deputy Director and Executive Secretary of the Governing Board.

The Governing Board conducted a 6-month-long formal review of the Central Bureau in 2018. A dedicated review panel, consisting of Ignacio Romero, Tom Herring, and Chris Rizos, engaged with Craddock and the JPL Central Bureau Task Manager, Michael “Mick” Connally, via email and telecons over the past six months. A Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis exercise was conducted (in consultation with the 2017 Terms of Reference), which laid the foundation for dialogue between the review panel members and CB, and served to identify areas of concern. Resulting from this dialogue, avenues of potential improvement were identified, providing guidance and direction for the Central Bureau in its future work.

Organizationally, the Terms of Reference were updated in early 2019 to be in alignment with a forward-looking and sustainable organizational vision. This includes the addition of appendix “procedures” documents, which outline such things as Associate Member Engagement, and Governing Board Elections processes, with more to come. The IGS continues to function as a service of the International Association of Geodesy (IAG), and a contributor to the Global Geodetic Observing System (GGOS). Accordingly, a number of the GB members continue to

participate in IAG and GGOS governance, bureaus, commissions and working groups, ensuring the IGS retains its strong level of relevance and impact, and therefore sustainability. Importantly, GB members also participate in the United Nations Global Geospatial Information Management (UN GGIM) efforts on Geodesy, which aims to enhance the sustainability of the global geodetic reference frame through intergovernmental advocacy for geodesy. GB members also routinely invited to present and provide valuable input at the National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board, providing input and recommendations to the United States government.

The IGS Governing Board met two times in 2019:

- 7 Apr. 2019 Governing Board Business Meeting, held prior to the 2019 European Geosciences Union meeting Vienna, Austria
- 8 Dec. 2019 54th Governing Board Meeting, held prior to the 2019 American Geophysical Union meeting, San Francisco, CA, United States

The IGS Executive Committee – consisting of Gary Johnston (Chair of the Governing Board), Felix Perosanz (Vice Chair of the GB), Rolf Dach, Charles Meertens, Chris Rizos, and Allison Craddock, with regular participation by other Governing Board and Central Bureau members as required – met several times via teleconference.

Strategic Planning

The current IGS Strategic Plan covers the period 2017–2020. Drafting and development of the 2021 IGS Strategic Plan is underway, through strategic dialogues at community events (such as the 2019 EGU) as well as a globally-distributed community survey.

Other Developments and Activities

IGS Workshop AC 2019

A dedicated analysis center workshop was held at the GFZ Potsdam (Helmholtz-Zentrum Potsdam; Deutsches GeoForschungsZentrum) from 15 to 17 April 2019. All ACs have been represented. It was discussed and finally agreed on the modeling standards and the schedule for the 3rd reprocessing campaign in order to support the ITRF2020.

Among others it was decided to include Galileo into the solution because of the availability of pre-launch satellite antenna calibrations. Together with an updated set of ground station calibrations GNSS may potentially contribute to the scale of the next ITRF solution for the first time. A series of test solutions have been carried out and analyzed during 2019 in order to prepare the reprocessing campaign.

For the first time, each AC has to submit the solution for one dedicated year for comparison before the data for all 25 years are going to be processed. These test solutions have been discussed at the AC meeting held in December 2019 during the AGU meeting in San Francisco, CA.

Troposphere SINEX Format Update

A new format for exchanging tropospheric and meteorological parameters (SINEX_TRO) was developed by R. Pacione (e-GEOS/ASI-CGS, Italy) and J. Douša (GOP/RIGTC, Czech Republic) within the last years. It considers numerous aspects from the troposphere application side (e.g., troposphere slant delays or long-term series for climatology) but also makes use of the long station identifiers (9 characters) as they are introduced with the naming convention of RINEX3 standard.

The format was endorsed by the troposphere working group in its December meeting. The ACs are encouraged to use the new format for the troposphere products generated in the frame of the repro3 campaign.

Real Time GNSS Service (RTS)

Currently, IGS combined products are limited to clocks and orbits for GPS, with GPS+GLONASS products still classed as experimental. Some multi-GNSS analysis center solutions are available, notably CNES (France) and GFZ (Germany), with the CNES stream currently disseminating (unmonitored and uncomparing) biases. ESA ESOC also plans to generate a multi-GNSS solution, but this is not yet at a stage where it can be disseminated.

IGS real-time orbit products are based on the ultra-rapid predictions. Thus, all information that helps to improve the IGS orbit products are needed, and of this, access to complete and accurate satellite metadata (information pertaining specifically to the physical properties of GNSS satellites) remains an issue.

It was recommended at the 2018 IGS Workshop that the IGS Real-Time Service should prepare for the transition to a true multi-GNSS service. In order to accomplish this, a number of prerequisites need to be fulfilled, such as the availability of predicted orbits for all constellations, the availability of processing, combination and validation capabilities as well as the selection of a suitable transfer format.

IGS Workshop

The next IGS Workshop was scheduled from 10 to 14 August, 2020, in Boulder, Colorado, USA (to be jointly hosted by UNAVCO and UCAR). Due to the COVID-19 situation it was postponed to take place 27 June to 1 July 2022.

Outreach

The IGS is represented on the GGOS Coordinating Board. It also plays a leadership role in the International Committee on GNSS (ICG), in

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

Official IGS Citation and IGS Library

In response to ever-growing applications for precise GNSS data as a public utility, the work of the IGS and its constituent elements continues to increase in relevance, especially as applications that essentially rely on IGS data and products expand both within and outside of the sciences.

As it enters its second quarter-century, the IGS is evolving into a truly multi-GNSS service. For more than 25 years, IGS data and products have been made openly available to all users for use without restriction, and continue to be offered free of cost or obligation. In turn, users are encouraged to participate within the IGS, or otherwise contribute to its advancement and to include a reference to the IGS in their citations.

The IGS Governing Board recently updated the official citation for acknowledging IGS data, products, and other resources in scholarly publications. The new official citation is the IGS chapter in the 2017 Springer Handbook of Global Navigation Satellite Systems.

The IGS Central Bureau gratefully acknowledges the contributions of IGS Governing Board and Associate members in the drafting of this article, as well as to Geoscience Australia for financially supporting the authorship. Special thanks to the article's authors, Governing Board Chairman Gary Johnston, as well as to Anna Riddell and Grant Hausler.

Johnston, G., Riddell, A., Hausler, G. (2017). The International GNSS Service. In Teunissen, Peter J.G., & Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed., pp. 967–982). Cham, Switzerland: Springer International Publishing. DOI: 10.1007/978-3-319-42928-1

The book is currently available for purchase and download on the Springer website: <https://www.springer.com/us/book/9783319429267>. A special pre-print version of this document may be found on the IGS Knowledge Base.

The IGS Library function has also transitioned to a Google Scholar-based platform. Please view <https://scholar.google.com/scholar?q=International+GNSS+Service> or <http://bit.ly/IGSLibrary> to learn more.

Rolf Dach

3.4.3 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 2019.

Network The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2019, the network remained very much in its past year's form. The only significant change was the introduction of a new system (laser) at the old Wuhan site in PR of China. From a technical perspective though, the quality and quantity of the observations has improved drastically during the past few years. The single-shot precision of an average station today is better than 10 mm (for the best stations this number is a few millimeters, Figure 2). The absolute quality of the individual observations is on average at the 10 mm level, with the best one dozen stations doing significantly better. Nearly all stations deliver normal points (NPs) with a precision of 1 mm or better, a firm requirement for the GGOS-era network as outlined in the GGOS2020 document, and several stations have upgraded to high repetition rate systems to meet such requirements. During 2019, the ILRS Central Bureau (CB) continued its efforts to encourage all stations to submit for archival their Full Rate (FR) data in addition to their NPs. These data are extremely important in characterizing correctly the response of each system with respect to each target array and calculate the precise correction that connects the ranges to the center of gravity of the target spacecraft, commonly known as the "center-of-mass" correction. Examination of the tracking over the past year indicates that the tracking targets increased by ~20% while the collected pass segments increased by ~13%, with no change in the number of tracking sites (Table 1 and Figure 8). NASA is moving forward with the deployment of the first next generation Space Geodesy SLR systems (SGSLRs) at McDonald Obs., Texas, to be followed by the one at Mt. Haleakala, Hawaii, and the development of a third system for the Norwegian Mapping Agency, to be deployed at their new core site of Ny-Ålesund, Svalbard. Russia's expansion and upgrade of their network continues, with the announcement of future deployment of a new system in co-location with the current one at Irkutsk and Mendeleevo in the coming year. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of the ILRS SLR.

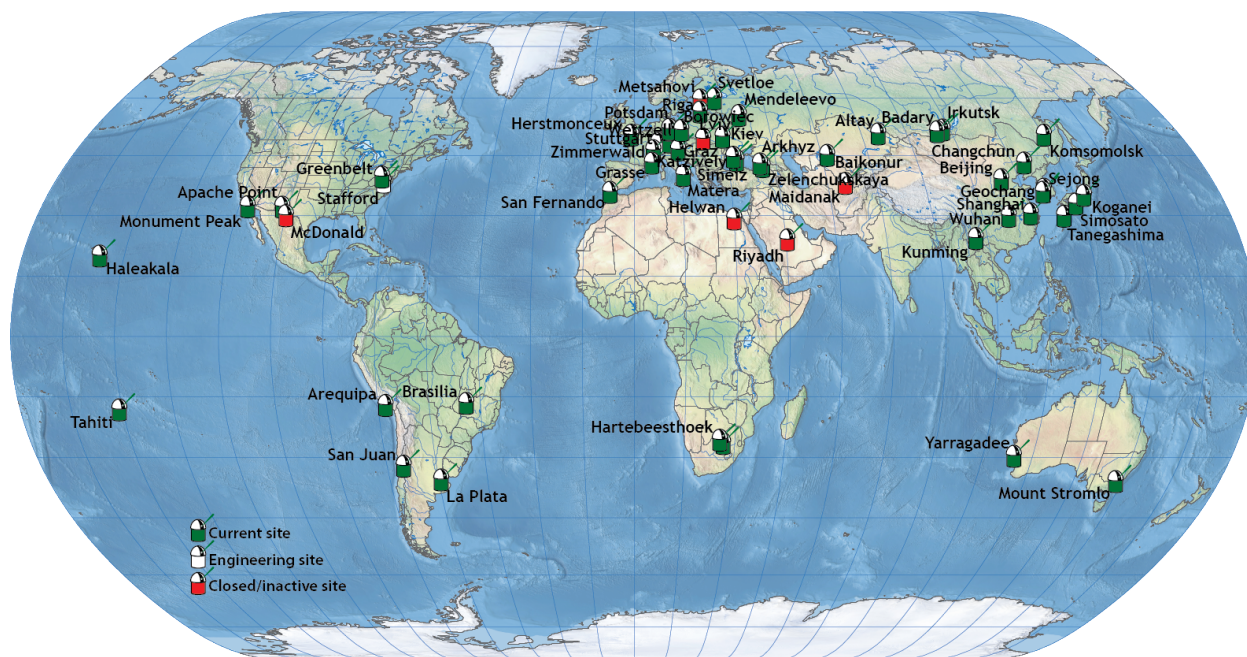


Fig. 1: The global network of SLR stations (status late 2019).

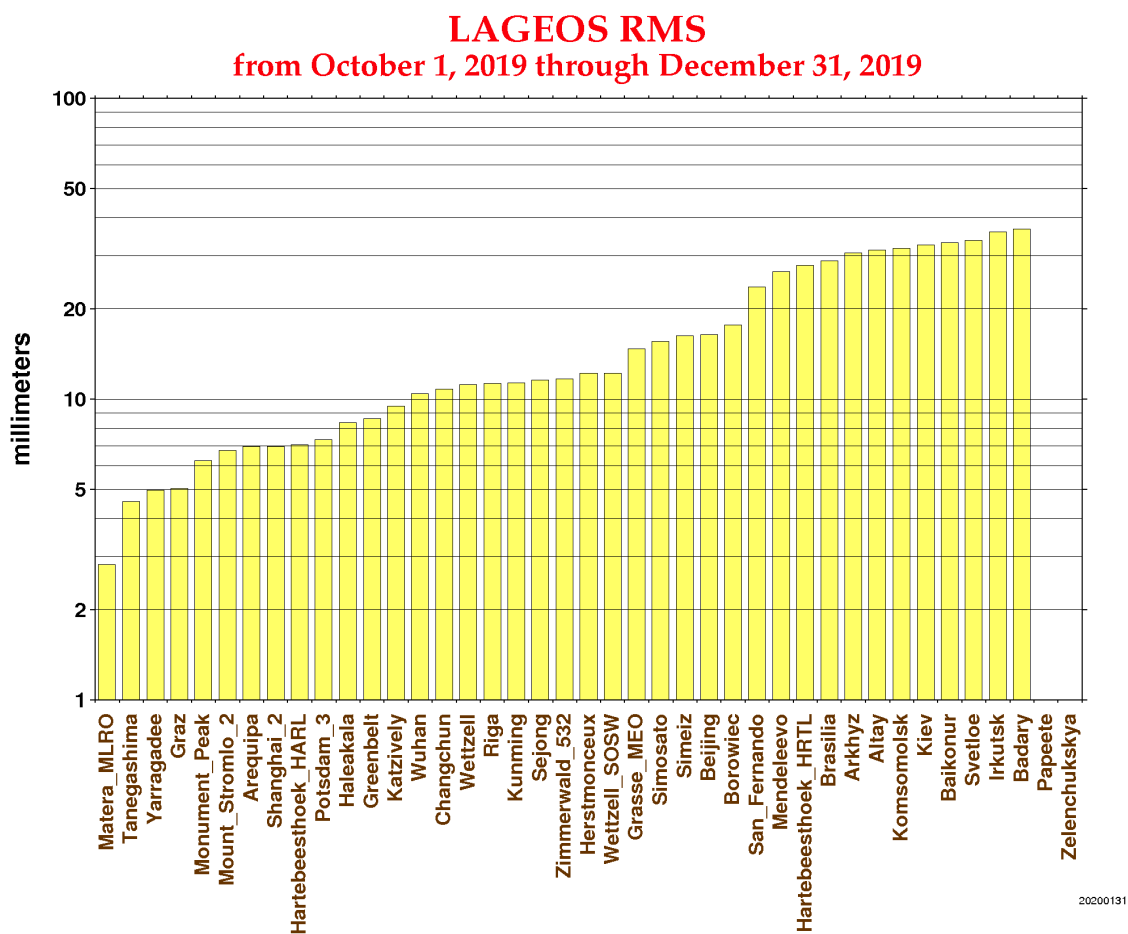


Fig. 2: Performance of the global network of SLR stations on LAGEOS (last quarter of 2019).

Table 1: *ILRS Network Tracking Statistics for 2019*

Site Name	Station	Low	LAGEOS	High	Grand
Altay	1879	61	273	1,769	2,103
Aueqripa	7403	3,722	194	0	3,916
Arkhyz	1886	550	363	622	1,535
Badary	1890	1,749	676	499	2,924
Baikonru	1887	0	416	594	1,010
Beijing	7249	1,546	368	1,355	3,269
Borowiec	7811	769	211	77	1,057
Brasilia	7407	181	278	916	1,375
Changuhcn	7237	8,895	1,294	5,585	15,774
Grasse	7845	262	676	3,034	3,972
Graz	7839	3,937	751	3,374	8,062
Greeneblt	7105	6,246	1,401	1,202	8,849
Haleaakla	7119	2,543	702	0	3,245
Hartebeesthoek (NASA)	7501	3,753	1,095	1,715	6,563
Hartebeesthoek (Russia)	7503	1,092	402	1,169	2,663
Herstmonceux	7840	5,591	1,268	3,738	10,597
Irkutsk	1891	1,340	245	402	1,987
Katzively	1893	1,961	357	6	2,324
Kiev	1824	783	87	0	870
Komsomolsk	1868	35	252	1,594	1,881
Kunming	7819	4,108	966	5,858	10,932
Matera	7941	3,791	1,534	2,390	7,715
Mendeleev	1874	64	71	128	263
Monument Peak	7110	5,801	509	615	6,925
Mount Stromlo	7825	7,507	1,454	1,970	10,931
Potsdam	7841	3,003	608	1,408	5,019
Riga	1884	611	194	102	907
San Fernando	7824	55	166	0	221
Sejong	7394	238	59	1	298
Shanghai	7821	2,921	811	3,406	7,138
Simeiz	1873	2,206	521	411	3,138
Simosato	7838	815	157	7	979
Svetloe	1888	891	330	195	1,416
Tahiti	7124	304	63	93	460
Tanegashima	7358	26	151	0	177
Wettzell (SOS-W)	7827	3,194	987	4,132	8,313
Wettzell (WLRS)	8834	4,903	1,602	3,744	10,249
Wuhan	7396	428	150	672	1,250
Yagraradee	7090	29,455	5,405	13,024	47,884
Zelenchukskaya	1889	285	55	88	428
Zimmerwald	7810	8,278	1,909	3,962	14,149
Totals:	41	123,900	29,011	69,857	222,768

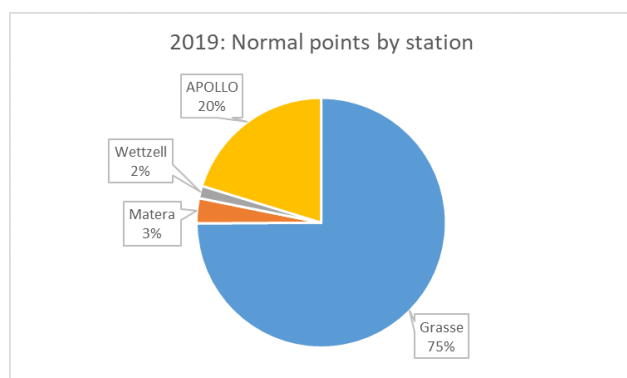


Fig. 3: Observatory statistics in 2019.

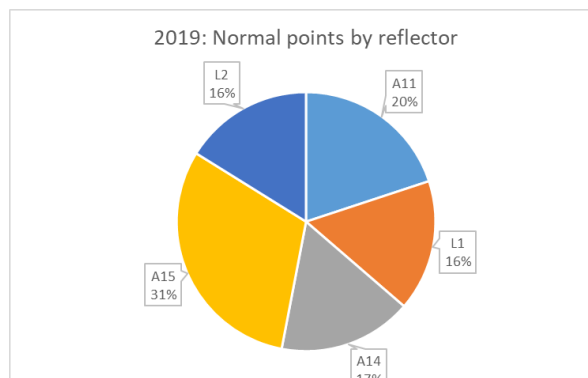


Fig. 4: Retro-reflector statistics by reflector in 2019.

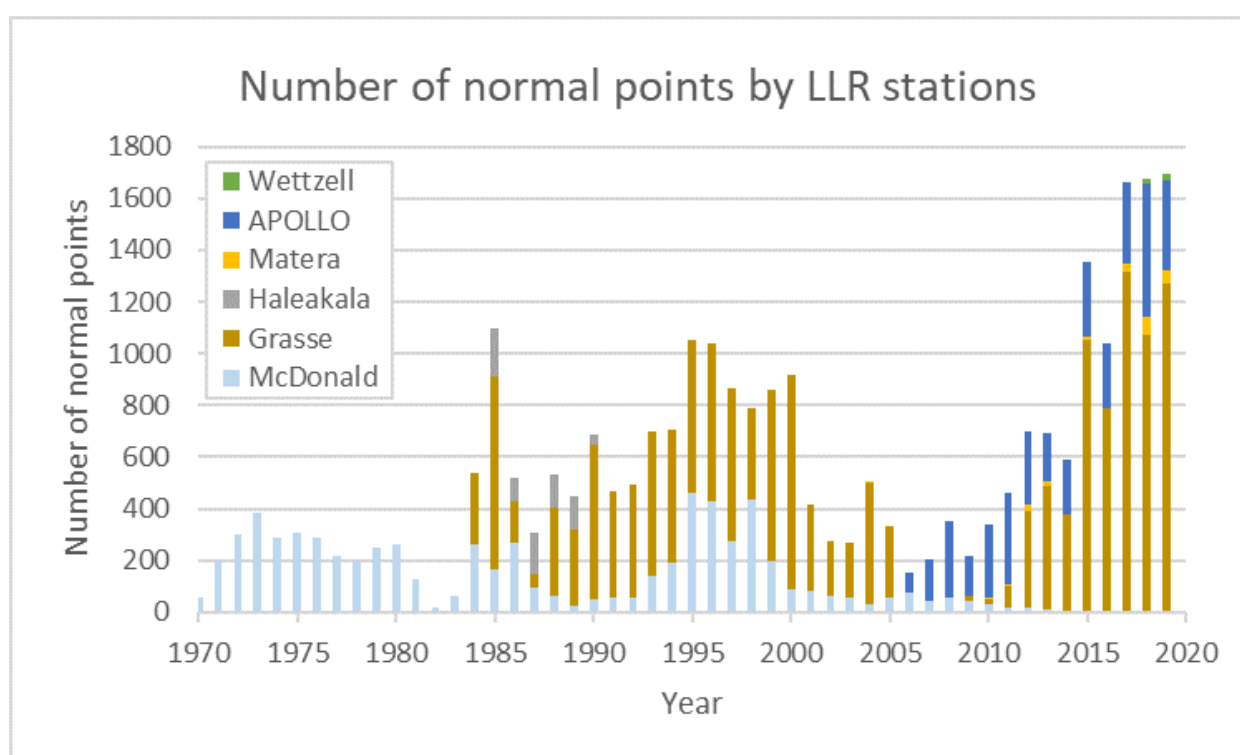


Fig. 5: Data yield of the global LLR network of stations (up to end of 2019). Note the increased contribution of Grasse's MeO system since 2016, a steady yield of APOLLO, small increase at Matera and welcome Wettzell! McDonald LLR Obs. officially shut down at the end of 2019.

Statistics of the SLR data collected as pass segments during the calendar year 2019 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 (MEO), and the High Earth Orbiters (HEO), GPS, GLONASS, Etalon 1 & 2, GIOVE-A/B, Galileo, BeiDou, IRNSS, QZSS and the moon.

Some of the SLR stations are technically equipped to track retro-reflector arrays placed on the surface of the moon. Currently there are only four Lunar Laser Ranging (LLR) capable stations within the

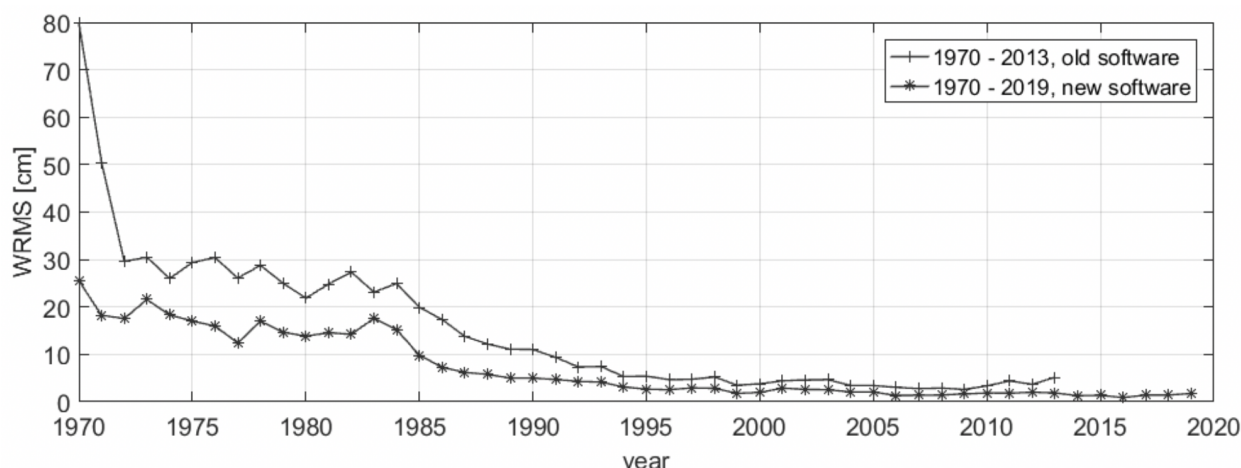


Fig. 6: LLR residuals, University of Hannover's IfE multiyear analysis, annual WRMS 1970 to 2019.

ILRS network of about 40 SLR stations. These are the Grasse station (MeO) in France, the Matera station (MLRO) in Italy, the Wettzell station (WLRS) in Germany, and the non-SLR station Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) in New Mexico, USA. Additionally, Kunming station, belonging to the Yunnan Observatories, in Popular Republic of China (http://english.ynao.cas.cn/research/rp/201801/t20180123_189509.html), successfully detected lunar returns since the beginning of 2018. Stations in Russia (Altay), China and South Africa plan to join the LLR network over the next few years.

Although data have been taken on the Apollo 11, 14, and 15, and the Lunokhod 1 and 2 reflectors, the bulk of the data has been from the largest reflector array, Apollo 15. In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the Lunar surface. After the 2018 initial tests at MeO with 2-way ranging in infrared to the Lunar Reconnaissance Orbiter-LRO, the next significant ranging sessions were collected in August of 2019, with the results highlighted in Mazarico et al. (2020). This experiment demonstrated routine 2-way ranging to a spacecraft at lunar distance. 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 few years, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan, have also increased their analysis activities. The six LLR analysis centers focus on different research topics (such as relativity, lunar interior, etc.). Some interest towards this end has also been shown by the Hartebeesthoek Radio Astronomy Observatory (South Africa) where an ex-Observatoire de la Côte d'Azur 1-m aperture telescope is being prepared for LLR

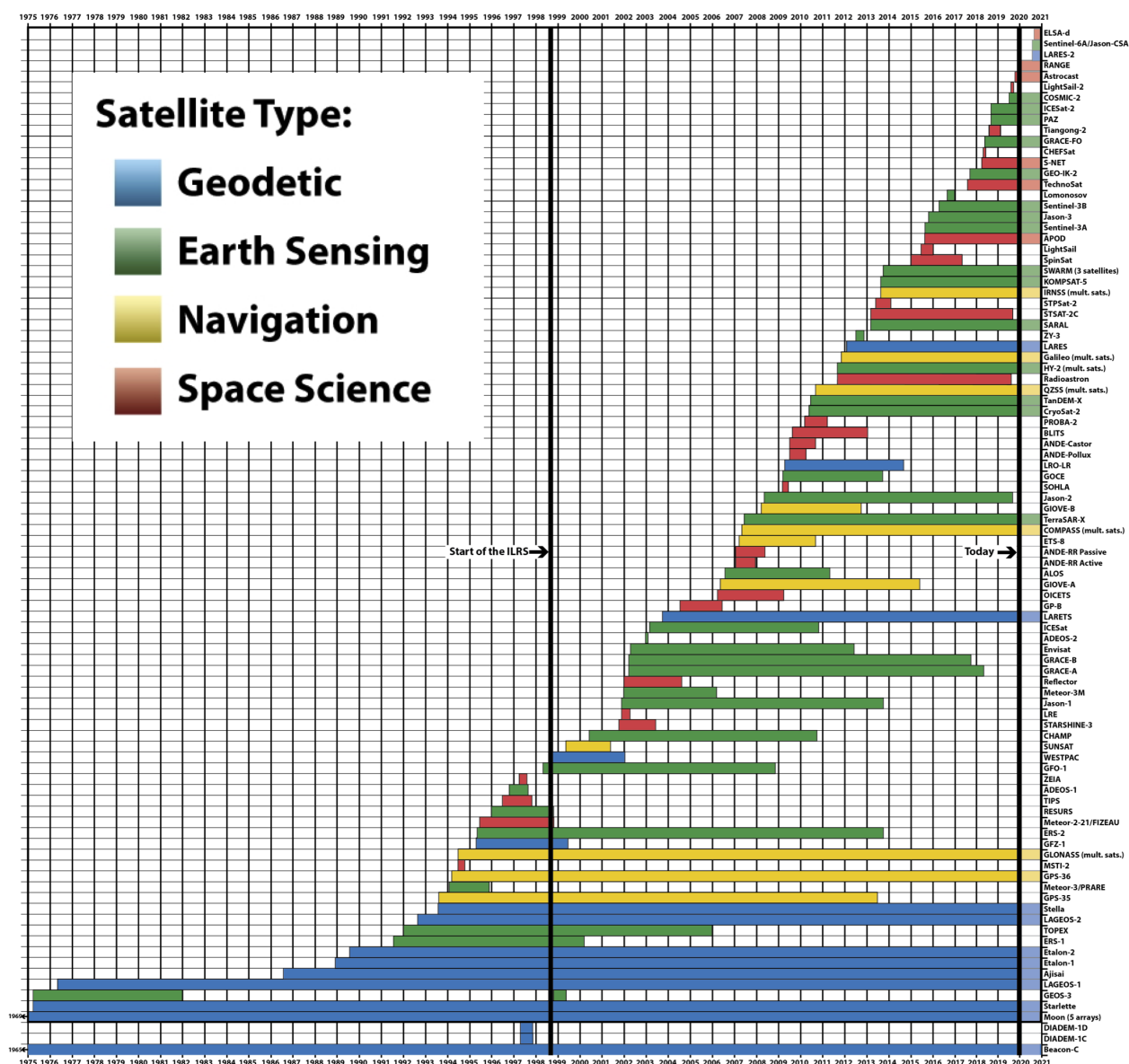


Fig. 7: The currently tracked SLR missions (status as of early 2020).

use. In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data.

During the last few years, the strong increase in the annual LLR normal point rate was mainly due to the effort at the French station in Grasse (Courde et al., 2017). The total data archive is still dominated by the Apollo 15 reflector, but its impact was reduced and for the period between 2016 and 2018 (Fig. 4) the contribution from the smaller reflectors has increased with the Apollo 15 share down to 30%. It should be noted however, that the data count from the APOLLO site is known approximately, since the exact number of normal points after 2016 have not been distributed to date and could only be guesstimated in the Figures 3–5.

LLR is an important tool to support lunar science, to study the Earth-Lunar dynamics and to test General Relativity in the solar system. Current improvements in the estimation of relativistic parameters include, e.g., tests of the equivalence principle, possible time variability of the gravitational constant and Lorentz symmetry (Hofmann and Müller, 2018). LLR based EOP results contribute to combined EOP solutions. With the larger LLR data set over time the lunar tidal acceleration has been more accurately determined (Williams and Boggs, 2016) as well as station coordinates and velocities. Through the studied of lunar tides, physical librations and the lunar orbit, LLR has been an important tool in improving our understanding of the physical properties and the interior of the moon. Discrepancies between LLR and GRAIL derived results (Pavlov et al., 2016) of elasticity parameters (Love numbers) and the degree-3 gravitational field which leads us to recognize that there is still very interesting and challenging science to address, especially in the modelling of dissipation and properties of the lunar interior.

Missions

In 2019, a total of 120 targets, including those on the moon, were being tracked by SLR/LLR (Figure 7). Of these, only about 1/3 are geodetic targets (cannonball satellites), about one half are navigation satellites (GNSS) and the rest are Earth Observation missions, including a small number of experimental space science missions. In 2019 the steady increase of tracking multiple GNSS targets continued at the same pace as in 2018. The launch of the GRACE Follow-On mission resulted in the initiation of a tracking campaign in late 2018, which was finalized in 2019:

- *December 15, 2018–January 15, 2019 – GRACE-FO tracking campaign*
- *February 15–May 15 – [Etalon](#) campaign of 2019*

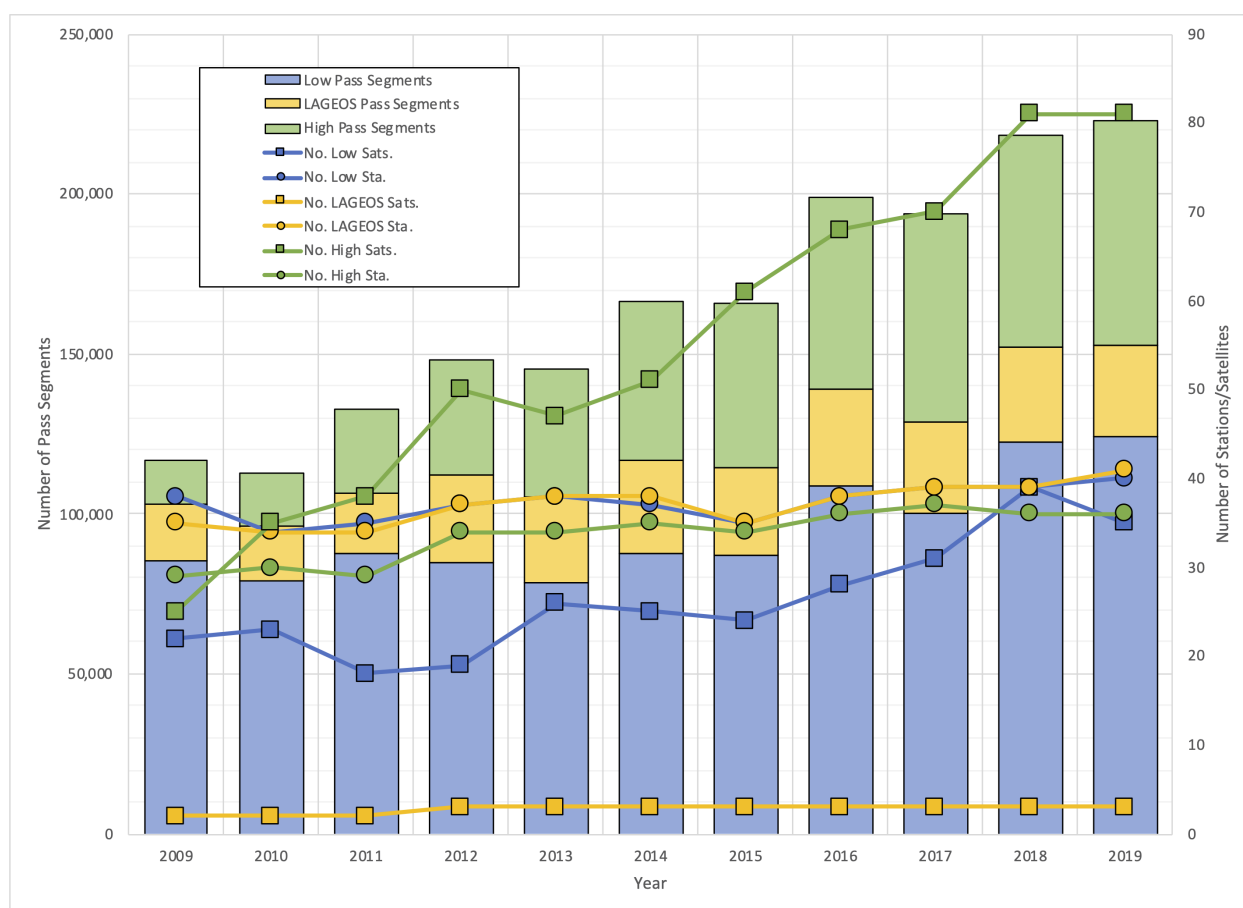
The data collected during the campaign were examined and compared to prior years. The analysis of these data indicated the improvement of EOP products and the findings were summarized in the [Etalon campaign report](#).

Table 2: *ILRS Supported Missions Launched or Initiating Tracking in 2018*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (s)	Altitude (km)	Inclination (°)	First Date Tracked
GLONASS-141	1908801	9141	44850	9	300	19,140	65	2019-12-11
GLONASS-140	1903001	9140	44299	9	300	19,140	65	2019-07-03

Table 3: *ILRS Supported Missions that Completed their Operations in 2019*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (s)	Altitude (km)	Inclination (°)	Last Date of Data
LightSail-2	1903629	4202	44420	3	15	720	24	2019-09-20
Jason-1	0105501	4378	26997	3	15	1336	66	2019-09-12
Tiangong-2	1605701	2207	41765	1	1	350-400	42	2019-01-03

Fig. 8: *ILRS network data yield by target type since 2009 and up to the end of 2019.*

Analysis and science

A new re-analysis of the data from the main ILRS targets LAGEOS, LAGEOS-2 and the two Etalons was completed in 2019. The results of the 2018 reanalysis indicated clearly that the response from these targets was not modeled sufficiently accurately, resulting in significant systematic errors. The re-analysis revealed serious shortcomings in the “target signature” model (aka “center of gravity”-CoG correction), so a new model was developed (Rodríguez et al., 2019), leading to significant changes. The improved model benefited from new and verified information about the ground tracking systems’ mode of operation and utilized hardware, delivering improved results across the entire network and for a significant portion of the recent tracking history. The regenerated combined series from 1993 to present resulted in revised long-term mean biases for the entire network demonstrating an improved, more random distribution with significantly reduced magnitudes at all stations (Figure 9). These revised preliminary results are very promising because they imply that the new SLR scale is significantly closer to that implied by VLBI, diminishing the gap between the two techniques to 0.24 ppb. When the re-analysis is completed the new approach will transition to a fully operational product that will become the standard mode for ILRS analysis products.

The next phase of the project is the development of this product as a service to the network, so that stations can be notified when an abnormal weekly estimate is obtained. The process requires careful implementation to limit false alarms and for that we first needed to develop a long history of the systematics for each station separately. Once this task is completed the operational service will become operational following the development of ITRF2020.

Meetings

In 2019 the ILRS held a Technical Workshop on Laser Ranging that took place in Stuttgart, Germany, October 21–25. For more information please see:

<https://ilrsworkshop2019.besl-eventservice.de>

The topic of the 2019 Technical Workshop was: “Laser ranging: To improve economy, performance, and adoption for new applications”. The workshop included for the first time the very successful “First One-day Introductory and Refresher Course on Satellite and Lunar Laser Ranging”, with tutorials for novices as well as SLR experts on many subjects, which was widely attended. The workshop was very well attended as well, with over 150 participants from many countries.

The ASC held two meetings in 2019, one prior to the 2019 EGU General Assembly in Vienna, Austria, on [April 6](#), and one prior to the GGOS/IERS Unified Analysis Workshop, on [October 1](#), in Paris, France. The ILRS planned ahead to hold future meetings in 2020 and 2021, however, due to the pandemic these have been now postponed. In

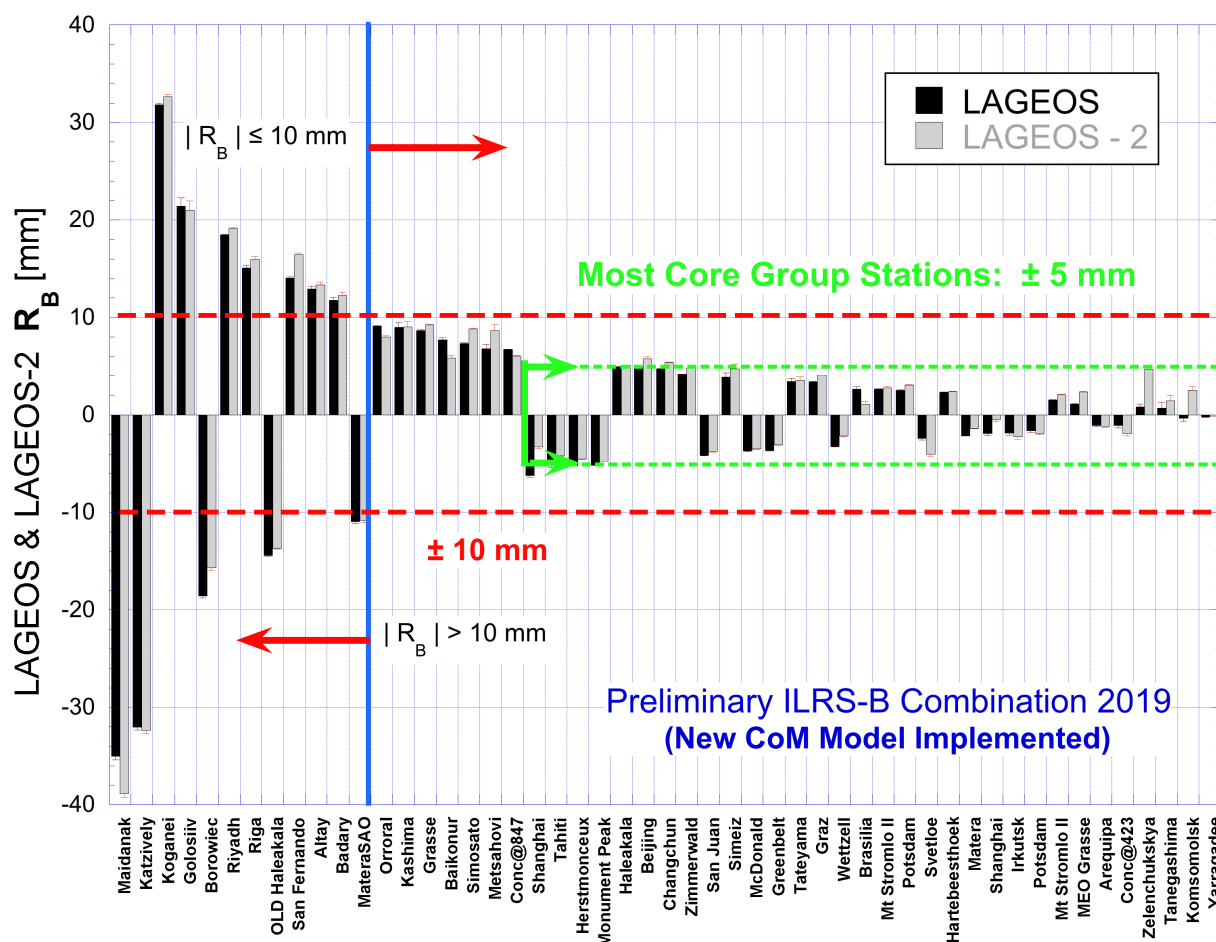


Fig. 9: Preliminary results from the SSEM Pilot Project: long-term mean biases on LAGEOS and LAGEOS-2 for the period 1993–2019, from a simultaneous estimation of weekly positions and biases for all systems. Note that the majority of the Core stations demonstrate a more random distribution in a ± 5 mm bracket, half of what it was using the older modeling approach.

particular workshops in Kunming, PRC (2020) and Arequipa, Peru (2021) were postponed to 2021 and 2022 respectively.

Publications

In 2019 the ILRS completed and published the 2nd Special Issue on Laser Ranging in the Journal of Geodesy, Vol. 93, 11, comprising of 287 pages, with twenty articles and a preface. An extensive list of general publications of interest to ILRS associates can be found at the ILRS website:

<https://ilrs.gsfc.nasa.gov/about/reports/biblio/bibliography.2019.html>

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3.4.4 International VLBI Service for Geodesy and Astrometry (IVS)

IVS Organization and Activities

During 2019, 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:

- The 3rd VLBI Training School was held in Las Palmas de Gran Canaria, Spain from March 14–16, 2019. Some 54 participants attended the school.
- The 10th IVS Technical Operations Workshop (TOW) was held at MIT Haystack Observatory from May 5–9, 2019. Directly following the TOW, a VGOS correlation/post-processing workshop was organized.
- The IVS published three IVS Newsletters in April, August and December, keeping the community informed about IVS activities. In August 2019, the proceedings volume of the 10th IVS General Meeting was published.
- A special issue on the Continuous VLBI Campaign 2017 (CONT17) is in preparation in Journal of Geodesy.
- The IVS continued an observing program to determine the alignment of the next radio frame (ICRF3) with the future *Gaia* optical frame by observing ICRF–*Gaia* transfer sources.
- Progress was made in achieving operational readiness of the next generation VLBI system, the VLBI Global Observing System (VGOS). 24-hour VGOS Test sessions were observed on a two-week basis. The network of 7–8 stations has matured enough to make the results available on the Data Center.

Table 1: *IVS meetings in 2019. The EVGA is a regional subgroup of the IVS organizing institutions that are active in geodetic and astrometric VLBI in Europe.*

Event	Location	Date
3rd VLBI Training School	Las Palmas de G.C., Spain	March 14–16, 2019
24th EVGA Meeting	Las Palmas de G.C., Spain	March 17–19, 2019
20th IVS Analysis Workshop	Las Palmas de G.C., Spain	March 20, 2019
40th IVS Directing Board meeting	Las Palmas de G.C., Spain	March 21, 2019
10h IVS Technical Operations Workshop	Westford, MA, USA	May 5–9, 2019
41st IVS Directing Board meeting	Bonn, Germany	September 30, 2019
8th Int'l VLBI Technology Workshop	Sydney, Australia	November 18–20, 2019

Network Stations and observing sessions

A total of 185 geodetic/astrometric 24-hour sessions were observed during the year 2019 using the legacy S/X system. That translates to about ~ 3.5 observing days per week that were coordinated by the IVS to determine operational products including EOP. Further, there were 487 1-hour Intensive sessions observed for the determination of UT1–UTC. Lastly, twenty-four 24-hour VGOS sessions were observed to further fine-tune the processing steps of the new VLBI system. The major observing programs during 2019 were:

- IVS-R1, IVS-R4** Weekly (Mondays and Thursdays) 24-hour, rapid turnaround measurements of EOP. Databases were available no later than 15 days after each session. The NASA Goddard Space Flight Center (R1) and the U.S. Naval Observatory (R4) coordinated these sessions.
- Intensive** Daily 1-hour UT1 Intensive measurements were made on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Ishioka (Japan), and on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Ishioka (Japan). In addition, about 120 2-hour Intensive sessions were observed using the VLBA stations at Mauna Kea (Hawaii, USA) and Pietown (New Mexico, USA) and Wettzell.
- IVS-T2** Bi-monthly sessions coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn, Germany (until September) and the Geodetic Observatory Wettzell, Germany, with 14–16 stations per session. Seven of these sessions were observed to monitor the TRF with all IVS stations.
- IVS-CRF** The Celestial Reference Frame (CRF) sessions, coordinated by the Hartebeesthoek Radio Astronomy 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 2019.
- VLBA** The Very Long Baseline Array (VLBA), operated by the National Radio Astronomy Observatory (NRAO), allocated six observing days for astrometry/geodesy. These sessions included the 10 VLBA stations plus up to four geodetic stations, providing state-of-the-art astrometry as well as information for mapping ICRF sources. Furthermore, the VLBA observed six sessions with the 10-station array concurrent with an IVS-R1 session.

Europe The European geodetic network, coordinated by the Institute of Geodesy and Geoinformation of the University of Bonn and the Geodetic Observatory Wettzell, continued with six sessions in 2019.

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 2019 six OHIG sessions were observed.

APSG The Asia-Pacific Space Geodynamics (APSG) program operated two sessions in 2018.

AUSTRAL In 2019, 12 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 and to improve the CRF in the southern sky.

AOV The Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) had 12 sessions during 2019.

IVS-R&D Ten research and development sessions were observed in 2019. The main goal of the 2019 R&D sessions was the observation of link sources between *Gaia* and the ICRF3.

VGOS-T Twenty-four VGOS Test sessions were observed in 2019 coordinated by MIT Haystack Observatory.

Correlators The correlators at the MIT Haystack Observatory (USA), the U.S. Naval Observatory in Washington (USA), the Max-Planck-Institute for Radio Astronomy (MPIfR) and BKG in Bonn (Germany), the Shanghai Astronomical Observatory (China), the Vienna University of Technology, and the Geospatial Information Authority of Japan (GSI) in Tsukuba efficiently processed the data recorded for the IVS. The majority of the legacy S/X 24-hour sessions were processed by the Bonn and Washington correlators. 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 Vienna correlator handled the AUSTRAL sessions and the Shanghai correlator analyzed CRF, APSG, and AOV sessions. The Haystack correlator processed select R&D sessions and all VGOS Test sessions. The Int2 sessions were processed at the Tsukuba correlator.

Data Centers The IVS Data Centers continued to receive databases throughout the year and made them available for analysis within one day of correlation.

The Data Centers also continued to receive solutions from Analysis Centers. All data and results holdings are mirrored several times per day among the three primary IVS Data Centers at BKG (Germany), Paris Observatory (France), and Goddard Space Flight Center (USA).



Fig. 1: Participants of the 3rd VLBI Training School in Las Palmas de Gran Canaria, Spain.

Education and Outreach

The IVS organized its third VLBI Training School following the rhythm of having a school every three years. The school was held in Las Palmas de Gran Canaria, Spain, in conjunction with the European VLBI meeting and attracted some 54 participants from all over the world: Spain (12), USA (11), China (8), Germany (7), Austria (4), Norway (4), Sweden (2), and Australia, Finland, France, South Africa, Thailand and The Netherlands (1 each). The lectures and hands-on tutorials gave all students a solid foundation and a wealth of information about the VLBI technique over the course of the three days of the event.

After 20 years of usage, the old IVS logo was retired at the end 2019 and replaced by a new one. The new logo has been designed to be usable in grayscale, to be visible at small sizes, to be editable for future customizations, to be reproducible in any file format needed, and to be clear against both light and dark backgrounds.



Fig. 2: *The new IVS logo that replaced the previous logo at the end of 2019.*

Data Analysis

Noteworthy data analysis activities in 2019 concern high-frequency EOP, gravitational deformation of VLBI antennas, loading effects, and source structure. The following subsections describe each of these activities in more detail.

Diurnal and Semidiurnal EOP Variation

Several IVS Analysis Centers participated in the work of the IERS Working Group on Diurnal and Semi-diurnal EOP Variation. Ten different models were evaluated by members of the IVS, the ILRS, and the IGS. Each technique used metrics appropriate to their technique. For example, the IVS looked at baseline repeatability and goodness of fit. The general consensus of all the techniques was that the two best models were 2017a_astro, an empirical model derived from VLBI data by John Gipson, and a model by Desai and Sibois of JPL derived from a TPX08, an altimetry model due to Egbert. Both models were improvements over the current IERS models, and each model had advantages and disadvantages. In order to avoid technique-specific signals, the working group recommended the use of the Desai and Sibois model which is the new IERS standard and will be used in ITRF2020.

Gravitational Deformation

VLBI antennas are structures, with a typical size of 30 m or larger. These antennas deform due to the effect of gravity, and the deformation is a function of the elevation angle. In 1988 Per Thomsen and Tom Clark built a finite-element model for the Gilcreek VLBI antenna and showed that the change in path length could be up to 2.4 mm. This causes a change in the observed differential delay, which in turn causes a change in the estimated geodetic parameters, particularly local up. Beginning in the early 2000s the deformation of several VLBI antennas was directly measured using surveying techniques, leading to a total of six antennas for which we had models. The change in path length can be as large as 97 mm. In preparation for ITRF2020, all IVS Analysis software was modified to be able to incorporate the effect of gravitational deformation.

Loading Effects

The standard IVS analysis includes the effect of pressure loading. Since the other space geodetic techniques do not routinely include these

effects, this meant that our estimates of station position were not consistent with other techniques. This is an issue when you are trying to combine data from several techniques. After consultation with the IERS, the IVS came up with the following compromise. We would do our analysis as we normally do, but we would modify the SINEX files that we produced so that loading effects could be removed a posteriori. This essentially involves adding in an additional normal equation vector which is due entirely to pressure loading.

Source Structure The ideal VLBI source is strong and point-like. In reality we know that the sources have structure. This causes changes in the observed delay. If not correctly accounted for, this will show up as noise in the measurements. In the past few years, several groups have looked at the effect of source structure. Although this is still very much an R&D effort, the results look promising. We anticipate that future VLBI analysis software will include the effect of source structure.

Technology Development Progress was made in achieving operational readiness of the next generation VLBI system, the VLBI Global Observing System (VGOS). 24-hour VGOS Test sessions were observed on a two-week basis. The network of 7–8 stations has matured enough to make the results available on the Data Center. The fledgling network will observe in operational IVS sessions starting in 2020. It is anticipated that the global network will grow to 25 stations and beyond in the coming years and will eventually replace the legacy S/X system as the IVS production system.

As part of the modernization process, other infrastructure components of the VLBI processing chain have been further developed as well, including the VGOS correlation and post-processing capabilities as well as VGOS data analysis. In May 2019, the Haystack group trained several other correlator groups in the processing of VGOS data in a dedicated workshop. Later in the year, an exercise was performed serving as a “blind test” that involved the correlators at Haystack, Bonn, Washington, Vienna, and Shanghai. Each correlator independently processed the exact same VGOS data (a one-hour VGOS Intensive session) and the results were compared to tease out any discrepancies.

The initial test resulted in slightly differing geodetic results (e.g., station positions, UT1–UTC) that could be traced to differences in the processing steps. These involved the correlator setup, fringe-fitting control file, delay calibration information, signal-to-noise ratio of scans, and treatment of the multi-band delay. A refinement of the data processing procedures largely reduced the discrepancies. In order to ensure that all correlators will process VGOS data consistently and generate validated quality products, a follow-up test using a typical 24-hour, multi-station

session is planned for 2020. Given a successful completion, the VGOS correlation load can then be distributed among five correlation centers. Other correlators, like Tsukuba and Onsala, are anticipated to join in the effort.

Publications

K. Armstrong, K.D. Baver, D. Behrend (editors): IVS 2018 General Meeting Proceedings “Global Geodesy and the Role of VGOS – Fundamental to Sustainable Development”, NASA/CP-2019-219039, Greenbelt, MD, USA, 2019, <https://ivscc.gsfc.nasa.gov/publications/gm2018/>

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3.5 Product Centres

3.5.1 Earth Orientation Centre

This section presents over the year 2019 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 Rotation Parameters (ERPs) including long term consistency, publications for time dissemination (DUT1) and leap second announcements. The ERPs: Pole coordinates (x,y), Difference UT1–UTC, Length of Day variation (LOD) and Celestial pole offsets (dX, dY) are available to a broad community of users in various domains such as astronomy, geodesy, geophysics, space sciences and time. Firstly, the ERPs are collected in the form of combined solutions derived by the Technique Centres (IGS, IVS, ILRS and IDS). Two main solutions are computed: a long-term solution (IERS C01) since 1846 until the end of the previous year and the Bulletin B / C04 given at one-day intervals, which is published monthly with a 30 day delay (Bizouard et al., 2018).

Monitoring of the geophysical fluid excitation of the polar motion and length-of-day

In this regard, our service maintain and improve since years an interactive tool (<http://iers.obspm.fr/eop-pc/index.php?index=excitactive&lang=en>) completing the products of the Global Geophysical Fluid Centre (GGFC) of the IERS. It allows to know, with a delay of at most 24 hours, to what extent the hydro-atmospheric excitation accounts for polar motion and length of days. This analysis can be made since the 1950's. As it gives the equatorial geodetic excitation corresponding to C04 pole coordinates, it has been the support of many published papers.

C04 series updates

- For UT1, the C04 solution was recalculated over the whole year 2018 and for the first months of 2019 due to the presence of a spurious bias over this period (MJD 58119–MJD 58560). The previous version, updated until 2019/12/27, has been put in the sub-directory /eopc04.2018.
- For deriving the last 30 days of the C04 solution (non-official IERS values, only for national use), we have introduced underweighted Ultra-rapid IGS values (x, y, LOD) at 0hUTC. This allows us to reduce the instability of the x pole coordinate for the last day of the solution.

Web site upgrade In the web page devoted to numerical analysis of the combined and intra-technique ERP time series <http://iers.obspm.fr/eop-pc/index.php?index=excitactive&lang=en>, we offer now the possibility to derive the parameter TT – UT1.

Statistics Statistics of 14 C04 for the year 2019 are provided in Table 1 (standard deviations of C04 – intra-techniques solutions), Table 2 (mean and standard deviations of C04 – intra-technique combined solutions) and Table 3 (mean and standard deviations of C04 – multi-technique combined solutions). Those results can be reproduced on line from <http://iers.obspm.fr/eop-pc/index.php?index=operational&lang=en>, and extended to any other time interval covered by the ERPs series.

Table 1: *Intra-techniques solutions: averaged time sampling and standard deviation with respect to the combined solutions Bulletin B / C04 over the year 2019. Solutions contributing to Bulletin B / C04 are flagged by stars (*)*.

Intra-techniques solutions	Estimated uncertainties				
	Time sampling	Terrestrial Pole	UT1	LOD	Celestial Pole
		μas	μs		μas
VLBI - 24h					
EOP(AUS)	~365 d	111	111		111
EOP(BKG)	~7 d	155	10.4		90
EOP(GSFC)	~2 d	189	8.4		151
EOP(IAA)	~4 d	114	8.5		70
EOP(USNO)	~3 d	59	6.8		53
EOP(IVS Comb*)	~3 d	77.5	6.5		64
VLBI - Intensive					
EOP(BKG)	~1 d		23.4		
EOP(GSFC)	~1 d		26.8		
EOP(IAA*)	~1 d		75.7		
EOP(PUL)	~1 d		14.0		

EOP(USNO*)	~1 d		7.7		
SLR					
EOP(MCC)	~1 d	212		208	
EOP(IAA)	~1 d	189		27	
EOP(ASI)	~1 d	197		54	
EOP(ILRS Comb*)	~1 d	134		23	
GPS					
EOP(CODE)	~1 d	34		12	
EOP(JPL)	~1 d	37		20	
EOP(GFZ)	~1 d	42.5		13	
EOP(ESOC)	~1 d	37		14	
EOP(NOAA)	~7 d	53		12	
EOP(SIO)	~1 d	71		26	
EOP(EMR)	~1 d	48		14	
EOP(GRGS)	~1 d	37.5		11	
EOP(CGS)	~1 d	48.5			
EOP(IGS-R Comb*)	~1 d	31.5		10	
EOP(IGS-F Comb*)	~1 d	32		12	
DORIS					
EOP(INASAN)	~-365 d	12			
EOP(IDS Comb*)	~-365 d	12			

Table 2: Mean and standard deviation (STD) in microarcsecond of the differences between intra-techniques combined solutions entering the combination and Bulletin B / C04 over 2019.

EOP	IGS Comb – IERS 14C04		ILRS Comb – IERS 14C04		IVS Comb – IERS 14C04		IDS Comb – IERS 14C04	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
$X(\mu as)$	25	34	40	128	-29	73	-29	73
$Y(\mu as)$	-10	30	37	140	-117	95	-117	95
$UT1(\mu s)$					1.8	7.8		
$LOD(\mu s)$	0	30	-1	23				
$dX(\mu as)$					29	46		
$dY(\mu as)$					42	82		

Table 3: Mean and standard deviation for Pole coordinates (x,y) and UT1 of the differences between combined solutions derived by both the Rapid Service/Prediction Centre at USNO, the JPL and Bulletin B / C04 over 2019.

EOP	Unit	Bul A – Bul B		Comb JPL – Bul B	
		Mean	Std	Mean	Std
X	μas	26	48	-11	58
Y	μas	2.2	18.0	13	43
UT1	μs	2.2	18.0	-1.6	15.1

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References <http://iers.obspm.fr/eop-pc/>

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3.5.2 Rapid Service/Prediction Centre

Introduction

This section provides a discussion and summary of the Earth orientation parameter (EOP) results produced by the IERS Rapid Service / Prediction Center (RS/PC) for the calendar year 2019. The accuracies of both the inputs used and the subsequent EOP combination and prediction results produced by the IERS RS/PC are provided. The combination and prediction comprise the Bulletin A results and are published in several human and machine readable formats. In addition, a plot of the polar motion path for the year, a summary of the expected times during each day at which inputs are provided to the IERS RS/PC solution, a low precision table of predictions of TT–UT1, and a comprehensive list of the inputs to the IERS RS/PC combination and prediction process are provided. This section also contains an overview of the combination processing techniques, the prediction processing techniques, the centre activities that include developmental work to improve EOP results, and the web and FTP locations available to users for obtaining results. Lastly, detailed analyses and discussions regarding results may not, in general, be discussed in this section, but may be presented at upcoming conferences and meetings.

Combination Processing Techniques and Results

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

Weights for each contributor in the algorithm may be either a priori values estimated by determining the standard deviation of a long history of residuals or values based on the internal precision reported by contributors. The estimated accuracies for each of the IERS RS/PC contributors to the EOP combination solutions for 2019 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 2019.

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 (CPOs), all the contributors provide direct measurements of these quantities. For all of 2019, the CPO contributor observational inputs used in the combination have been in terms of dX and dY , and are consistent with the IERS Conventions 2010 and IAU 2006 precession and 2000A nutation models. For UT1–UTC, some contributors provide direct measurements and others provide estimates based on the derivative of UT1.

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

Each day at approximately 17:00 UTC, input data spanning one year into the past are provided to the WSCS software to update EOP solutions. The data consists of the following: the epoch of observation, the observed EOP value, and the corresponding weight. The software computes the spline coefficients for every unique input data point, which are then used to interpolate the Earth orientation parameter time series so that x , y , UT1–UTC, dX , and dY values are computed for the midnight (00:00) UTC epoch for each day.

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

Two groups of data points are excluded from the combination process. One group are those EOP inputs that have contributor reported errors

Table 1: *Estimated accuracies of the contributions to the IERS RS/PC combination results for 2019 with respect to the IERS RS/PC EOP series. Units are milliseconds of arc (mas) for x, y, dX, and dY and milliseconds of time (ms) for UT1–UTC. (All acronyms used in this table are defined in the Acronyms section of the Appendix of the IERS Annual Report 2019.)*

Contributor	Estimated accuracy				
	x	y	UT1–UTC	dX	dY
ILRS SLR	0.16	0.15	–	–	–
IAA SLR	0.24	0.20	–	–	–
MCC SLR	0.15	0.20	–	–	–
GSFC VLBI Intensive	–	–	0.018	–	–
USNO VLBI Intensives	–	–	0.014	–	–
GSI Intensives	–	–	0.016	–	–
GSFC ⁺ VLBI	0.13	0.09	0.005	0.06	0.06
IAA ⁺ VLBI	0.30	0.29	0.008	0.06	0.09
IVS ⁺ VLBI	0.11	0.12	0.004	0.05	0.06
USNO ⁺ VLBI	0.11	0.07	0.005	0.06	0.06
IGS Final	0.01	0.01	–	–	–
IGS Rapid	0.03	0.03	–	–	–
IGS Ultra [*]	0.04	0.04	0.028 [*]	–	–
USNO GPS UT [*]	–	–	0.047 [*]	–	–

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

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

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

Comparing statistics provided in Table 1 versus the same table in the IERS RS/PC section of the IERS 2018 Annual Report⁴, a few differences are worth mentioning. The 2019 versus 2018 Polar Motion x ILRS SLR estimated RMS accuracy was 0.16 versus 0.22 milliseconds

⁴The IERS Annual Report (AR) 2018 and previous ARs are found at <https://www.iers.org/IERS/AnnualReports>

Table 2: Mean and standard deviation of the differences between the Rapid Service/Prediction Center combination solutions and the 14 C04 EOP solutions for 2019. Polar motion x and y values are in milliseconds of arc (mas) and UT1–UTC values are in units of milliseconds of time (ms).

	Bulletin A – C04	
	Mean	Std. Deviation
Bulletin A Rapid Solution (finals.data)		
x	0.02	0.05
y	-0.01	0.05
UT1–UTC	0.001	0.016
Bulletin A Weekly Solution (finals.data)*		
x	0.01	0.07
y	-0.02	0.06
UT1–UTC	0.005	0.025
Bulletin A Daily Solution (finals.daily)		
x	-0.01	0.04
y	0.00	0.04
UT1–UTC	-0.001	0.042

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

of arc (mas), respectively; and for Polar Motion y , 0.15 versus 0.22. Comparing the 2019 versus 2018 GSFC, IVS, and USNO VLBI Polar Motion x RMS accuracies, all deteriorated by at least 30%, whereas the Polar Motion y were accuracies were very similar.

When comparing the integrated IGS Ultra LODs (IIUL) RMS residual value provided in Table 1 to that shown in Table 1 in the AR 2018, one can see an improvement (0.028 for 2019 vs 0.034 milliseconds (ms) for 2018). The RMS provided is computed using the first IIUL residual for that solution if any IIULs were used in the combination for that day. The exact causes for the change are being considered; however, reasons for the change could be affected by the manner in which the following were computed: a) the RMS statistics and b) the IIUL constants of integration for each day. A discussion of the computation of the RMS statistics and IIUL constants of integration for each day were provided in the IERS RS/PC section of the IERS AR 2017 and the reader is referred to that detailed discussion.

Table 2 shows the accuracies of RS/PC combination solution for the running, weekly, and daily products compared to the 14 C04 series maintained by the IERS EOC for 2019; the latter series uses somewhat different data inputs and a different combination algorithm, which

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

Figure 1 contains plots of the 2019 residuals between the daily rapid and the 14 C04 solutions, and the corresponding statistical results are listed in Table 2 under “Bulletin A Daily Solution (finals.daily).” These daily rapid solutions are considered the last combination or 0-day prediction results. The statistics for the Daily Solution are the differences between the EOP solution, updated daily and at each corresponding daily epoch for 2019, versus the respective 14 C04 series solution for that epoch when it becomes available. (An example of the method used to compute the Bulletin A Daily solution (finals.daily) statistics is provided in the RS/PC section of the IERS Annual Report 2015 on pages 82 and 83.)

Comparing the “Bulletin A Daily Solution (finals.daily)” UT1–UTC statistics between 2018 and 2019, the difference in mean was only 1 microsecond, however, the standard deviation (STD) improved to 0.042 in 2019 compared to 0.074 in 2018. The reasons for this welcome improvement are under investigation and may be provided at a conference or meeting later in 2020 or 2021. In addition, the PMx statistics between 2018 and 2019 showed a small improvement in mean and STD from 2018 to 2019; a mean of 0.05 and STD of 0.08 in 2018 compared to 0.01 and 0.07 mas in 2019. The PMy statistics between 2018 and 2019 were fairly similar.

The running solution statistics, shown under the label “Bulletin A Rapid Solution (finals.data),” are the residuals of the combination solution, contained in finals.data, versus the 14 C04 series over the 365-day period covering 2019. The finals.data file used in computing these statistics was computed on January 14, 2020 (and also archived). Nominally, the last observational input data for the year (in this case, 2019) is processed and provided to the IERS RS/PC by January 14 of the following year (in this case, 2020); the last observational data to become available are usually the 24-hour VLBI input series. Thus, the running solution includes the effects of any late-submitted, but highly accurate data.

As seen in Table 2 under the label “Bulletin A Rapid Solution (finals.data)”, there were some noteworthy improvements in the comparison of the polar motion x mean and UT1–UTC STD between the 2019 and corresponding 2018 results. The polar motion x mean differences were reduced from 0.07 in 2018 and 0.02 mas in 2019. There was a welcome improvement in UT1–UTC STD from 2018 to 2019, namely 0.052 to 0.016 ms. The cause of the improvement is under investigation and may be explained in more detail in a subsequent conference or meeting later in 2020 or 2021.

The “Bulletin A Weekly Solution” results shown in Table 2 are the statistics of the residuals obtained from the 2019 Bulletin A combination values, contained in the ser7.dat format, versus the 14 C04 series. These combination values for 2019 are the concatenation of all 52 Bulletin A, 7-day EOP combination results. For each Bulletin A, there is a set of 7-day EOP combination results listed prior to the solution epoch. (For example, the Bulletin A solution computed on 9 July 2020 has EOP combination results from 3 through 9 July, 2020.)

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 may cause poor quality short-term polar motion predictions. It is anticipated that within a few years, an evaluation effort recently funded by USNO will yield improved prediction algorithms.

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*

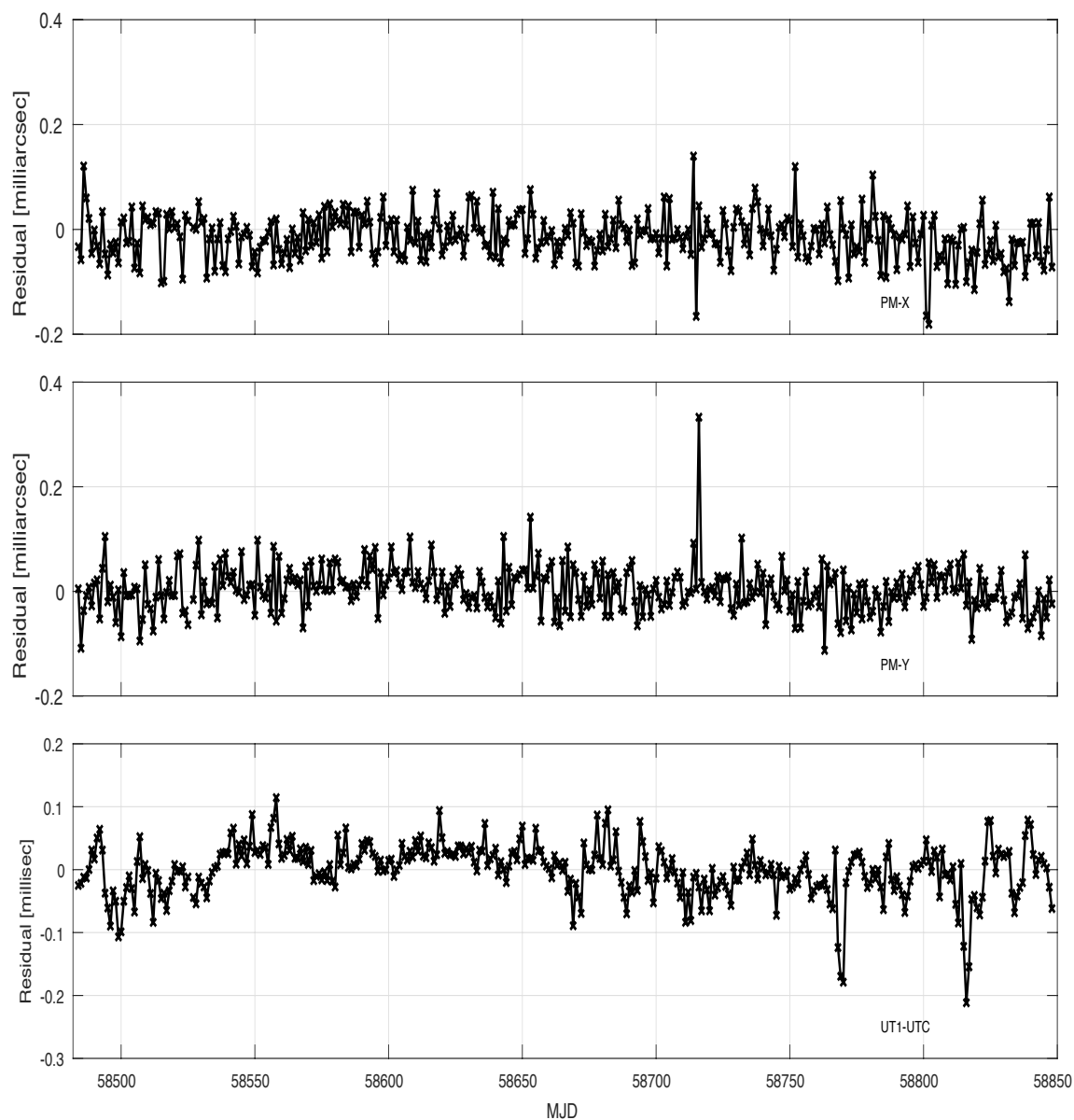


Fig. 1: Differences for 2019 between the daily updated EOP solution at the day of the solution update and the 14 C04 series combination solution. (The day of the solution is also known as the last combination or 0-day prediction epoch.) Earth Orientation Parameters shown are: a) Polar Motion x ; b) Polar Motion y ; and c) $UT1-UTC$.

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 UT2S–TAI. (UT2S is a smoothed version of UT1, removing periodic seasonal and long-period variations due to tides, including the long-period tides up to 18.6 years.) Then, to create the prediction of $(UT2S - TAI)_N$ N days into the future, the smoothed time value from N days in the past, $(UT2S - TAI)_{-N}$, is subtracted from 2-times the most recent value, $2(UT2S - TAI)_0$ to yield:

$$(UT2S - TAI)_N = 2(UT2S - TAI)_0 - (UT2S - TAI)_{-N}.$$

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

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

Errors of the prediction estimates are derived from analyses of the past differences between observations and the published predictions. Formulas published in Bulletin A can be used to extend the Bulletin A tabular data, but predictions derived from these formulas are significantly less accurate than the tabular predictions and are not recommended for operational use.

For several representative prediction days, the RMS of the residuals between USNO produced polar motion and UT1–UTC predictions and the 14 C04 series combination values for 2019 are shown in Tables 3a through 3d. Prediction day “N” is defined as “N” days into the future from the current day for which the EOP solution was updated. For example, prediction day 0 for the EOP solution that was updated at 17:00 UTC on MJD 58757 (October 1, 2019) was at 00:00 UTC on MJD 58757 (i.e., 17 hours prior to the solution update time.) As a further example, prediction day 10 for the EOP solution that was updated at 17:00 UTC MJD 58757

(October 1, 2019) is 00:00 UTC MJD 58767 (October 11, 2019). Table 3a provides the RMS prediction errors for EOP solutions updated at 17:00 UTC; Tables 3b, 3c, and 3d provide RMS prediction errors for solutions updated at 21:10, 03:10, and 09:10 UTC, respectively. (So, going back to the example of prediction day 0 for MJD 58757, if one can wait to obtain EOPs at update times of 21:10 UTC, or 03:10 or 09:10 on the MJD 58758, one generally can be assured of more observational data and obtain an improved estimate of EOPs at 00:00 UTC MJD 58757 over that obtained at the 17:00 UTC on MJD 58757 update time.)

As Table 3a shows, for most prediction days (although certainly not all) there were no noteworthy changes in the polar motion versus the same table in the AR 2018; however, there was a substantial improvement of UT1–UTC in 2019 compared to 2018 for the 0 and 1 day predictions. The 0- and 1-day changes from 2018 to 2019 were 0.074 ms versus 0.042 and 0.087 versus 0.063, respectively. This improvement occurred even with a missed update of the EOP solution on December 13, 2019 due to network issues. More detailed explanations for the improvements (including the effect of the missing update) may be provided at upcoming conferences.

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. In general, the results are very similar since on most days an observation is made either on the solution day or the day before.

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

At each Nxdaily UTC solution time listed in Tables 4a and 4b, major contributors, whose latencies between observations to availability for the EOP solution are under a few days, are listed with an associated

Table 3a: *RMS of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14 C04 combination solutions for 2019. Note that the prediction length starts counting from the day after the date of the solution epoch.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.05	0.04	0.042
1	0.30	0.23	0.061
5	1.90	1.25	0.198
10	3.46	1.88	0.463
20	5.75	2.84	1.851
40	7.21	4.04	6.259
90	8.45	8.66	19.983

Table 3b: *RMS of the differences between the EOP time series predictions produced by the 21:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2019.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.05	0.05	0.041
1	0.29	0.23	0.063
5	1.89	1.23	0.199
10	3.45	1.85	0.463
20	5.73	2.84	1.846
40	7.23	4.03	6.255
90	8.37	8.69	20.012

Table 3c: *RMS of the differences between the EOP time series predictions produced by the 03:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2019.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.05	0.05	0.041
1	0.27	0.21	0.061
5	1.85	1.19	0.197
10	3.45	1.81	0.463
20	5.77	2.81	1.854
40	7.23	3.99	6.269
90	8.39	8.54	20.046

Table 3d: *RMS of the differences between the EOP time series predictions produced by the 09:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2019.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.05	0.05	0.040
1	0.26	0.21	0.060
5	1.81	1.18	0.197
10	3.41	1.79	0.463
20	5.73	2.80	1.853
40	7.21	3.98	6.269
90	8.40	8.53	20.047

“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

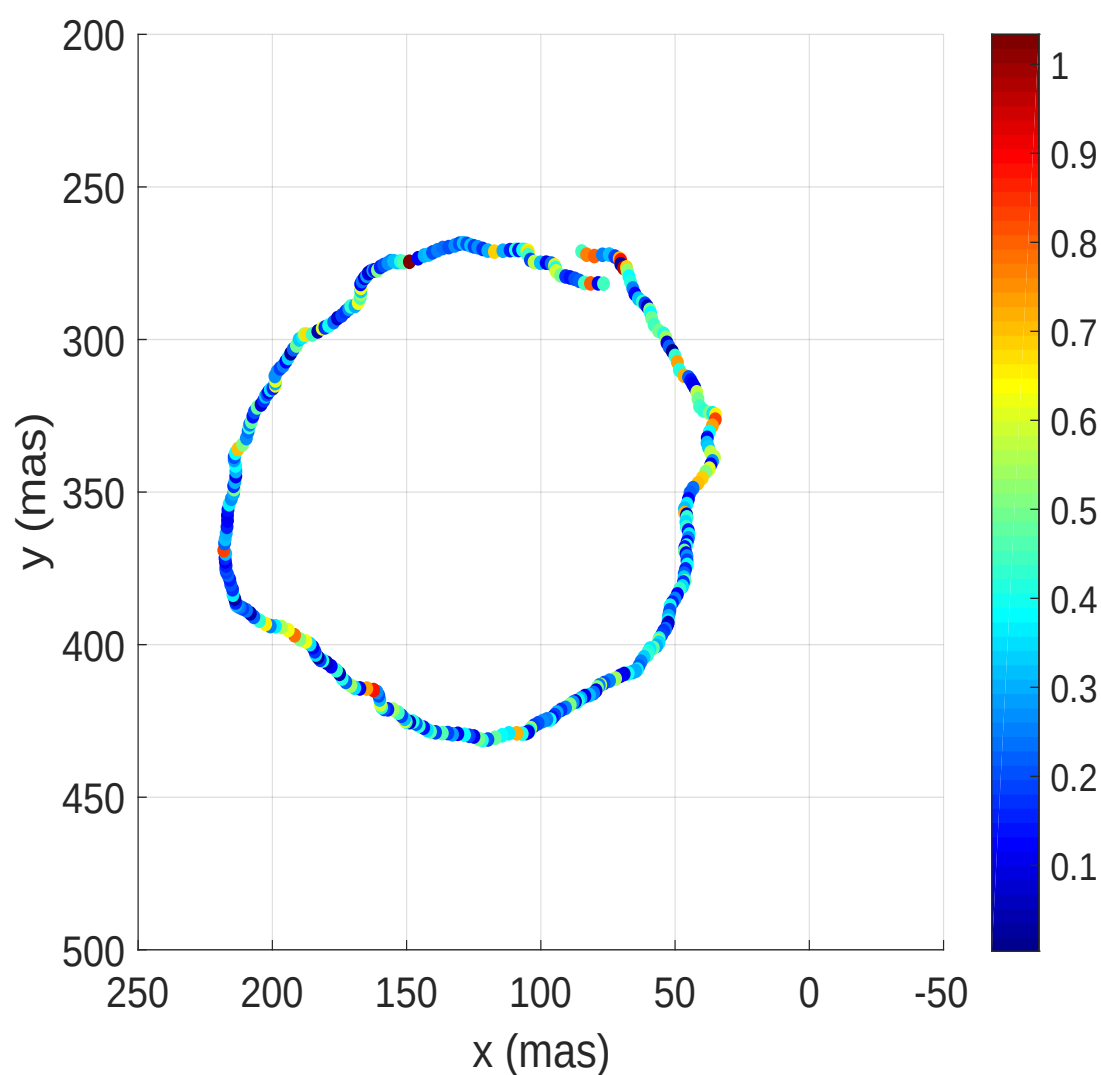


Fig. 2: Plot of the polar motion path for 2019 with corresponding 1-day prediction residual values. The residuals are the RMS of the combined polar motion x and y residual values and are in units of milliseconds of arc (mas) and correspond to the color-coded vertical bar at the right ranging from less than 0.1 (dark blue) to greater than 1.0 (dark red) mas.

Nxdaily solution. For example, by the polar motion 17:00 UTC <MJD> solution time, the most recently computed IGS rapid observation solution (IGS rapid), which has an epoch at midpoint of 12:00 UTC noon from the previous day, <MJD-1>, is available. In addition, there are two IGS

ultras available that contain an epoch at midpoint after the IGS rapid. By 21:10 UTC <MJD>, the IGS has produced an updated IGS ultra, the 18-hr solution, and the corresponding EOP solution will use this latest data. Similarly, the 03:10 UTC and 09:10 UTC solutions will have later IGS ultra data available as shown in the table. Finally, for the next day, <MJD+1>, the sequence of IGS Rapids and Ultras will repeat – the 17:00 UTC <MJD+1> solution will have the next IGS rapid solution whose midpoint was at 12:00 UTC <MJD> along with the next 6-hr and 12-hr Ultras.

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

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

Unfortunately, unlike the AR 2017 Tables 3a, 3b, 3c, and 3d, the prediction days (especially the 0 and 1-day predictions) for polar motion and UT1–UTC RMS residuals, shown in Tables 3a, 3b, 3c, and 3d, do not follow an expected pattern. The expected pattern was that as more observations become available (as shown in Figure 3 and Table 4b), the RMS values would become smaller; however, for 2019 (and for 2018), the resulting statistics do not follow this pattern in most cases. These results were caused by an error in the Nxdaily EOP software that prevented additional updated data from being used, and on September 15, 2019, the software problem was corrected.

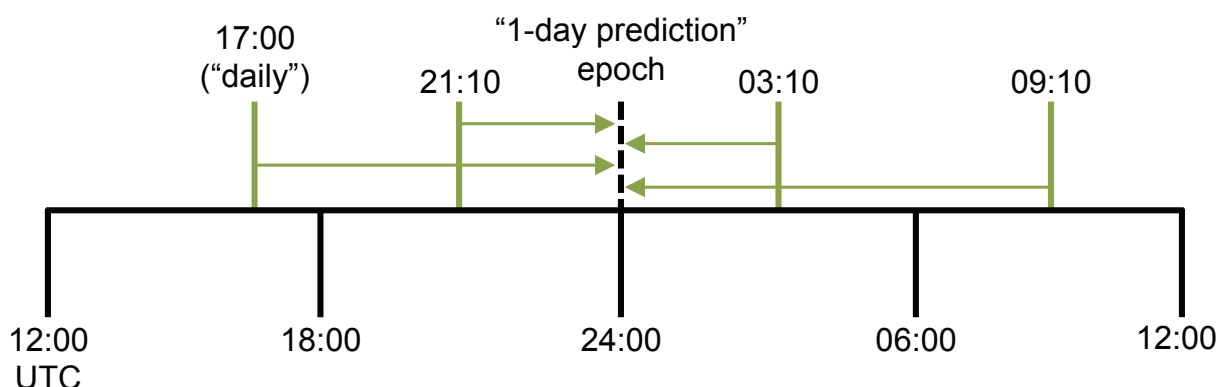


Fig. 3: Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP “daily” solution produced at 17:00 UTC. Each EOP solution update time is shown by the vertical green lines at 17:00, 21:10, 03:10 and 09:10 UTC, respectively. At each of these times, the latest observations are obtained.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

To highlight the effect of this code correction, using only the period 15 September to 31 December 2019, the PMx and PMy statistics corresponding to those in the Table 3c were computed. The 1-day PMx and PMy residuals during this period were 0.172 and 0.133 mas (respectively), which are comparable to the 2017 statistics, namely, 0.13 and 0.092 mas; the 5-day PMx and PMy residuals were 1.70 and 1.04 for 2019 and 1.78 and 1.15 mas in 2017. Thus, with this correction implemented, it is anticipated that this trend will continue for the 2020 statistics; namely, that the Nxdaily residuals, especially for polar motion, will show noteworthy improvements as more input observations become available and used as indicated in Figure 3.

A flowchart that shows the algorithm used in determining the CPOs is shown in Figure 4. Celestial pole offsets are predicted for up to 90 days in advance using a combination of projected empirical models and autoregressive components. The empirical models are fit to past VLBI observations of dX and dY and the autoregressive [AR(4)] components are fit to the residuals between the past VLBI observations and models. The empirical models for dX and dY are composed of offsets, rates, annual and semiannual periodic terms as well as terms with periods of 423.28 days (free-core nutation), 9.1 years, and 27.55 days. In addition the residuals from the model starting with the observations of the four days preceding the date of prediction are used in autoregressive adjustments. Expected errors associated with the predictions are computed based on the past performance of the process. In addition, a bias, based on several years of past observations compared to the 14 C04 solution, is computed and applied to ensure consistency with the 14 C04 solution. Since CPOs are based solely on VLBI data, if

no new VLBI 24-hour session observations are available, a new rapid combination/prediction of these angles is not determined. Therefore, the predictions of celestial pole offsets start before the solution epoch and the length of the prediction into the future can and does vary in the daily solution files. The RMS differences between the daily predictions and the 14 C04 for 2019 are provided in Table 5.

The results in Table 5 contain the RMS of the differences between CPO predictions produced by the daily EOP solutions (as described in the previous paragraph) and the 14 C04 combination solution for 2019. For the dX residual prediction days, it was noticed that there were several outliers that were greater than 3σ . When the outliers are removed, the dX RMS residuals are reduced to 0.07, 0.07, and 0.09 mas for the 0-, 1-, and 40-day prediction days. Similarly, for the $d\psi$ residual prediction days, removal of outliers would result in 0.18, 0.20, 0.21, 0.21, and 0.22 mas for the 0-, 1-, 5-, 10-, and 20-day prediction days. If a reason is determined for the large outliers, this information may be presented at an upcoming conference or meeting.

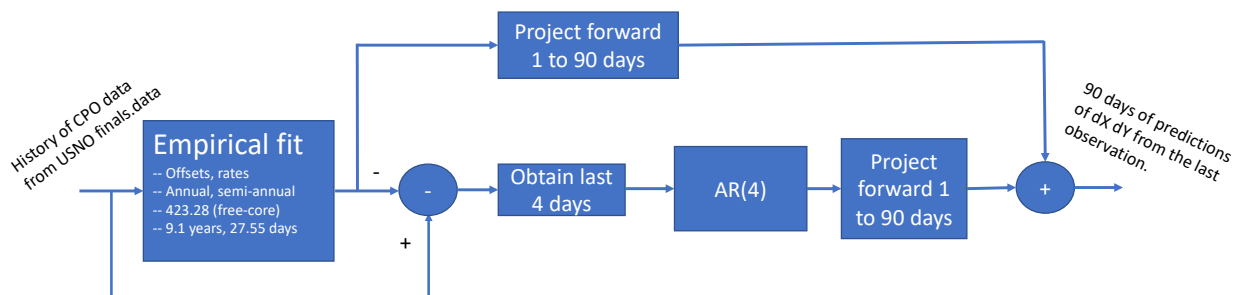


Fig. 4: Flowchart of CPO prediction algorithm. Predictions out to 90 days are made from a) combining an extrapolated empirical model forward in time and b) an extrapolated autoregressive fit to residuals of past CPO observations minus an empirical fit.

Predictions of TT–UT1, up to 1 October 2030, are given in Table 6. They are derived using a prediction algorithm similar to that employed in the Bulletin A predictions of UT1–UTC. Up to twenty years of past observations of TT–UT1 are used. Estimates of the expected one-sigma error for each of the predicted values are also given. These errors are based on analyses of the past performance of the model with respect to the observations.

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

Table 4: Available data for each Nxdaily solution is listed in Table 4a) for Polar Motion and Table 4b) for UT1–UTC. The 24-hr VLBI contributors are not included due to a > 7 day latency between observation and EOP solution integration. (Note that 00:00 refers to midnight UTC; -06:00 refers to 18:00 UTC of the previous day; +06:00 refers to 06:00 UTC of the current day, etc.)

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

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

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

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

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

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

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

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

Table 5: *RMS of the differences between the celestial pole offset predictions (also known as nutation offsets) produced by the daily solutions and the 14 C04 combination solution for 2019.*

Days in Future	dX (mas)	dY (mas)	d ψ (mas)	d ϵ (mas)
0	.10	.06	0.26	0.08
1	.11	.06	0.28	0.08
5	.09	.07	0.26	0.08
10	.10	.07	0.26	0.09
20	.09	.08	0.25	0.09
40	.10	.08	0.25	0.10

Center Activities for 2019

During 2019, several changes to the input data series, the usage of such data, or to output results were made.

A list of these upgrades is as follows:

- a) On 01 August 2019, the USNO VLBI 24-hour and intensive data series were upgraded to the usno2019c series, and
- b) On 29 August 2019, the NASA Goddard VLBI 24-hour and intensive data series were upgraded to the gsfc2019a series;

In addition, the method of computing statistics for the second instance of the IGS Final comparison in the file gpspol.asc during the last 30 days has been updated to use the more accurate smoothing cubic spline used in the EOP combination.

Efforts continued in the following areas as well:

- a) Studying combined U.S. Navy AAM and OAM inputs to improve polar motion predictions (Stamatakos *et al.*, 2016a and 2016b; Stamatakos *et al.* 2017a, 2017b, 2018a, 2018b, and 2019);
- b) Studying methods to i) improve UT1–UTC derivative (or LOD) inputs, such as UTGPS, IGS LOD, USNO LOD, and AAM, to the EOP combination, and ii) better optimize the use of these inputs in the EOP solution;
- c) Upgrading the simulation environment algorithms used to test code changes, input data series, and configurations to the EOP software and processing;
- d) Continuing efforts to test a greatly improved WSCS being developed to improve the EOP combination. One significant improvement that has been developed is that this greatly improved

Table 6: Predicted values of $TT-UT1$, 2020–2030. Note that $UT1-TAI$ can be obtained from this table using the expression $UT-TAI = 32.184s - (TT-UT1)$.

DATE		TT–UT1 (s)	Uncertainty (s)	Table 6 cont.			
2020	1 Jul	69.56	0.024	2025	1 Oct	73.	1.738
2020	1 Oct	69.4	0.600	2026	1 Jan	73.	1.778
2021	1 Jan	69.4	0.668	2026	1 Apr	73.	1.816
2021	1 Apr	69.4	0.736	2026	1 Jul	73.	1.853
2021	1 Jul	69.4	0.803	2026	1 Oct	73.	1.887
2021	1 Oct	70.1	0.870	2027	1 Jan	73.	1.921
2022	1 Jan	71.0	0.936	2027	1 Apr	74.	1.953
2022	1 Apr	71.1	1.000	2027	1 Jul	74.	1.983
2022	1 Jul	71.	1.064	2027	1 Oct	74.	2.012
2022	1 Oct	71.	1.126	2028	1 Jan	74.	2.039
2023	1 Jan	71.	1.186	2028	1 Apr	74.	2.065
2023	1 Apr	72.	1.245	2028	1 Jul	74.	2.090
2023	1 Jul	72.	1.302	2028	1 Oct	74.	2.114
2023	1 Oct	72.	1.358	2029	1 Jan	74.	2.136
2024	1 Jan	72.	1.411	2029	1 Apr	75.	2.157
2024	1 Apr	72.	1.463	2029	1 Jul	75.	2.177
2024	1 Jul	72.	1.514	2029	1 Oct	75.	2.196
2024	1 Oct	72.	1.562	2030	1 Jan	75.	2.214
2025	1 Jan	72.	1.609	2030	1 Apr	75.	2.231
2025	1 Apr	73.	1.654	2030	1 Jul	75.	2.247
2025	1 Jul	73.	1.697				

WSCS will accept derivative state inputs (such as LOD in combination with $UT1$);

e) Continuing efforts to improve the EOP prediction algorithms. (These efforts would involve literature searches of advanced algorithms, prototyping, testing, and evaluation.);

f) Using new VLBI w-series intensive series (such as the Mauna Kea to Wettzell baseline) as an additional input series in the operational EOP solution;

g) Preparing to possibly use the Very Long Baseline Array (VLBA) estimates as additional $UT1-UTC$ inputs to the EOP solution (Stamatakis, Luzum, Zhu, & Boboltz (2012));

- h) Finalizing scripts to validate a new-version EOP solution file that has the following characteristics: i) updated daily, ii) contains EOP data going back to 1973, iii) re-solved combination results for one year in the past, and iv) re-computed polar motion and UT1–UTC prediction data for one year in the future.

Rapid Service Input Data Contributors and Products

A list of the observational and forecast inputs to the EOP combination and prediction solutions are provided in Table 7a. Table 7b lists a few non-observational and non-forecast inputs; in addition, these tables indicate which EOPs are used from each contributor.

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

As indicated in each IERS Bulletin A since late October 2019, the US Naval Observatory's Rapid Service/Prediction Center web and FTP sites (at maia.usno.navy.mil and toshi.nofs.navy.mil) are undergoing modernization and have been offline since 24 October 2019. The expected completion of work and return of service is no earlier than Autumn of 2020. The official announcement from the U. S. Naval Observatory of this information is contained in Figure 5. One may visit <https://www.usno.navy.mil> and submit a Requirements Form to the USNO Public Affairs Official (PAO) if the information you are seeking is not accessible via another means. If the Requirements Form is not available, please contact the USNO PAO Geoff Chester directly at email address geoff.chester@navy.mil or phone number 202 762 1438.

This modernization has also lead to the indefinite cessation of IERS Bulletin A distribution emails. Alternative methods for email distribution were researched, however, given: a) the resources involved in using an approved email distribution method, b) more modern and reliable distribution methods available to users, and c) that no future plans for the creation agreed-upon, reliable email distribution have been made, it is doubtful that there will be restoration of the Bulletin A distribution email service.

Until 31 October 2020, the daily and Bulletin A EOP data will be hosted by NASA's Archive of Space Geodesy Data server at <ftp://cddis.gsfc.nasa.gov/pub/products/iers>. Daily EOP data is uploaded by 18:00 UTC and Bulletin A EOP weekly data are available by 20:00 UTC, nominally on Thursdays. Users should please verify results obtained from this site, as the RS/PC cannot guarantee the integrity or timeliness of files provided at this site. It is expected that as of 31 October 2020, all unencrypted ftp service will be permanently discontinued at CDDIS. For other download options from CDDIS, such as HTTPS or FTPS, please refer to the https://cddis.nasa.gov/About/CDDIS_File_Download_FAQ.html.

Lastly, updated EOPs may be available at IERS: <https://datacenter.iers.org/eop.php>. EOP data files are uploaded directly from USNO to this site each day. For further information, contact the IERS directly.



DEPARTMENT OF THE NAVY
U.S. NAVAL OBSERVATORY
3450 MASSACHUSETTS AVE. N.W.
WASHINGTON, DC 20392-5420

IN REPLY REFER TO
5230
Ser N3-EO/072
19 Mar 2020

From: Superintendent, U. S. Naval Observatory
To: Internal Earth Rotation and Rapid System

Subj: NOTIFICATION OF USNO USER IERS RAPID SERVICE/PREDICTION WEBSITES

1. The U. S. Naval Observatory's IERS Rapid Service/Prediction web/FTP sites (maia.usno.navy.mil; toshi.nofs.navy.mil) and the IERS Conventions web site (maia.usno.navy.mil/conventions), are offline as they undergo modernization. These modernization efforts have been interrupted by current events and estimated return to service is no earlier than autumn of 2020.
2. Please visit <https://www.usno.navy.mil> and submit a Requirements Form to the USNO Public Affairs Official (PAO) if the information you are seeking is not accessible by another means. If the Requirements Form is not available, please contact the PAO Mr. Geoff Chester at email address Geoff.chester@navy.mil or telephone +1 (202) 762-1438.

D. R. KUEHN

Fig. 5: Official notification from the U. S. Naval Observatory stating that the web and ftp servers, maia.usno.navy.mil and toshi.nofs.navy.mil, are offline as they undergo modernization.

Table 7a: Operational input data used in the IERS Bulletin A EOP combination and prediction software. All the observational and forecast data used in operations is listed in the Contributor column. For each contributor, a check mark is provided under each EOP column if that particular EOP is used operationally. For example, the GSFC intensives (GSFC Int.) is used in the combination and prediction software, and the EOP that is used is UT1–UTC; no other EOPs from this contributor are used in the software.

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

^a The word “Int” is an abbreviation of the word Intensive.

^{b, c, d, e, f} Defined in the Acronyms of the Appendix of this report.

^g Both observational and forecast inputs are available.

Table 7b: Miscellaneous input data available to the IERS Bulletin A EOP solution. The IERS EOC solution is used in diagnostic calculations and plots and is used in polar motion predictions. The IERS RS/PC solution is used in diagnostic calculations and plots and is used as the a priori solution to the WSCS.

Contributor	PM-x	PM-y	UT1–UTC	LOD	$d\psi$	$d\epsilon$	dX	dY
IERS EOC	✓	✓	✓	✓	✓	✓	✓	✓
IERS RS/PC	✓	✓	✓	✓	✓	✓	✓	✓

Table 8 lists the locations and update times of several of the EOP solutions discussed in this report. The first column lists the EOP solution time in UTC. These are the approximate times when an EOP result

is computed; if a problem occurs, the solution may actually become available as much as one hour later than what is listed. The second column contains the subdirectory under each FTP or web address listed in the above paragraph where an EOP solution resides. For example, at <ftp://cddis.gsfc.nasa.gov>, there exists a subdirectory called “eop0300utc” (i.e., <ftp://cddis.gsfc.nasa.gov/pub/products/iers/eop0300utc>), where an EOP solution update computed at approximately 03:10 UTC will be uploaded each day.

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

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

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

² The delay between solution time and posting time occurs for two reasons: a) the time it takes EOP personnel to verify and confirm the solution prior to its uploading to the CDDIS ingest server and b) an additional few minutes for transfer from ingest to publication servers at <ftp://cddis.gsfc.nasa.gov/pub/products/iers> (and the corresponding HTTPS and FTPS sites).

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

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

3.5.3 Conventions Centre

Introduction

The Conventions Centre provides updated versions of the IERS Conventions in electronic form following approval by the IERS Directing Board (DB) and printed versions at less frequent intervals than the electronic updates, mainly when major changes are introduced. The Centre is operated jointly by L'Observatoire de Paris (OP) and the U.S. Naval Observatory (USNO).

The IERS Conventions web is located at <http://iers-conventions.obspm.fr>. Until 24 Oct 2019 the IERS Conventions web and ftp were located at <http://maia.usno.navy.mil/conventions/> and <ftp://maia.usno.navy.mil/conventions>. The US Naval Observatory's Rapid Service/Prediction Center web and FTP sites (at maia.usno.navy.mil and toshi.nofs.navy.mil) have been undergoing modernization since that date. The expected completion of work and return of service is no earlier than Autumn of 2020. The printed IERS Conventions (2010), IERS Technical Note 36, is available in electronic form at these URLs and at <https://www.iers.org/IERS/TN36>. Updates continue to be provided in electronic form and are configuration managed starting in 2018. Conventions versions, starting with v 1.0.0 through the latest update, v 1.3.0, are found at the following URL: http://iers-conventions.obspm.fr/conventions_versions.php

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

Technical Content of the IERS Conventions

During 2019, one change in the technical content was completed. On 1 April 2019, Chapter 4 was re-written to be consistent with the International Terrestrial Reference Frame 2014 (ITRF2014). Note that Table 4.1 transformation parameters, relating ITRF2014 to previous ITRFs, has been revised.

Conventions Software

Software recommended for use in connection with the IERS Conventions consists largely of the library maintained by the IAU Standards of Fundamental Astronomy (SOFA) available at <http://www.iausofa.org>. The 16th release of this library was made available on 21 July 2020. Further details regarding the specifics of the release can be found at <http://www.iausofa.org/current.html>.

Chapter	Old Chapter #	Title	Position	Applicant	Status of Rewrite as of 30 SEP 2020
1	1	General definitions and numerical standards	Chapter Editor-in-Chief	Nick Stamatakos	In late 30-Sep-2020, Detlef Angermann provided a status update.
			Chapter Expert	Detlef Angermann	
			Assistant Chapter Expert	George Vergos, Riccardo Barzaghi	
2	10	General relativistic models for space-time coordinates and equations of motion	Chapter Editor-in-Chief	Michael Efroimsky	A conversation among the Chapter Editor and Experts and the IERS CC staff has taken place, regarding software issues. Discussions of the necessary changes for the Chapter have started.
			Chapter Expert	Sergei Klioner	
			Assistant Chapter Expert	Sergei Kopeikin	
3	2/3 *	Celestial reference system and frame	Chapter Editor-in-Chief	Jean Souchay, Bryan Dorland	
			Chapter Expert	Sebastien Lambert	
			Assistant Chapter Expert	Dmitry Pavlov	
4	4	Terrestrial reference systems and frames	Chapter Editor-in-Chief	Dennis McCarthy, Frank Lemoine.	Altamini has made several requests and schedules for obtaining data needed for ITRF. New ITRF needed for rewrite.
			Chapter Expert	Zuheir Altamimi	
			Assistant Chapter Expert	Xavier Collilieux; Mathis Blossfeld	
5	5	Transformation between the International Terrestrial Reference System and the Geocentric Celestial Reference System	Chapter Editor-in-Chief	José Ferrandiz Leal, Nick Stamatakos	Chapter 5 re-write proposed for simplification guide by McCarthy, Stamatakos and Bizouard. Bizouard requests tex version for more editing. Stamatakos preparing tex version. Leal and Escapa will provide a status update Oct 2020.
			Chapter Expert	Alberto Escapa	
			Assistant Chapter Expert	Nick Stamatakos, Dennis McCarthy	
			Software Editor	Maria Davis	
6	6	Geopotential	Chapter Editor-in-Chief	John Ries, Srinivas Bettadpur, Erricos Pavlis	
			Chapter Expert	Jean Paul Boy	
			Assistant Chapter Expert		
7	7	Displacement of reference points	Chapter Editor-in-Chief	Erricos Pavlis	
			Chapter Expert	Jean Paul Boy	
			Assistant Chapter Expert	Nick Stamatakos, Dennis McCarthy, Dmitry Pavlov	
			Software Editor	Maria Davis	
8	8	Tidal variations in the Earth's rotation	Chapter Editor-in-Chief		
			Chapter Expert	John Gipson.	
			Assistant Chapter Expert	Christian Bizouard	
			Software Editor	Maria Davis	
9	9	Models for atmospheric propagation delays	Chapter Editor-in-Chief		
			Chapter Expert		
			Assistant Chapter Expert	Johannes Boehm; Erricos Pavlis, Manual Hernandez ^A	
			Software Editor	Maria Davis	
10	11	General relativistic models for propagation	Chapter Editor-in-Chief	Michael Efroimsky	Discussions on possible improvements of the Chapter have started. The active re-writing of the Chapter will begin after the content of Chapter 2 is clarified.
			Chapter Expert	Sergei Klioner	
			Assistant Chapter Expert	Sergei Kopeikin	

Table 1: Status of participation in the IERS Conventions major update. "Old Chapter #" refers to what was published at the time of applications. A reordering of Chapters was agreed to at the 18 Sep 2018 IERS Conventions Centre staff telecon. For Chapter 9 (Models for atmospheric propagation delays), the following is noted: Boehm said he could help with the Microwave troposphere section; Pavlis said he could help with the optical wavelengths section. Hernandez cannot start to contribute until 2021.

Major Conventions Update

In anticipation of rewriting the IERS Conventions within the next few years, a call for participation was made. Many experts volunteered to be Chapter Editors-in-Chief, Chapter Experts and Assistant Experts, along with a Software Editor. The table below lists the Conventions major revision chapters along with the latest associated list of filled and vacant positions. There are still many positions vacant, and we urge those reading this report to reach out to colleagues to inform them of open positions or to consider volunteering by submitting a curriculum vitae along with a possible letter of support from their sponsoring institution.

In addition, on 17 June 2020, a call for a status update was provided to all Conventions contributors. The last column of Table 1 shows the

responses that have been received from that call for a status update. Additional calls for status updates will be sent in 2020 and 2021.

As part of the Conventions update, the Conventions staff has begun using the GitLab web-based DevOps lifecycle tool to implement a more robust and comprehensive configuration management scheme for Conventions updates. (Within some resources limitations, the Conventions Centre staff can provide assistance with using GitLab upon request. A training class led by Conventions staff member, Maria Davis, was to have been held in early 2020 to aid those unfamiliar with using GitLab; however, due to COVID-19 travel restrictions, the training class has been suspended pending safer travel and attendance and pending future funding approvals.)

In addition, Slack instant messaging has been implemented to enhance communication among Chapter contributors. Many of the re-write staff have signed up and are utilizing Slack to provide quick turnaround for discussions and dissemination of information regarding the Conventions. All contributors were notified via email and via Slack instant messaging of proposed simplifications to the Conventions text. An example from Chapter 5 was provided to contributors to guide them in this recommendation. Lastly, many contributors attended the 2019 Unified Analysis Workshop in Paris, France, where Conventions-related topics were discussed among various disciplines of the IERS, Global Geodetic Observing System (GGOS), and other associated organizations.

Acknowledgements

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

Conventions Centre Staff

- Nick Stamatakos (USNO), co-director since 1 January 2016. (Per existing agreement between the IERS DB and the IERS Conventions, the USNO co-director became the representative to the IERS Directing Board on 1 January 2019.)
- Christian Bizouard (OP), co-director since 1 September 2016 (and the representative to the IERS Directing Board through 31 December 2018).
- Sébastien Lambert (OP)
- Maria Davis (USNO)
- Dennis McCarthy (USNO, contractor)

Nick Stamatakos, Christian Bizouard

3.5.4 ICRS Centre

The International Earth Rotation and Reference System (IERS) International Celestial Reference System (ICRS) Centre is tasked with the maintenance of the International Celestial Reference System (ICRS) and the International Celestial Reference Frame (ICRF) for the international astronomical and geodesy communities. Responsibilities are shared jointly between Paris Observatory (OP) and the U.S. Naval Observatory (USNO). Critical ICRS and ICRF-relevant activities from 2019 are described for both OP and USNO in the following sections.

Paris Observatory IERS ICRS Centre Activities During 2019–2020 The International Reference Frame ICRF3

Resolution B2 of the XXX IAU General Assembly (IAU 2019) resolves that as from 1 January 2019 ICRF3 is the fundamental realization of the International Celestial Reference System (ICRS). This third representation of the International Celestial Reference System (ICRS) in radio wavelengths is a catalog of radio source positions described in Charlot et al. (2020). The ICRF3 consists of three catalogs at bands S/X, K and X/Ka with 4536, 824 and 678 objects, respectively (<http://iers.obspm.fr/iers-pc/newwww/icrf>). Objects in the new frame had been used to orient the second Gaia data release DR2 catalog onto the ICRS, as will be the case for the Gaia final catalog.

Monitoring of the ICRS

Monitoring the ICRS is a mission of the IERS ICRS Centre. This includes verifications of the stability of the axes of the system materialized through the frame, identification of the possible deformations of the frame and tracking the astrometric evolution of its defining sources. Another aspect of this activity consists of the analysis of individual solutions submitted by the VLBI analysis centers to the International VLBI Service for Geodesy and Astrometry (IVS). The IERS ICRS Centre at Paris Observatory developed the tools for determining the orientation of the axes, characterizing the deformations of the frame and analyzing the astrometric quality of radio source positions (Lambert 2014). For this report, analyses with respect to the conventional reference ICRF3 are presented, as well as with respect to Gaia DR2, which constitutes a preliminary version of the catalog that will allow access to the ICRS in optical wavelengths.

Analysis of Recent VLBI Catalogs Data

We analyzed five catalogs submitted to the IVS in 2019. The catalogs were respectively submitted by the Space Geodesy Centre of the Italian Space Agency (ASI/CGS; solution asi2019a), by Geoscience Australia (aus2019a and 2019b), by Paris Observatory (opa2019a) and by the United States Naval Observatory (usn2019c). The two solutions aus2019a and aus2019b were obtained with the OCCAM geodetic VLBI analysis software package (Titov et al. 2004), whereas the other four

catalogs were obtained with Calc/Solve (Ma et al. 1986). The catalogs were released after the date of adoption of the ICRF3; therefore, their individual frames had been oriented to ICRF3 by applying no net rotation constraints, with the exception of the ASI solution, which has been oriented to ICRF2 (Fey et al. 2015). Positions in ICRF3 had been adopted for the a priori catalogs in the solutions, with the exception of ASI, where the a priori source positions are the ICRF2 coordinates. In our analysis we have compared these individual solutions to the catalog representing ICRF3 in the S/X bands (ICRF3X in this report). The 2983 sources in common between the ICRF3 and the second Gaia data release (DR2; Prusti et al. 2016; Brown et al. 2016, 2018; Mignard et al. 2018) have been used also as a reference for comparison.

Overview of the Catalogs

The number of sources in each catalog, the mean epoch of the observations, and the median positional errors (for RA cos DEC, Dec, and for the error ellipse major axis) are reported in Table 1. The standard error of the catalog positions differs in the solutions; the smallest values from ASI may depend on the choice of very good sources, AUS positions might be influenced by a large number of sources with errors in the range 0.6 – 1 mas in the Southern hemisphere. The USN solution did not consider a number of “special” sessions including VCS sessions and provide therefore coordinates for a relatively small number of sources.

Table 1: *Statistic information of the catalogs here reported. N is the number of sources. The mean epoch corresponds to the average of the mean observational epochs of each source. N is the number of sources, e_RA*, e_Dec are respectively the median standard errors in right ascension (scaled by cos dec) and in declination, e_EEMA is the median major axis of error ellipses. Unit is μ as.*

Catalog	N	Epoch	e_RA*	e_Dec	e_EEMA
opa2019	a4468	2010.93	116.90	196.55	205.89
aus2019	a4529	2012.71	261.57	478.00	496.19
aus2019	b4645	2012.96	273.72	471.20	493.59
asi2019	a3850	2013.78	74.98	130.80	133.37
usn2019	c2390	2012.01	171.77	259.80	289.09

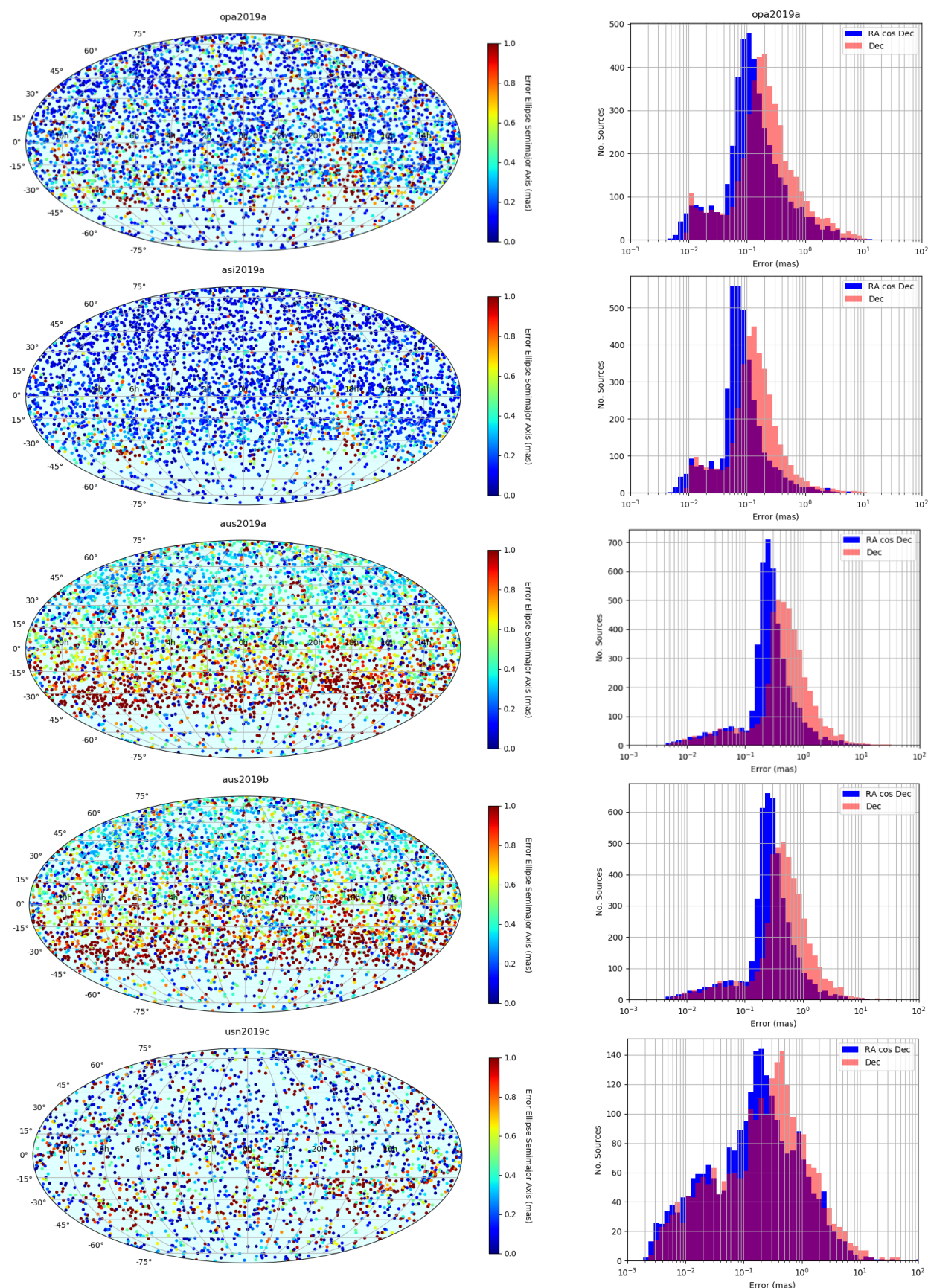


Fig. 1: Left: sky distribution of the catalogs highlighting the overall positional error computed as the major axis of the error ellipse. Right: distribution of the standard errors on source position.

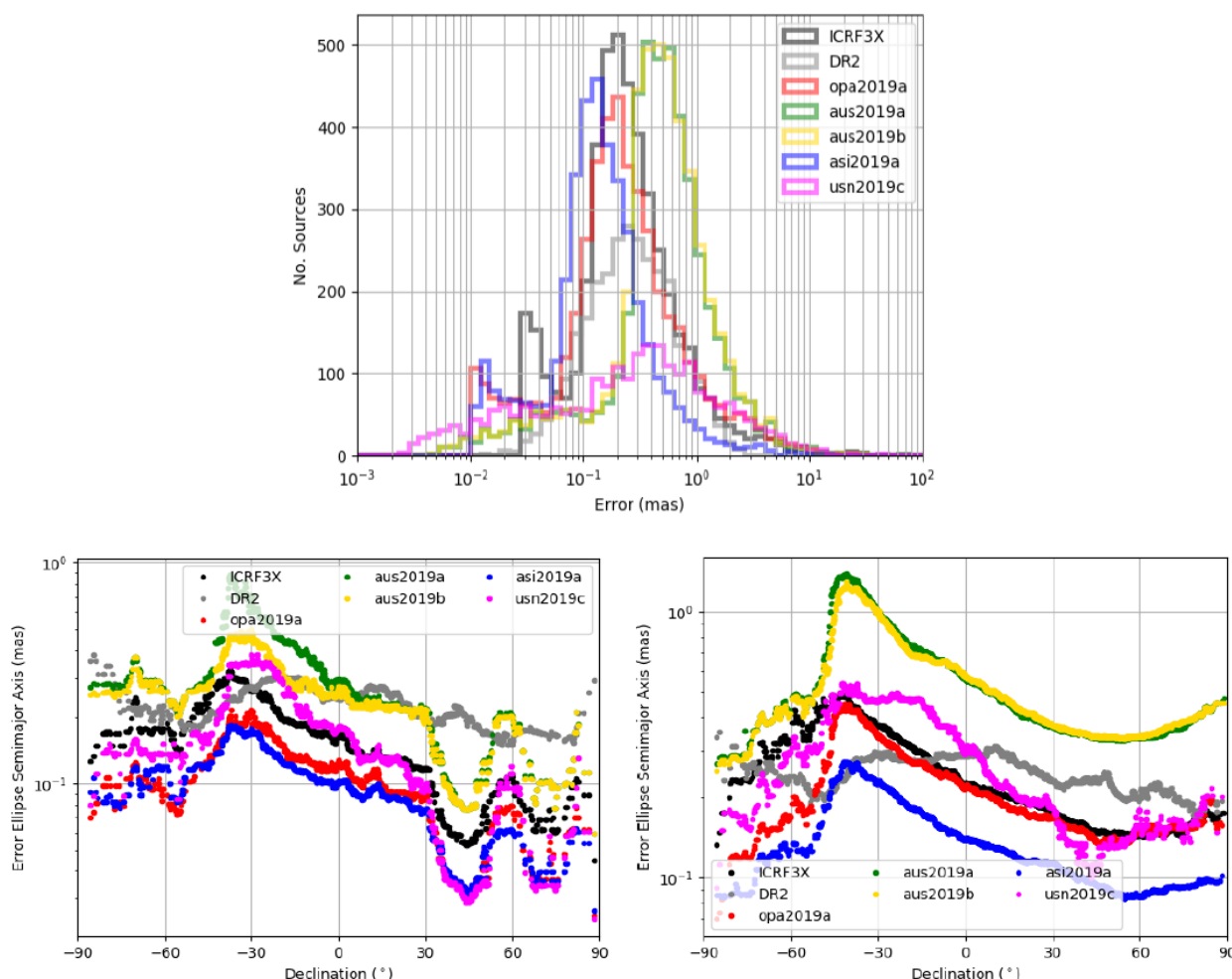


Fig. 2: Top: overall comparison of the standard error distribution. Bottom: standard errors in source positions as a function of the declination smoothed by taking the running median within bins of 15 degrees, for sources common to all catalogs (left) and for all sources in each catalog (right).

The sky distribution of the radio sources in each catalog is plotted in Figure 1 together with the distribution of the standard errors. In the sky maps, the color indicates the overall error computed as the major axis of the error ellipse, calculated using the correlation information between the coordinates as provided in the catalogs. Figure 2 presents three plots; on top the error distribution, including that of the catalogs used as reference in the comparisons (ICRF3X and Gaia DR2); at the bottom the dependence of the error on the declination including the common sources to all catalogs (left) and all sources in each catalog (right) are displayed for which we took the running median error within windows of 15° . The plots show a clear declination-dependent error for the individual catalogs. When sources common to all catalogs are considered, the behavior of the VLBI solutions is similar, peaking at about -30° declination, and reaching small error values around $+45^\circ$ declination, certainly due to the presence of a substantial number of

good astrometric common sources in that region. This effect is not visible in the plot where all sources in each catalog are considered. Both AUS solutions show the largest errors, particularly at mid-latitudes in the Southern hemisphere, very probably due to the network asymmetry and the quality of the sources in the South, visible in the plots of Fig. 1. The Gaia scanning law allows to cover both hemispheres symmetrically, and in consequence the Gaia DR2 catalog does not show such systematic effects.

Comparison with ICRF3 and Gaia DR2

Figure 3 displays the differences in declination between the catalogs and the references averaged within bins of 200 sources in two configurations: all sources (left) and sources common to all catalogs (right).

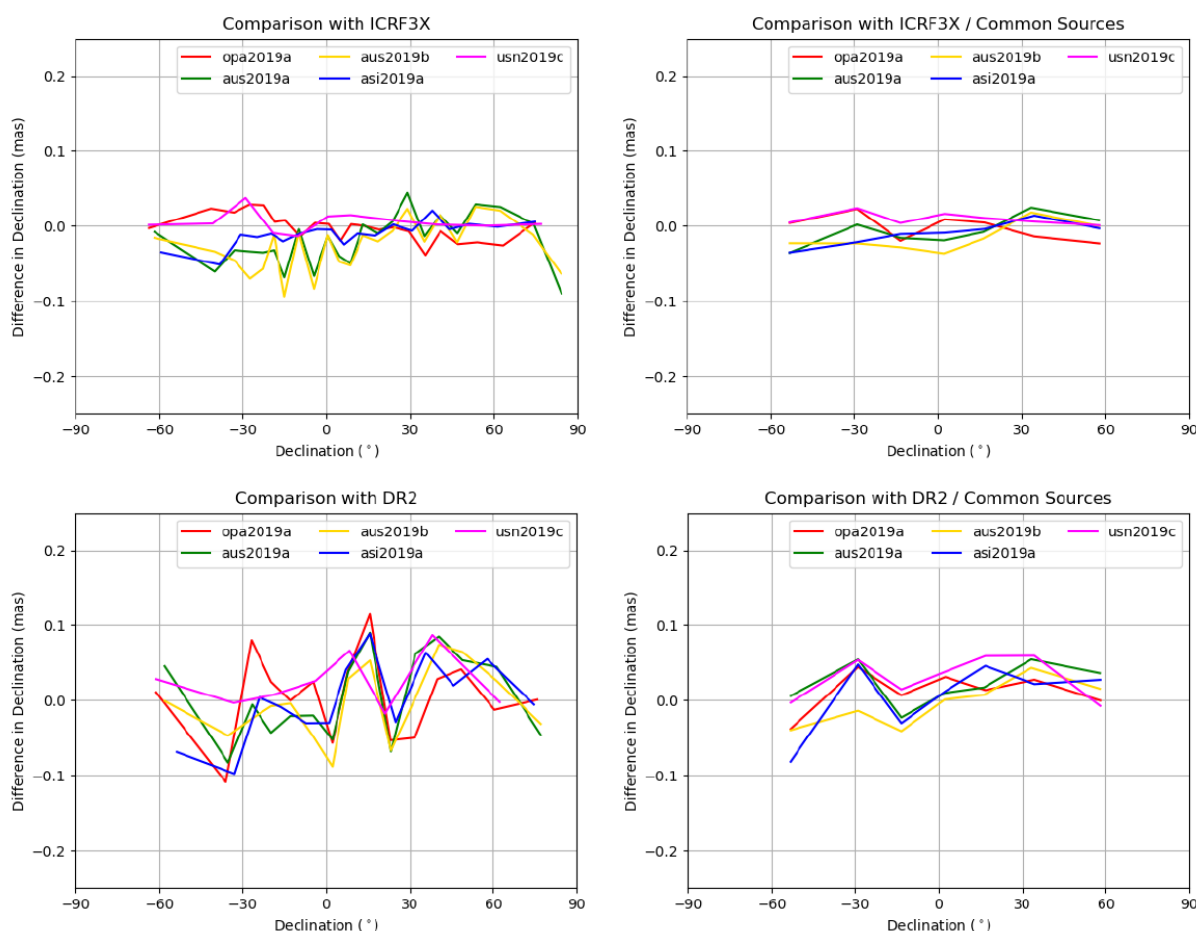


Fig. 3: Differences in declination between the catalogs and the references (ICRF3X: top; Gaia DR2, bottom) averaged in bins of 200 sources sorted by declination for all sources (left) and for common sources to all catalogs (right).

Most deformations are smaller than $50 \mu\text{as}$ when the differences with respect ICRF3X are computed with all the sources in each catalog (top left), only the AUS solutions present effects close to 0.1 mas between

0° and -30° , probably due to the network geometry and the quality of sources at negative declinations. Deformations are smoother when the differences are computed with common sources (top right), they remain within less than $40 \mu\text{as}$. The amplitude of the deformations is bigger when the differences are computed with respect to Gaia DR2, since the sphere of Gaia is in principle not affected by deformations.

Catalog comparisons had been computed using the 16-parameter transformation accounting for rotations around the three axes, a glide, and degree-2 electric- and magnetic-type deformations (see e.g., Mignard and Klioner 2012). The coordinate differences $\Delta\alpha$ and $\Delta\delta$ between a catalog and a reference catalog read:

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

where α and δ are the coordinates of the object in the reference catalog. We used weighted least-squares to solve the system, with weights computed using the available covariance information (i.e., the standard errors on individual source coordinates and their correlation). The values of the transformation parameters adjusted to the catalogs compared to the ICRF3X and Gaia DR2 and their standard errors are reported in Figure 4 for two different set of sources, those common to all catalogs and each reference, and those common between each catalog and the reference. The resulting statistics after removal of systematics are reported in Table 2. Fig. 4 reveals that the results are similar independently from the set of sources used for the comparisons. The comparisons with ICRF3X show rotations of about $50 \mu\text{as}$ around the x and y axes for the OP and ASI solutions, and no significant deformations in all cases. Gaia DR2 has been oriented onto ICRF3, and we could expect no significant rotation between its axes and the VLBI solutions; this is the case, since the significant rotations in the plot correspond to the OP and ASI solutions, rotated with respect to ICRF3X. Deformations are visibly dependent on declination, consistent with Figure 2.

Table 2: *Statistics of the differences of the catalogs to ICRF3X and Gaia DR2 with different sets of common sources, and after removal of large-scale systematics. RA* stands for RA cos_dec. Unit is μ as.*

a. With respect to ICRF3X, N: number of sources common to ICRF3X and each individual catalog.

Catalog	N	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec
opa2019a	4381	76.52	92.83	0.71	0.75	73.31	82.92	0.65	0.6
aus2019a	4433	107.19	122.07	0.83	0.83	106.91	121.4	0.83	0.82
aus2019b	4434	110.68	121.56	0.9	0.84	109.92	120.55	0.88	0.82
asi2019a	3799	69	84.52	0.68	0.71	66.05	75.36	0.62	0.57
usn2019c	2274	62.83	63.88	0.81	0.68	62.74	63.61	0.81	0.67

b. With respect to ICRF3X, N: number of sources common to all catalogs.

Catalog	N	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec
opa2019a	1375	50.55	66.06	0.67	0.89	45.79	51.35	0.55	0.54
aus2019a	1379	69.7	75.32	0.9	0.87	69.21	74.37	0.89	0.85
aus2019b	1379	71.81	75.92	0.97	0.9	70.77	74.4	0.94	0.86
asi2019a	1375	53.85	65.4	0.76	0.85	49.81	53	0.65	0.56
usn2019c	1375	53.9	54.19	0.77	0.63	53.79	53.9	0.76	0.62

c. With respect to Gaia-DR2, N: number of sources common to DR2 and each individual catalog.

Catalog	N	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec
opa2019a	2912	301.75	316.07	2.44	2.37	298.93	311.05	2.39	2.3
aus2019a	2920	354.26	355.35	2.1	1.73	352.41	353.16	2.08	1.71
aus2019b	2920	356.79	353.53	2.14	1.76	354.8	350.8	2.12	1.73
asi2019a	2525	263.54	286.96	2.41	2.48	262.29	283.17	2.39	2.41
usn2019c	1596	262.69	263.91	2.3	2.27	260.82	262.14	2.27	2.24

d. With respect to Gaia-DR2, N: number of sources common to all catalogs.

Catalog	N	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec	Std_RA*	Std_Dec	Chi2_RA*	Chi2_Dec
opa2019a	1375	261.61	262.76	2.54	2.56	258.68	256.66	2.49	2.45
aus2019a	1379	291.64	285.37	2.36	2.09	288.84	281.43	2.31	2.04
aus2019b	1379	288.29	287.63	2.35	2.2	285.41	282.94	2.3	2.13
asi2019a	1375	245.37	253.55	2.45	2.49	243.96	248.34	2.43	2.38

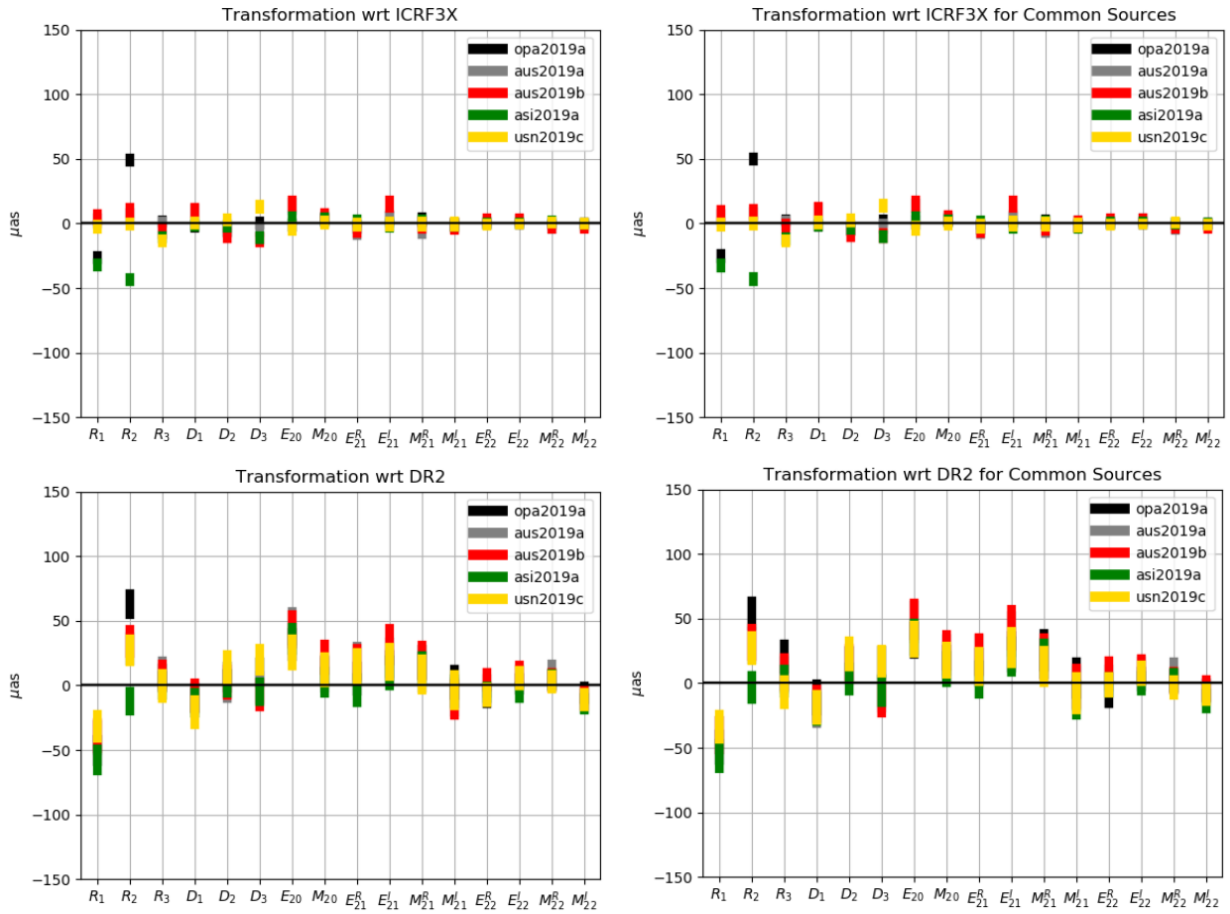


Fig. 4: Transformation parameters between the catalogs under analysis and the reference frames (ICRF3X: top, Gaia DR2: bottom). The plots on the left represent parameters computed with sources common to each individual catalog and the frame used as reference (from top to bottom they correspond to the statistics in Tables 2a and 2c); the plots on the right represent parameters computed with sources common to all the catalogs involved in the comparisons, including the references (from top to bottom they correspond to the statistics in Tables 2b and 2d).

Galactic aberration has been accounted for at the construction of ICRF3. Uncorrected Galactic aberration should provoke a glide of amplitude close to $5 \mu\text{as/yr}$ (e.g., Kovalevsky 2003; Titov et al. 2011) towards the Galactic center (approx. R.A. 265° and declination -29°). A value of $5.8 \mu\text{as/yr}$ for the amplitude of the Galactic aberration has been evaluated in analyses performed at the construction of the ICRF3 (MacMillan et al. 2019). The descriptions of the solutions provided to the IVS used in this report indicate that this correction has been applied in the OP, AUS, and USN solutions (for details refer to <http://ivsopar.obspm.fr/vlbi/ivsproducts/crf/>). The effect of uncorrected Galactic aberration in the ASI solution is not clearly visible in the deformation parameters since the mean epochs of the catalogs are close to that of ICRF3 (2015.0) and Gaia DR2 (2015.5).

**Conclusions and
recommendations**

Five individual catalogs submitted to the IVS in 2019 are analyzed in this report. The axes of their frames are consistent with ICRF3X at the level of $50 \mu\text{as}$ without any zonal deformation beyond $15 \mu\text{as}$. This result is also valid for the ASI solution, which has been aligned to ICRF2, confirming the good consistency between ICRF2 and ICRF3. Compared to Gaia DR2, a similar misalignment, of order $50 \mu\text{as}$ is visible, with significant zonal deformations particularly for the AUS solutions.

For a better evaluation of the consistency of the VLBI products and a better maintenance of the reference frame, we request analysis centers submit solutions aligned to the new reference ICRF3, as well as to adopt the ICRF3 catalogue for the a priori positions in the solutions. In all solutions the correction for the amplitude of the Galactic aberration must be implemented using the recommended value. These catalogs should be as complete as possible, i.e., processing as many VLBI sessions as possible since 1979. Analysis strategies should be rigorously documented and motivated. The main points that will be scrutinized in the next reports will be the zonal systematics, their relation with the Galactic aberration, and the agreement with the current (DR2) and future releases of Gaia.

**Photometric follow-up of ICRF
quasars**

During the year 2019 the funding dossier creation phase for the 1m telescope dedicated to the photometry of active galactic nuclei (AGNs) was completed. The dossier was sent to the French DIM-ACAV financial support and accepted mid-2019. The funds obtained represent more or less one half of the total amount of necessary funds. A second independent funding request was then prepared and sent at the end of the year; results have yet to be received during 2020. This project was initiated in 2015 “ex nihilo” by the choice of the site and the demonstration of its quality (median value of the seeing is $1''$, mode seeing is $0.7''$). A feasibility phase to ensure the possibility to manage a remote instrument was then initiated and completed. The last phase will be the realization of the telescope and the implantation on site once the result for the second funding request is known. The heart of the scientific program of the telescope will be the monitoring of AGNs. Asteroid and exoplanet observations together with GRB optical counterpart follow up, and teaching, will be other tasks devoted to this instrument.

During 2019 the collaboration with Dr. Damjanovic (Belgrade Observatory) continued its program of observations of AGNs for the link between reference systems (magnitude monitoring). Another collaboration with USNO has been established during two meetings at Paris Observatory (FRAMEX project in February and October). The goal is to observe AGNs at various wavelengths (radio, infrared, optical, and X-ray) to better understand some significant radio-optical astrometric offsets.

Validation of the Gaia catalogue in the CU9

The main goal of the Gaia mission is to create an extraordinarily precise three-dimensional map of more than one billion objects (stars, asteroids, quasars) throughout our Galaxy and beyond. The Gaia mission through its successive releases delivers an astronomical catalogue and data archive of unprecedented scope, accuracy and completeness. A large pan-European team of expert scientists and software developers known as DPAC (Data Processing and Analysis Consortium) is responsible for the processing of Gaia's data with the final objective of producing the Gaia Catalogue. Coordinated by the DPAC Executive, the consortium is sub-divided into nine smaller, specialist units known as Coordination Units, or CUs, with each unit being assigned a unique set of data processing tasks.

Some members of the ICRS Centre belong to the CU9/WP944 group, responsible for validation of Gaia Catalogue Data Release with the validation Test Report. The aim of these tests is to check that Gaia data is coherent compared to other known catalogues, so as to accept or reject them for publication. In 2019, we have updated external catalogue files, tests code and reports to validate QSOs and AGNs included in the Gaia Catalogue Data Release DR3. These tests include rotation, cross-matching and completeness of these sources compared with QSO and AGN from external catalogues. The external catalogues used are ICRF3, LQAC5, GIQC, SDSS DR14Q, as well as specific catalogs as AGNs in Extended Sources Catalog where the probability for a QSO or AGN status is well defined.

Astrometric and Photometric Studies from the LQAC-5

One of the important tasks which the ICRS Centre is responsible for concerns the selection of the extragalactic sources that are likely to belong to the future generations of the ICRF. For that purpose, successive updates of the LQAC (Large Quasar Astrometric Catalogue) were constructed, including the LQAC-3 (Souhay et al. 2015) and the LQAC-4 (Gattano et al. 2018).

In 2019 we have published the fifth version of the LQAC, LQAC-5 (Souhay et al. 2019). It consists of a compilation of all the objects identified as quasars by the authors involved in the compilation of the catalogues, with criteria depending on each of these catalogues. In particular, new quasars from the SDSS DR14Q release (Pâris et al. 2018) were cross-matched with the previous LQAC-4 compilation, which lead to 149,084 new objects. Moreover, a great advantage with respect to this previous LQAC-4 version was the cross-match with the Gaia DR2 catalogue, which improved considerably the quality of astrometric data of the common objects. Furthermore, a precious new additional dataset was the inclusion of mid-infrared photometry from AllWISE (Wright et al. 2010). The LQAC-5 contains a total number of 592,809 quasars, which represent a 34% increase with respect to the number of objects recorded in the LQAC-4. Among them, 398,697 quasars were cross-matched with the Gaia DR2 catalogue, which correspond to 67% of the whole LQAC-5 population. Notice that in complement to original information such as multi-band photometry and redshifts directly obtained from the catalogues, we have provided in the LQAC-5 additional information such as morphology index and absolute magnitudes.

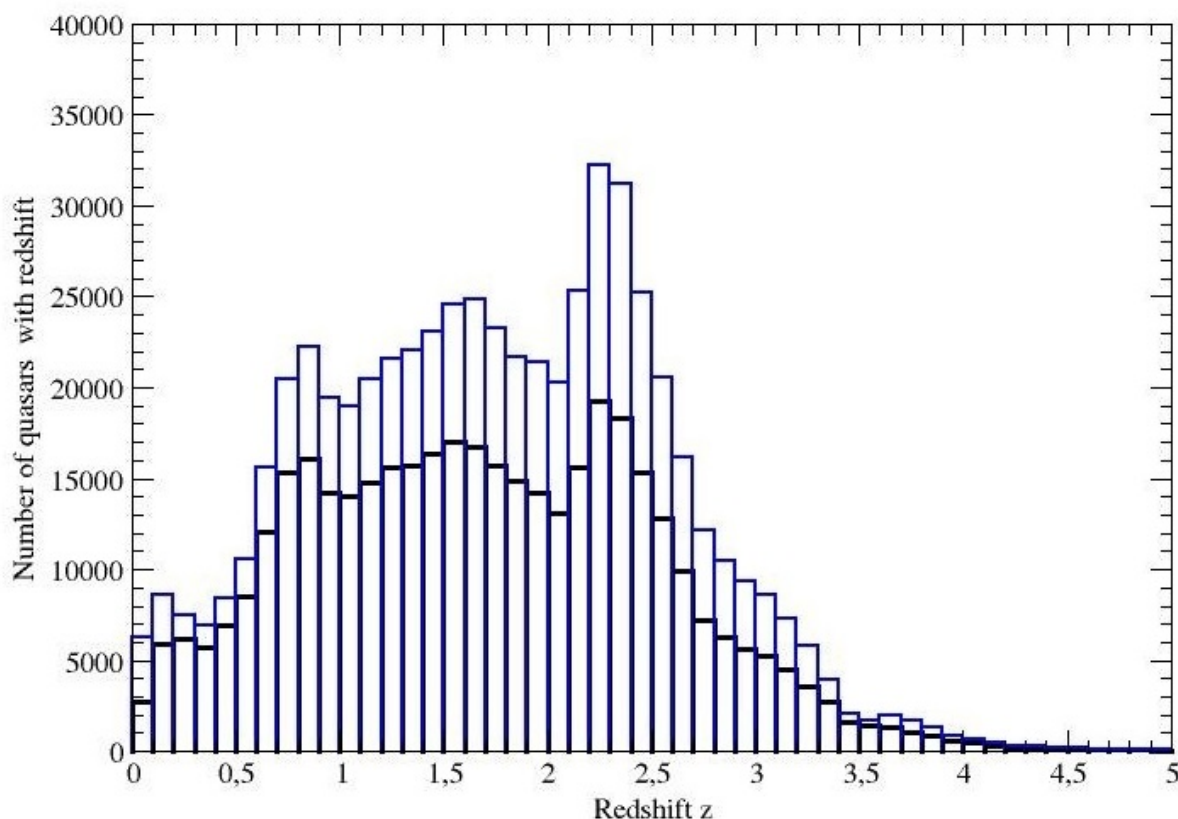


Fig. 5: Redshift distribution of the whole LQAC-5 sample (blue) and of the Gaia DR2 sub-sample (black).

In the following we give some interesting results related to the cross-match between the LQAC-5 and the Gaia DR2 catalogue. In particular, when it is possible, we compare our results with those of Mignard et al. (2018) who constructed what they called the Gaia CRF2, starting from a set of 566,869 AGNs still selected from mid-infrared color-color criteria. The important difference between these objects with respect to our LQAC-5 compilation lies in the fact that no redshift or related spectrum is available, so that they cannot be identified definitively as quasars. In Figure 5 we show the distribution of redshifts both for the whole LQAC-5 objects and for the objects in common with the DR2. We observe that the feature of both histograms is quite similar, in particular with the two peaks occurring respectively for $z = 1.5$ and $z = 2.5$. It means that the limitation of the LQAC-5 to the DR2 sub-sample does not affect significantly the redshift distribution.

In Figure 6 we show the cumulative histogram of the G magnitude of the common LQAC-5 – DR2 quasars. We remark that the number of quasars increases significantly in the interval $20 < G < 20.8$ whereas it decreases considerably in the case of the CRF2.

We investigated the completeness of the Gaia DR2 catalogue with respect to the g magnitude of SDSS quasars belonging to the LQAC-5. Results are shown in Figure 7. We remark that all the quasars with $g < 20.6$ have been detected by Gaia, but that the number of objects with no Gaia counterpart increases steadily after this threshold to reach 30% at $g = 21$ and 80% at $g = 21.7$.

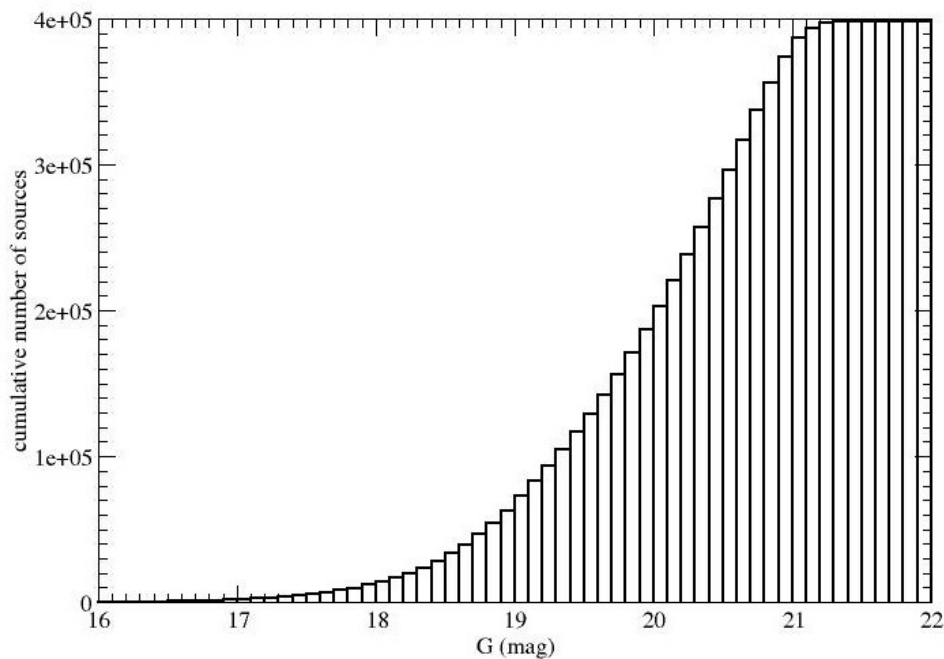


Fig. 6: Cumulative distribution of the Gaia G magnitude of the LQAC-5 sub-sample of quasars cross-matched with Gaia DR2.

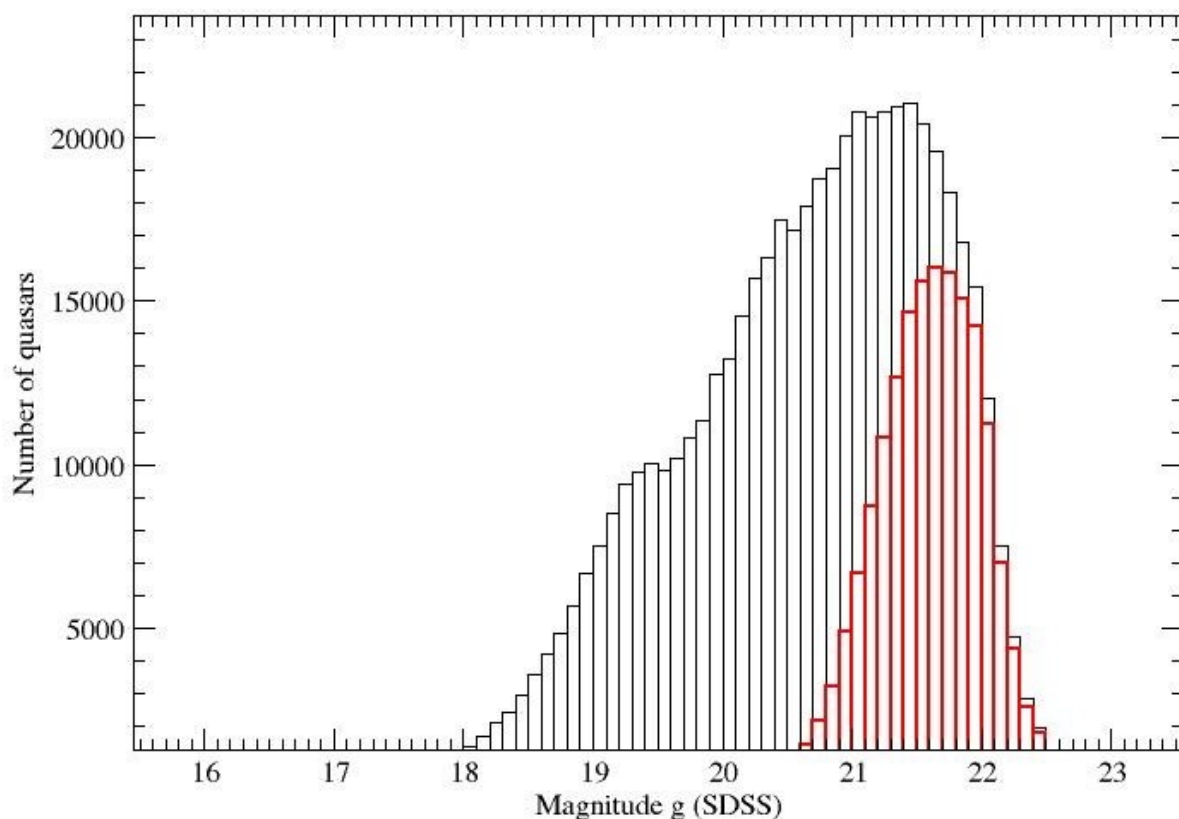


Fig. 7: Distribution of the number of quasars per g magnitude bin, for the SDSS objects belonging to the LQAC-5 (in black). Distribution of the objects no cross-matched with Gaia DR2 (in red).

For cross-matched objects, the correspondence between G (Gaia) and g (SDSS) gives insight in the amplitude of the discrepancy between these magnitudes, which can be due to two origins: one is the difference between the photometric systems, the other is the variability of fluxes of the objects, which can reach more than one magnitude for a limited period of time. In Fig. 8 we plot this correspondence, after using the polynomial fit between the two photometric systems established by (Jordi et al. 2010). This fit converts the initial G (Gaia) magnitude in the g (SDSS) through a polynomial transformation between the two photometric systems.

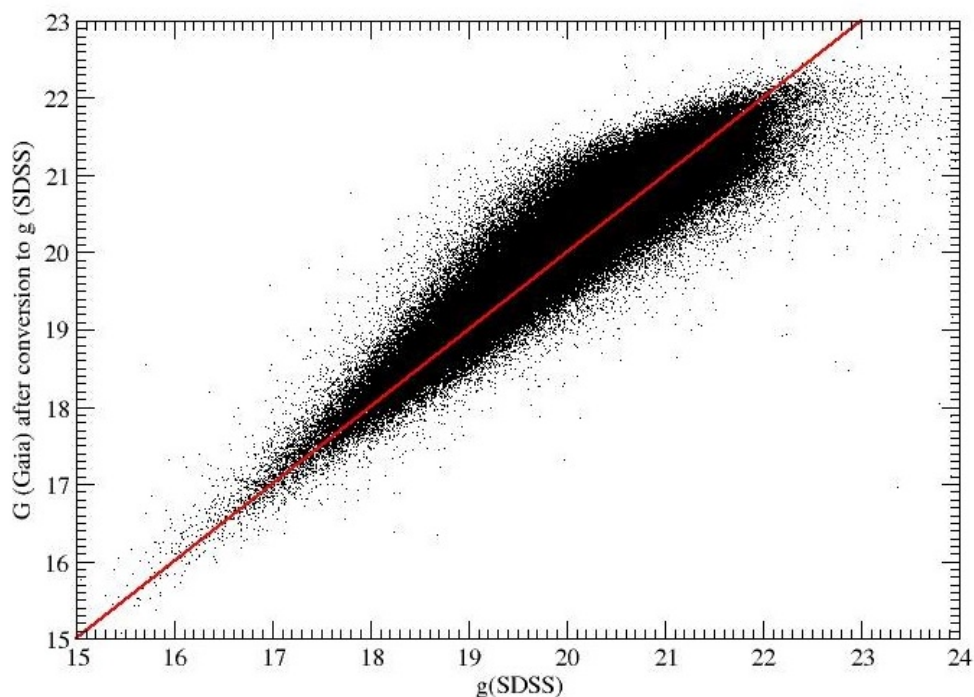


Fig. 8: Correspondence of the g (SDSS) magnitude computed from G (Gaia) (Jordi et al. 2010) with respect to the g magnitude for SDSS quasars with a Gaia counterpart.

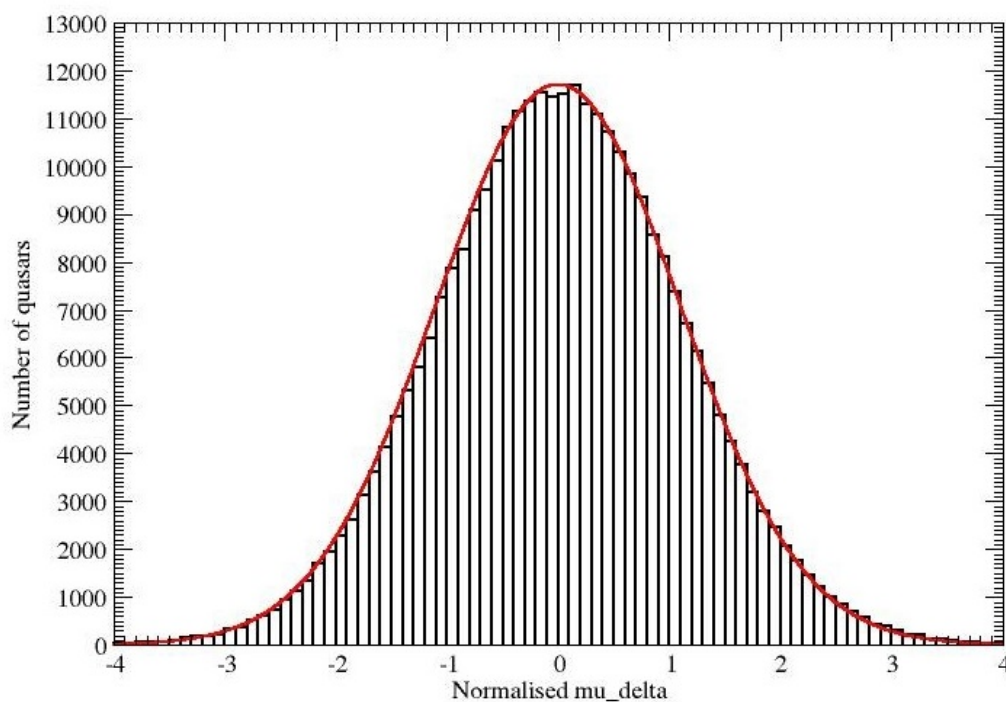


Fig. 9: Normalized value $\mu(\delta)/\sigma_{\mu(\delta)}$ of the component of the proper motion in declination (from Gaia DR2 data) of the LQAC-5 quasars cross-identified with Gaia. The red line is a Gaussian distribution with a mean of 0 and standard deviation of 1.1.

One of the up-to-date attractive subjects of investigation concerns the presence of quasars with a significant value of proper motion according to Gaia DR2 measurements. First, we analysed the behaviour of the normalized value μ/σ_μ of both components of proper motion in right ascension and in declination. The distribution is quasi-perfectly Gaussian for both coordinates as shown in Figure 9 in declination, thus confirming a statement already found by Mignard et al. (2018) for their CRF2 extragalactic sources. Then we analysed the distribution of the total amplitude of the proper motions, taken from the DR2 data, whose result is displayed in Figure 10. We observe a Rayleigh-like distribution with a median value around 1.5 mas/yr and with a peak at 0.5 mas/yr. Remark that a very big proportion of objects (95.4%) verify $\mu/\sigma_\mu < 2$ so that we cannot categorically conclude that they are not fixed with respect to the ICRF. On the other hand, we concentrated our study on objects with proper motion larger than 10 mas/y and with $\mu/\sigma_\mu > 5$, which characterizes a high probability of existence of a real proper motion. Results are shown in Table 3 where 16 objects could be found satisfying the conditions above. In a second step we studied the ICRF3 quasars (Charlot et al. 2020) with proper motions larger than 1 mas/y and with $\mu/\sigma_\mu > 5$. In view of their criteria of selection from VLBI observations, the conditions above can be considered as characterizing a significant displacement of the photo-centre. Results are presented in Table 4. All these results show that searching for the astrophysical causes of significant proper motions for the objects above should be of invaluable interest.

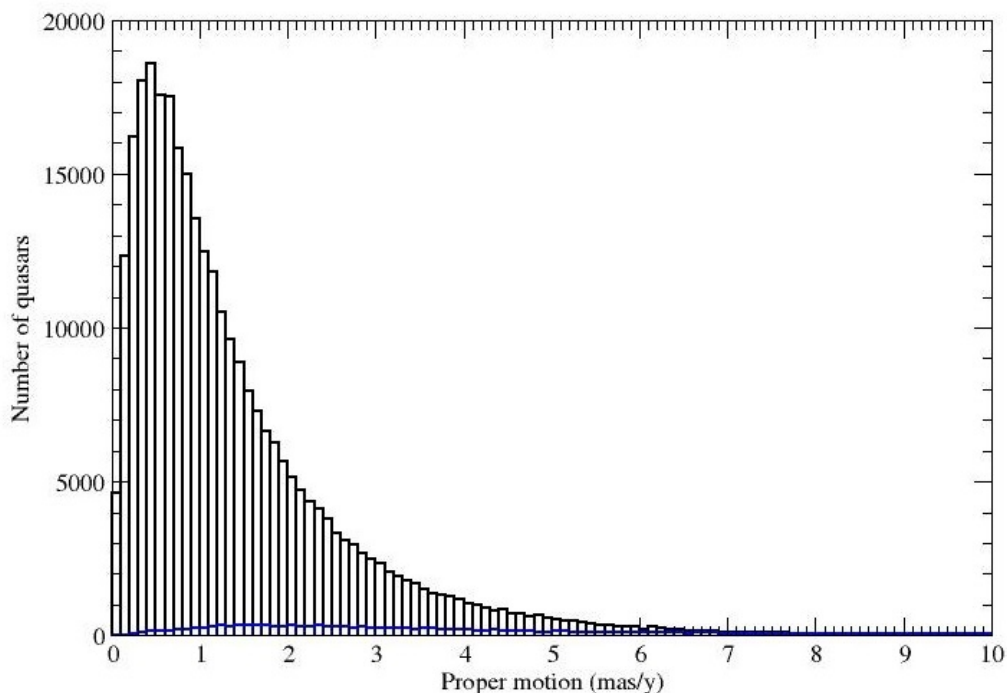


Fig. 10: Distribution of the amplitude of proper motion for the LQAC-5 quasars cross-matched with Gaia DR2.

Table 3: List of the quasars of the LQAC-5 cross-matched with Gaia DR2, having a proper motion μ larger than 10 mas/yr, and satisfying the condition $\mu/\sigma_\mu > 5$

α ($^{\circ}$)	σ_α mas	δ ($^{\circ}$)	σ_δ mas	$\tilde{\omega}$ mas	$\sigma_{\tilde{\omega}}$ mas	μ mas/y	σ_μ mas/y	z	G	BP	RP
8.2089013648	0.743	-10.8993572519	0.546	-5.384	0.983	22.444	2.230	2.435	19.026	18.781	18.306
16.3946967299	0.320	-27.6160917371	0.236	7.124	0.479	24.986	1.074	0.850	17.804	17.805	17.454
117.3123508035	0.517	27.1662716358	0.308	2.560	0.605	15.233	1.314	6.260	19.922	19.688	19.662
119.6010993806	0.651	14.9645671193	0.365	3.842	0.806	12.546	1.447	2.568	19.298	19.515	18.418
134.5416611091	0.616	55.1697373421	0.449	0.139	0.671	10.090	1.564	1.417	20.210	20.449	19.563
135.3152311805	0.620	-66.6093714049	0.562	0.644	0.598	12.377	1.882	0.000	20.215	20.781	18.912
139.3137082009	0.905	-2.3852827588	0.830	-0.259	1.063	20.358	3.037	1.287	19.454	19.327	18.681
235.8657942859	0.625	-1.4926802927	0.463	6.271	0.851	15.892	1.540	1.231	18.174	18.125	17.089
235.8727613597	0.064	33.9857684441	0.082	0.328	0.092	15.225	0.229	2.160	16.422	16.729	15.899
237.0639192279	0.330	28.7475575704	0.399	-0.109	0.563	10.801	1.325	2.306	20.063	20.173	19.392
237.0746243522	0.518	4.6837787907	0.432	3.170	0.637	18.969	1.514	1.034	19.309	18.952	18.267
242.1217994774	0.622	27.2740965329	0.691	1.513	0.989	14.643	2.271	2.591	20.151	20.224	19.146
249.0882074948	1.123	11.6285202879	0.799	-18.609	1.819	14.477	2.830	1.591	20.036	19.914	18.989
250.4949708516	0.120	15.4254595973	0.110	0.092	0.197	11.599	0.347	0.871	18.676	18.982	18.151
261.9937121681	0.545	56.7386750497	0.668	-1.434	0.634	14.633	1.950	1.773	19.833	19.997	19.069
359.2572207669	0.823	-2.4293386938	0.370	-1.015	0.945	17.422	1.938	0.719	19.755	20.035	18.655

Table 4: List of ICRF3 quasars having a proper motion μ larger than 1 mas/yr, and satisfying the condition $\mu/\sigma_\mu > 5$.

Name	α ($^{\circ}$)	σ_α mas	δ ($^{\circ}$)	σ_δ mas	$\tilde{\omega}$ mas	$\sigma_{\tilde{\omega}}$ mas	μ mas/y	σ_μ mas/y	z	G	BP	RP
0149+710	28.3577065085	0.314	71.2517957182	0.349	0.051	0.384	4.856	0.874	0.022	17.691	100.000	100.000
0321+467	51.3345987257	0.531	46.9185095434	0.331	0.161	0.646	7.196	1.747	0.000	19.211	18.836	17.755
0600+063	90.8096981410	0.103	6.3742787710	0.097	0.676	0.122	5.146	0.322	0.000	16.067	16.497	15.310
0603+476	91.8468957878	0.069	47.6630394728	0.064	-0.081	0.078	6.418	0.186	0.540	16.829	17.275	16.090
0620-011	95.7414266030	0.352	-1.1575327855	0.341	0.050	0.382	5.713	0.989	1.400	19.374	19.811	18.662
0757+441	120.2844842386	0.402	44.0194876510	0.292	1.442	0.622	6.680	1.064	1.072	19.653	20.051	18.879
0805-077	122.0647334850	0.165	-7.8527462146	0.093	0.084	0.173	7.282	0.398	1.837	18.269	18.637	17.471
0927-378	142.4893922167	0.069	-38.0300832649	0.081	0.404	0.112	5.371	0.211	0.000	17.767	18.327	16.997
1045-620	161.9285907721	0.232	-62.2873964223	0.196	0.207	0.263	8.582	0.543	0.000	18.879	19.309	18.068
1055+567	164.6571986351	0.032	56.4697797770	0.032	-0.072	0.050	9.337	0.100	0.143	16.181	16.323	15.438
1228+126	187.7059264664	0.525	12.3911248881	0.490	-2.816	0.666	13.405	1.502	0.004	15.794	100.000	100.000
1508-656	228.2151958153	0.315	-65.8840198033	0.385	1.318	0.557	8.918	1.015	0.000	19.651	20.280	18.516

U.S. Naval Observatory IERS ICRS Centre Activities During 2019–2020

USNO concentrated on nine primary areas of work in support of maintenance and improvement of the Celestial Reference Frame:

1. Continued support, maintenance, and improvement to the ICRF by implementing new parameters and features from the IAU-sanctioned and adopted ICRF3.
2. URAT bright stars southern hemisphere surveys
3. Development and deployment of the Deep South Telescope (DST) at Cerro Tololo Interamerican Observatory (CTIO).
4. Execution of a deep, near infrared (near-IR) survey in the northern hemisphere using the United Kingdom Infrared Telescope (UKIRT)

5. Management of ICRS/ICRF observations utilizing the Very Long Baseline Array (VLBA)
6. Determination of ICRF objects with multiple radio components.
7. Assembly of the Washington Multiple-AGN catalog for consideration in CRF work.
8. Development, jointly with Paris Observatory, of the Fundamental Reference AGN Monitoring Experiment (FRAMEx).
9. Characterization of Gaia Early Data Release 3 (Gaia EDR3).

Support, Maintenance, and Improvement to the ICRF3

USNO continued to contribute and make improvements to the global VLBI solutions throughout 2019 and 2020 in support of the ICRF. The USNO global VLBI solutions were updated and improved in a number of ways. We implemented the 303 S/X band ICRF3 defining sources into our solutions by using this list as the a priori positions for defining the axes of the reference frame. These 303 defining sources differed from the previous 295 defining sources from the ICRF2 that we used prior to 2019, by their more isotropic distribution over the celestial sphere.

In addition, we changed the reference epoch in accordance with the ICRF3 recommendations to 2015.01.01, thus updating the nearly 20-year-old epoch 2000.01.01, used prior to 2019. We included a Galactic aberration term equal to $5.8 \mu\text{as/yr}$ in order to correct for the amplitude of the solar system barycenter acceleration vector (see Fig. 3, Charlot et al. 2020). Finally, the last improvement that USNO made in its global VLBI solutions was the utilization of the Vienna mapping function (VMF1) instead of the neo-mapping function used prior to 2019 for improved calibrations of the troposphere. Together, these updates facilitated all of the USNO IVS Analysis Center data products, such as the daily intensive observations and individual rapid 24-hour sessions, to be in agreement with the ICRF3.

We compared the difference between the USNO 2018 VLBI global solution (usn2018b) and the USNO 2019 solution (usn2019c) in order to assess how the changes affected the five Earth Orientation Parameters (EOPs). Figure 11 shows the results of this analysis and we find good agreement between the 2018 and the 2019 solutions.

In addition to implementing updates to the USNO VLBI global solution, USNO also began contributing to the ITRF2020 by submitting SINEX files to be used in the final solution. These activities are ongoing and USNO is planning to submit a final set of SINEX files in time for the ITRF2020 solution, which is expected to be released in mid-2021.

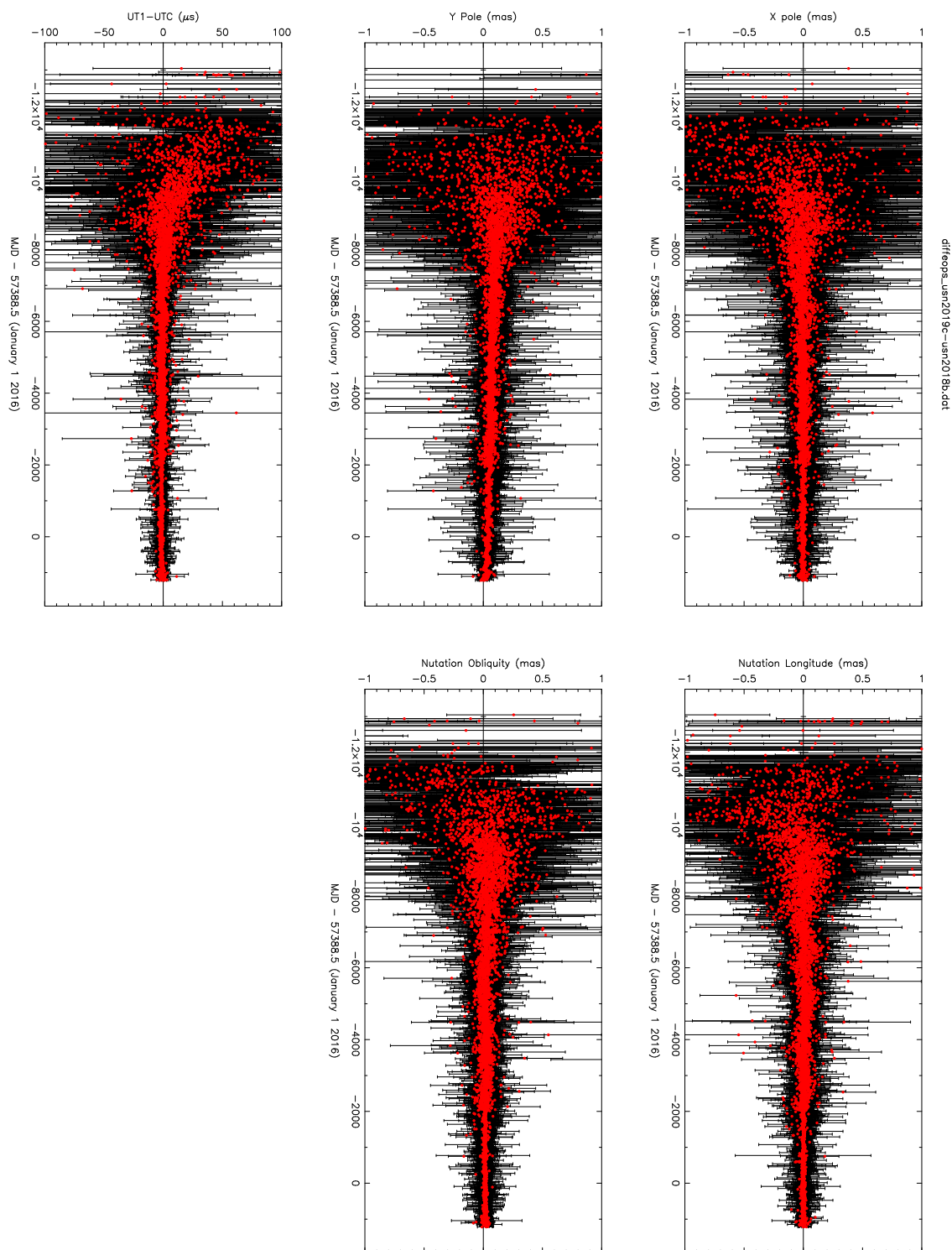


Fig. 11: The difference between the 2018 and 2019 VLBI global solutions for each of the five EOPs.

URAT Southern Hemisphere Bright Star Survey

While the core of optical astrometric data for the next few decades is expected to come from the Gaia mission (Mignard et al. 2018), there are limitations with Gaia. Specifically, the Gaia focal plane physically saturates at $G=12$ in regular observing mode. The second Gaia data release (April 2018) contains astrometric results for some stars in the 3.5 to 6 magnitude range, observed with special “bright star modes”. As summarized in Brown et al. (2020), bright star astrometry in Gaia Early Data Release 3 (EDR3) is improved somewhat over DR2, with uncertainties in positions and parallaxes respectively reduced to 0.43 and 0.27 of their DR2 values, although Gaia EDR3 is similarly incomplete at the bright end.

In order to address this gap in the optical reference frame, USNO is producing the UBSC (USNO Bright Star Catalog), which is based on UBAD, URAT and Hipparcos data. UBAD is an observational program in the northern hemisphere using the 1.55m Strand Reflector at the Naval Observatory Flagstaff Station (NOFS). A preliminary UBAD catalog of over 340 stars of magnitude 3 and brighter was generated. The USNO Robotic Astrometric Telescope (URAT) observational program run for 2.7 years at Cerro Tololo Interamerican Observatory (CTIO) to cover the southern sky. For the UBSC data of about 1200 stars of magnitude 4.5 and brighter were used. The intermediate level Hipparcos data are used as early epoch to allow a rigorous solution of all 5 astrometric parameters. More UBAD observations were performed in 2020 to conclude this observational program. Reductions of UBSC are in progress, and construction of a final catalog is expected in 2021.

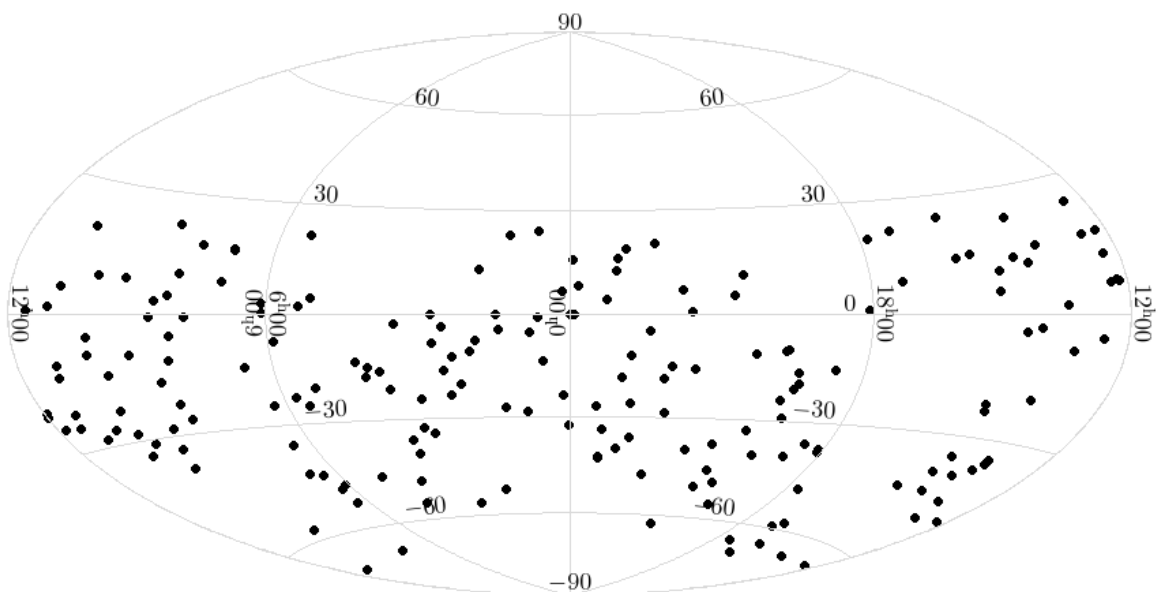


Fig. 12: Aitoff projection of the 2019–2020 DST target list, which is comprised of 199 objects.

Deep South Telescope (DST) About 10% of ICRF sources display abnormally large optical vs. radio position differences when comparing Gaia results with VLBI data. In order to investigate this further, USNO acquired a new 1-meter telescope from PlaneWave Instruments in 2018. This Deep South Telescope (DST) was deployed at CTIO in Chile in March 2019. A 4k Sophia CCD camera was ordered from Princeton Instruments. A mishap during shipment of the camera and other instrumental issues caused a delay of several months. Survey observations with DST began in August 2019 with a target list of about 200 extragalactic sources, shown in Figure 12. Observing at CTIO continued until shutdown due to pandemic in April 2020. Over 12,000 on-sky exposures were obtained with about 6,300 of sufficient quality to pass astrometric reductions. An investigation into systematic errors lead to various calibrations of the data and to preliminary position results for over 150 targets. In November 2020 DST observations resumed, however, a camera problem was discovered. Various instrumental issues need to be fixed before reaching full operations capabilities. This program is part of the joint USNO/OP collaboration (FRAMEx, see below for more information). We show images of the DST from 2019 in Figure 13.

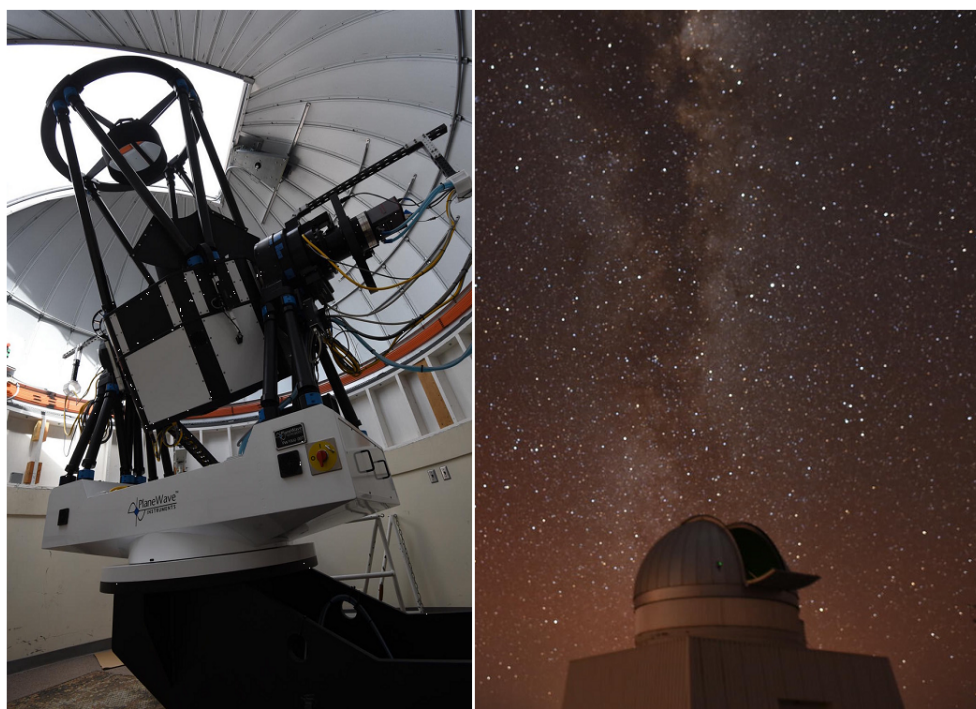


Fig. 13: *Left: DST at CTIO, 2019. Right: DST night operations, 2019.*

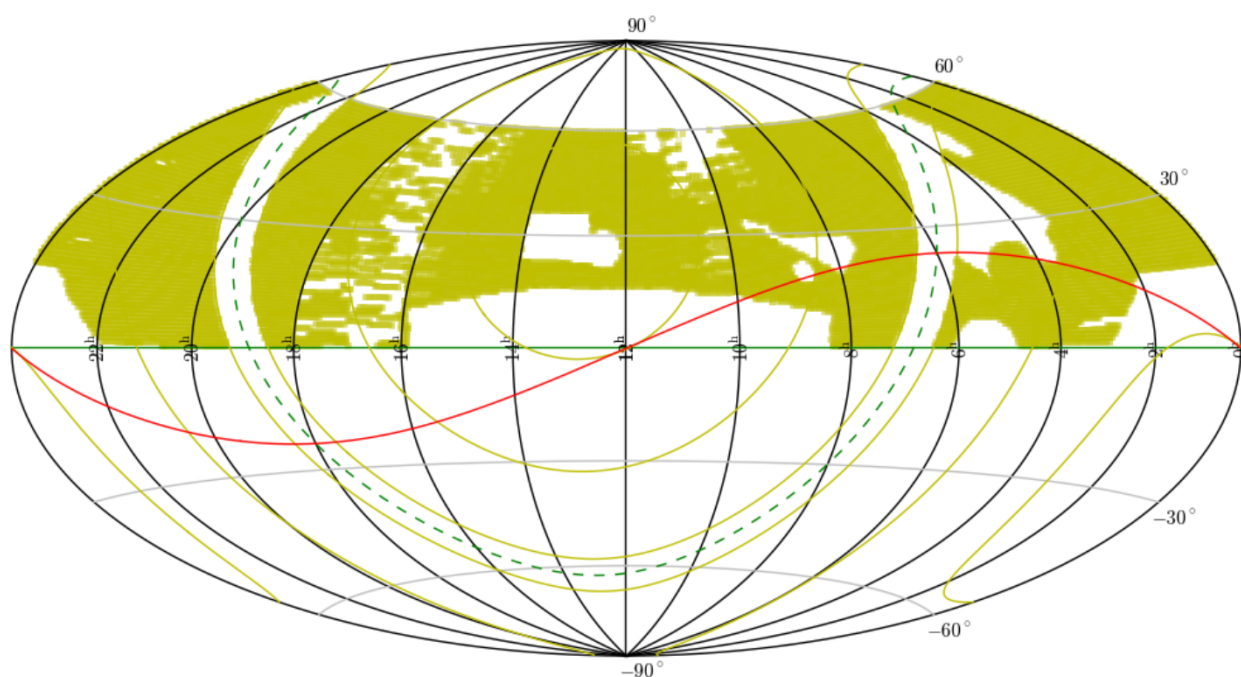
**USNO UKIRT Hemispherical
Survey**

USNO, in collaboration with the Institute for Astronomy (IfA) at the University of Hawaii (UH); the School of Physics and Astronomy, Nottingham University; Institute of Astronomy, University of Cambridge; and the Institute for Astronomy, University of Edinburgh, continued a K-band

(2.2 μm) multi-year, northern hemisphere survey in the near-IR using the United Kingdom Infrared Telescope (UKIRT). This survey is targeted for completion in the 2021 timeframe. When completed, the K-band survey will provide a catalog to fainter than 18th magnitude that complements the VISTA Hemisphere Survey in the southern hemisphere (McMahon 2013). A similar multi-year UKIRT survey in H-band (1.6 μm) to fainter than 19th magnitude has been initiated with completion expected during 2022. When combined with the J-band (1.2 μm) UKIRT survey (Dye 2018), the K- and H-band data will provide deep photometric and astrometric data for the three standard NIR astronomical photometry bands. Figure 14 shows the progress of the K and H-band surveys through November 2020. Approximately 90% of the K-band and 10% of the H-band data have currently been obtained. When combined with earlier surveys, 100% of the northern sky between declinations 0 and +60 deg will have been covered to unprecedented depths and astrometric accuracy.

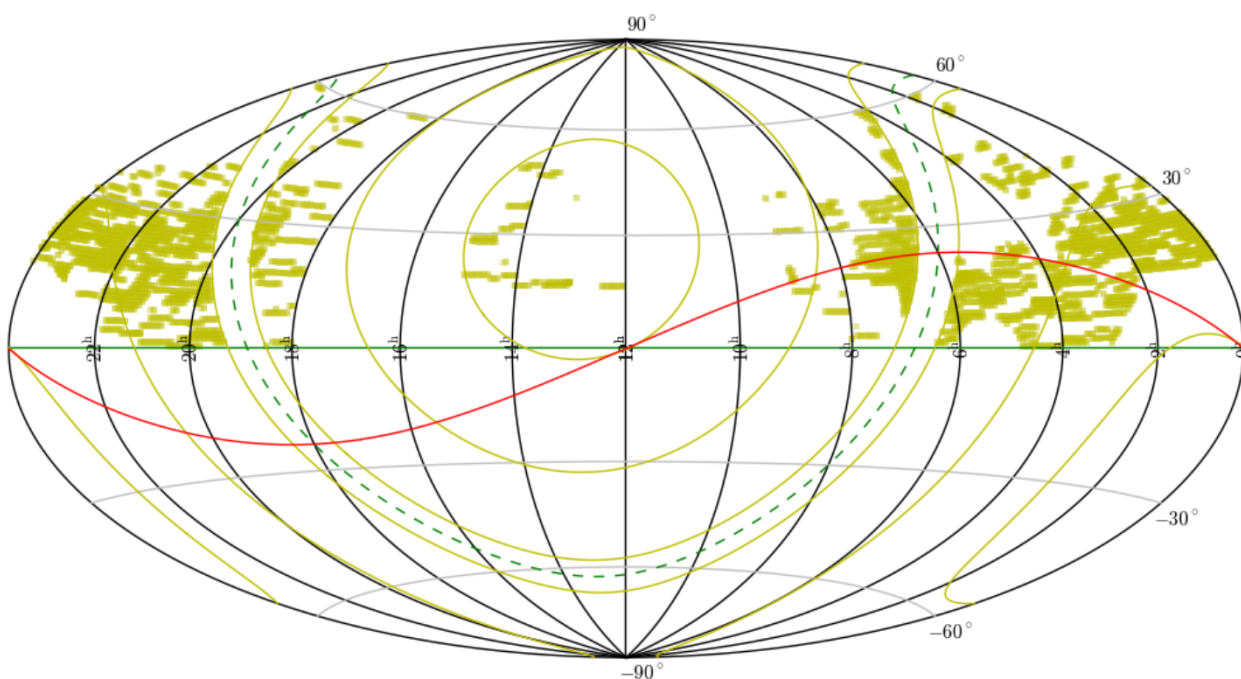
ICRS/ICRF Observations with the Very Long Baseline Array (VLBA)

USNO sponsored multiple 24-hour astrometric/geodetic-style observations on the VLBA at S/X bands and K-band through the USNO 50% Timeshare Agreement on the VLBA. These sessions were optimized for imaging by ensuring adequate on-source integration time and uv coverage for each ICRF target observed such that high fidelity images could be produced in addition to astrometric measurements. In 2019, USNO provided the time for 19 sessions at S/X as part of the UG002 series and 13 sessions at K-band as part of the UD001 series where each 24-hour session contained approximately 250 ICRF sources. The S/X observations increased the number of observations for ~3500 individual sources for improving the astrometry of the ICRF. In 2019, USNO also sponsored an IVS series of six 24-hour sessions known as the CN-series, which were executed simultaneously to the IVS R1 rapid sessions such that systematic errors in the astrometry and EOPs could be determined. USNO also sponsored six Research and Development with the VLBA (RDV) sessions, which combine the VLBA array with a handful of IVS stations for the purposes of imaging and monitoring faint ICRF sources. The RDV series is in collaboration with Bordeaux Observatory and the data are used for producing all of the images that comprise the Bordeaux VLBI Image Database (BVID).



Date Range: 20170729 - 20201121

Last Updated: 20201205



Date Range: 20190112 - 20201121

Last Updated: 20201205

Fig. 14: *Top*: UKIRT K-band survey progress, as of November 2020. Note that the galactic plane and the region centered around the North Galactic Pole (RA 12 h 510, DEC +27 deg 070) were previously surveyed; the current survey fills in the gaps. Also note that UKIRT cannot observe above DEC +60 deg; this “polar cap” will be filled in with dedicated observations using a different telescope at a later time. *Bottom*: H-band survey progress, as of November 2020.

In 2020, USNO continued to sponsor ICRF 24-hour astrometric and geodetic observations on the VLBA through the USNO-VLBA 50% time-share allocation agreement. In 2020, USNO provided the time for 6 RDV sessions, 12 K-band sessions, and 12 S/X-band sessions. Beginning in August 2020, the K-band and S/X-band sessions were aligned in time such that they were run back-to-back in a pseudo-simultaneous manner. The source lists between the K and S/X bands were also matched. These alignments allow for monitoring and studying ICRF quasars in the radio at three frequencies in a quasi-simultaneous fashion for the purposes of understanding flux and/or astrometric variability and source structure so that we can better understand the nature of the emission and perhaps form predictions for when sources might become problematic.

USNO began creation of its own image data archive called the Fundamental Reference Image Data Archive (FRIDA) which will be hosted on the new USNO website scheduled for debut in 2021. Initially, the observations that will contribute the majority of the images that will be available on FRIDA come from the VLBA-only sessions as these are the sessions through which development of a calibration and imaging pipeline using the NRAO Common Astronomy Software Applications (CASA) package has been accomplished. FRIDA will be an interactive web interface for users to obtain access to USNO's data archive containing all of the radio images created with data from the VLBA. USNO intends to host calibrated images in FITS format as well as provide the calibrated uv datasets and ancillary information including plots showing the amplitude versus uv distance and uv sky coverage as diagnostic tools of the data quality for each image. Users will be able to download all of the data made available through FRIDA. Eventually, USNO plans to host all of the K-band images from the UD001 series as well as the RDV data. In addition, USNO will host all ancillary archival data that were previously part of the Radio Reference Frame Image Database (RRFID) which span frequencies from S/X, K, and Q-bands for a number of ICRF sources. Figure 15 gives a series of example images that will be hosted on FRIDA.

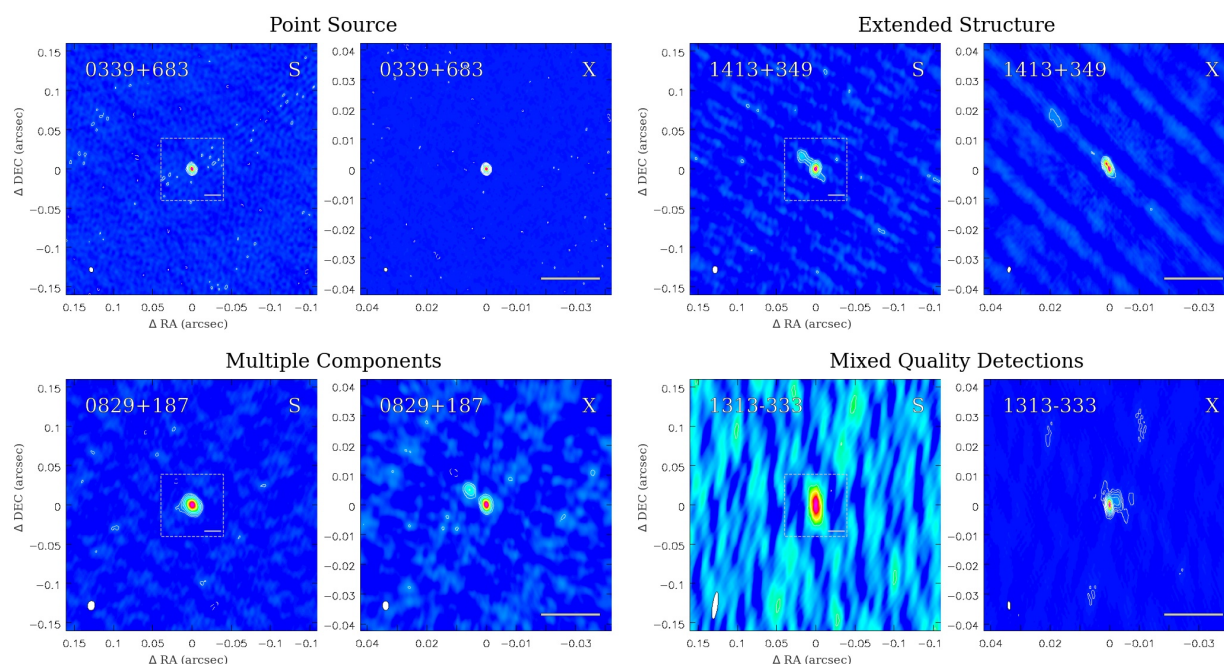


Fig. 15: *S*-band (left) and *X*-band (right) images showing a sample of sources from the ICRF that will be available on FRIDA. The white dashed box in the *S*-band images denotes the size of the *X*-band images. The restoring synthesized beam is shown in the bottom left corners, and the angular scale bars are 20 mas.

ICRF Objects with Multiple Radio Components

USNO has produced VLBA images of ~3500 out of 4536 S/X ICRF3 sources above a declination limit of -45° , to be described in Hunt et al. (2021, in preparation), and made available through FRIDA. In brief, the VLBA S/X dual frequency system provided astrometric measurements similar to that of the IVS S/X observations and comprise the majority (68%) of ICRF3 data (Charlot et al. 2020). Twelve 32-MHz channels were used in *X*-band (8.6 GHz) and four 32-MHz channels were used in *S*-band (2.3 GHz), the latter of which is used for astrometric calibration of the ionosphere. Integration times were ~60 to ~160 seconds for target sources and ~24 seconds for defining sources that were used to tie the astrometric results to the ICRF. Images were produced at both *S*- and *X*-bands.

We visually classified the ICRF source images in order to select those with multiple sources, which may pose an issue for the link to Gaia-CRF. For example, a heavily reddened quasar with a collimated jet may suffer from a large optical-radio offset, as the Gaia counterpart will be centered on the jet, missing the location of the radio core. If the system is a dual supermassive black hole (SMBH) quasar, predicted from hierarchical cosmological simulations to be common, then it is possible that the Gaia optical counterpart does not in fact correspond to the ICRF source but rather its neighbor. While strong optical emission from the accretion disk of an AGN is ubiquitous, only about 15–20% of quasars are “radio-loud”, meaning that their radio emission dominates over their optical emission

(Kellermann et al. 1989). As the ICRF quasars are selected to be radio sources, this means that they are more likely to be radio-loud, and any neighboring AGN may well be much less luminous in the radio. If the neighboring AGN's optical emission becomes a significant fraction of the ICRF quasar's optical emission, be it from intrinsic luminosity variability or variable reddening, then the ICRF quasar will exhibit an optical-radio offset. Note also that differential luminosity variability is likely to be the true cause of astrometric jitter even in true, unresolved, binary (gravitationally-bound) systems. At the astrometric limit of ICRF3, $\sim 30 \mu\text{as}$, even a 10^9 solar mass black hole binary system at $z = 1$ will have an orbital period of ~ 100 yr (Figure 16).

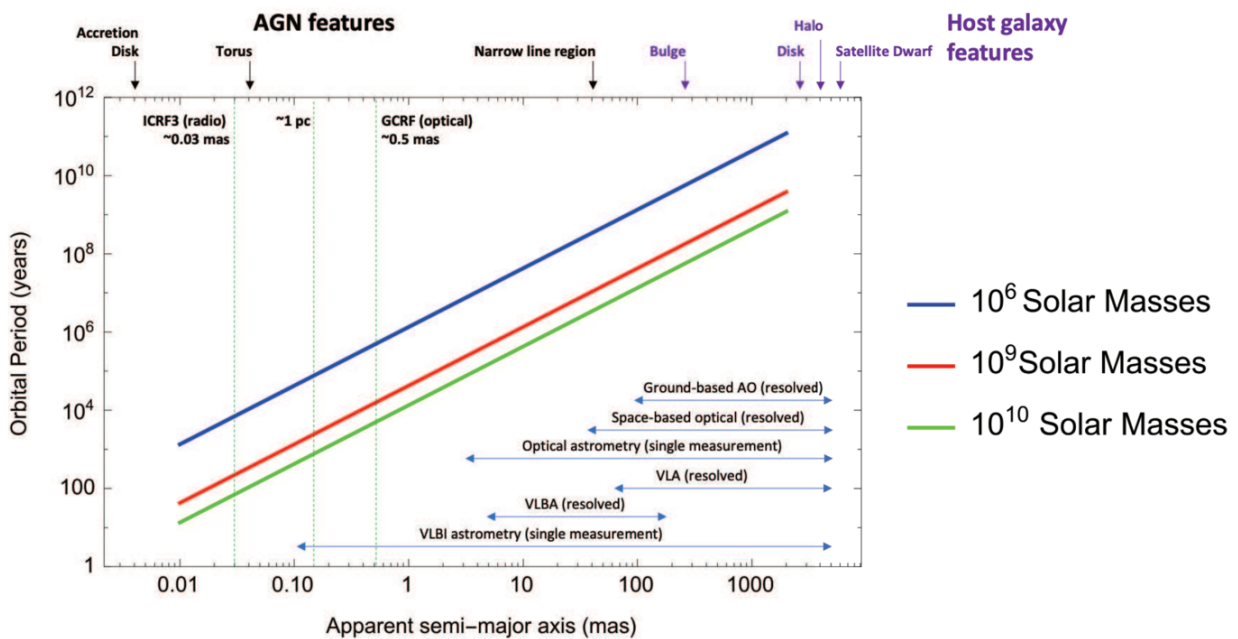


Fig. 16: Angular separation versus orbital period for a $z = 1$ binary black hole system (from Dorland et al. 2020).

To flag images with potential multi-sources, we used SExtractor (Bertin & Arnouts 1996). This produced a list of 143 images of 110 unique ICRF objects. The three study leads (N. Secrest, J. Frouard, and L. Hunt) independently classified each image in terms of the number of compact components (N_c), defined as components consistent with the synthesized beam of the observation, and extended components (N_e), defined as those components with additional structure inconsistent with the synthesized beam. For objects not agreed upon in the first round of classification, a second round of classification was done, without knowledge of how the objects were first classified. After this second round, remaining disagreements were jointly classified by all three inves-

tigators. The point during the process that consensus was reached will be used to estimate the reliability of classification. Additional information on the reliability (and completeness) of this method will be obtained by comparing with images of multi-source objects not initially flagged for inspection, and morphological differences between this analysis and images available on the Bordeaux VLBI Image Database will be noted. The multi-source classifications, along with reliability and completeness estimates, will be published as a catalog in the 2021 timeframe, likely as an ApJS owing to broad interest in these sources from the wider astronomical community. We show some examples of our classifications in Figure 17.

The Washington Multiple-AGN Catalog

As explained above, knowledge of whether or not an ICRF object is a dual or binary AGN may prove essential to flagging likely “pathological” sources with large optical-radio offsets, thereby helping to refine the optical-radio CRF link. Towards this goal, in 2020, USNO started developing the Washington Multiple-AGN Catalog (WMAGN), its name being a nod to the venerable Washington Double Star Catalog maintained by USNO (e.g., Mason et al. 2001). The current goal of this catalog is to concatenate all confirmed and candidate dual and binary AGNs in the literature into a single catalog, for future use when considering optical-radio offsets and CRF link sources, as well as to be of use to the wider astronomical community.

The WMAGN catalog, version 0.1, was completed in the fall of 2020. It was assembled over the summer by GMU PhD candidate R. Pfeifle, whose PhD thesis is on dual and multiple AGNs, as part of an ongoing USNO-GMU collaboration. WMAGN version 0.1 contains 422 unique multiple AGN systems, 18 of which are ICRF3 sources. Of these 18, 11 are confirmed or candidate binary AGNs. The catalog is estimated to be 90 – 95% complete up to 2010. Once it is complete up to 2020 and undergoes some additional quality control tests, USNO intends to publish it, likely in ApJS. In the long term, the catalog will be updated on a yearly basis. The current WMAGN data model is shown in Table 5.

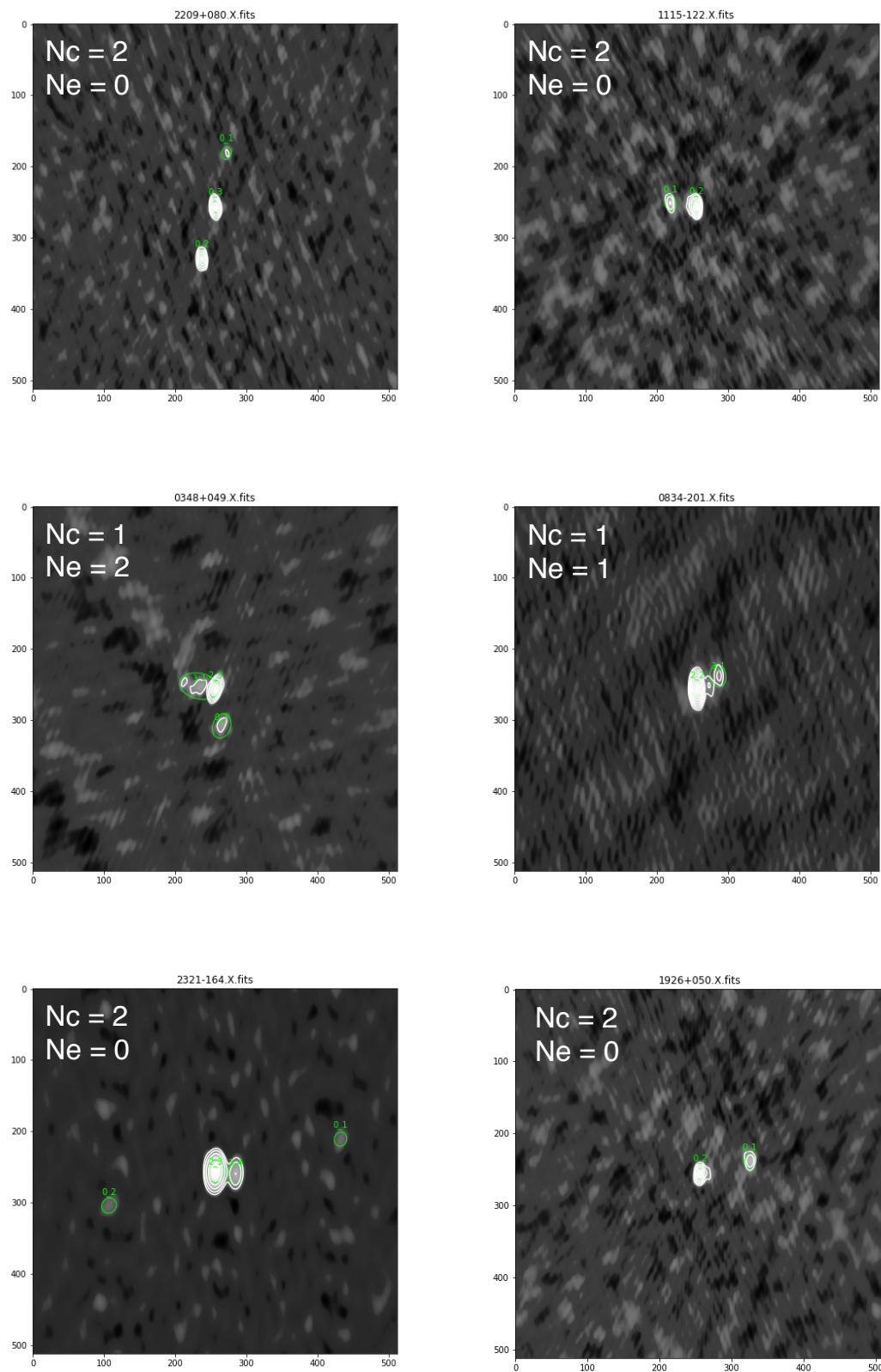


Fig. 17: Example VLBA X-band images of ICRF objects with multiple sources, either resolved (Ne), or compact (Nc).

Table 5: *WMAGN version 0.1 data model.*

index	Unique internal system identifier
System Type	Type of multiple AGN (e.g., dual AGN)
Literature Name	Identifier used in literature source
Name	Used name
Selection Method	Criterion used to identify multiple AGN system
Confirmation Method	Criterion used to confirm multiple AGN system (do not use in v0.1)
z	Redshift
z_type	Spectroscopic or photometric
RA	Right Ascension
Dec	Declination
RA_deg	Right Ascension in degrees
Dec_deg	Declination in degrees
Equinox	RA/Dec equinox (always J2000)
Coordinate_waveband	Wavelength/passband of RA and Dec
Coordinate_Source	Source of RA and Dec
Brightness	Apparent magnitude
Brightness_band	Passband of apparent magnitude (e.g., V, SDSS g, 1.4 GHz NVSS)
Brightness_type	(e.g., mag, asinh mag, mJy)
Sep	Angular separation of multiple AGNs, in arcsec
Sep(kpc)	Projected physical separation of multiple AGNs
delta_z	Difference in redshifts between multiple AGNs
dV	delta_z times the speed of light in km/s
Paper(s)	System source literature
BibCode(s)	NASA ADS bibliography code for Paper(s)
DOI(s)	URL of Paper(s)
Notes	Salient peculiarities or caveats for system

**Fundamental Reference Frame
AGN Monitoring Experiment
(FRAMEx)**

The Fundamental Reference AGN Monitoring Experiment (FRAMEx) was conceived at a May 2018 USNO-Paris Observatory IERS ICRS Centre meeting. The purpose of FRAMEx is to study representative samples of AGN/quasars to understand the physical processes potentially involved in optical-radio positional offsets seen in many ICRF sources. We defined two samples for study: a volume-complete sample of local AGN and a sample of quasars with significant optical-radio (Gaia-VLBI) positional offsets. Photometric observations of the latter sample, which are being taken with the new USNO Deep South Telescope (DST; PI: Zacharias, see above) are currently being analyzed.

The details of the volume-limited sample target selection were provided in IERS Annual Report 2018, but here we provide the salient findings since that report:

- Despite all of the hard X-ray (14 – 195 keV) selected AGNs in the local volume being detected with the VLA, only 9 out of 25 (36%) AGNs were detected with the VLBA, indicating that the “core” radio emission from these AGNs is being resolved-out on mas scales.
- Including both detections and upper limits, AGNs systematically “jump out of the plane” of the “Fundamental Plane” of black hole accretion (e.g., Merloni et al. 2003) when using high-resolution VLBA data, despite being consistent with the Fundamental Plane for lower-resolution VLA data. See Figure 18, taken from FRAMEx paper I (Fischer et al. 2020).
- The L_R / L_X ratios of our detections are between $10^{-7} - 10^{-4}$, roughly in line with expectations from coronal synchrotron emission ($L_R / L_X \sim 10^{-5}$; Laor & Behar 2008). However, given the sensitivity of our observations to L_R / L_X ratios as low as 10^{-7} , our findings raise the possibility of truly radio-silent AGNs.
- The only object in our sample that does not exhibit this jump is NGC 1052, which is an ICRF object (IERS B0238-084). It has an L_R / L_X ratio of $\sim 10^{-2}$, in line with the radio-loud / radio-quiet demarcation of $L_R / L_X = 10$ -4.5 from Terashima & Wilson (2003).

These findings are consistent with a bimodality in radio loudness amongst AGNs. This being the case, the volume-complete AGN sample is of less utility for studying accretion physics relevant to ICRF quasars. However, we have continued to monitor these objects, and several projects are being carried out with USNO and its partner institutions.

Characterization of Gaia EDR3

Gaia EDR3 was released 3 December 2020, allowing for some exploration of the properties of EDR3 matches to the ICRF3, compared with Gaia DR2. ICRF3 was matched with a tolerance of 1” to Gaia DR2 and EDR3, producing a list of 3384 matches (74.6%). The overall distribution of optical-radio offsets between Gaia and ICRF3 is somewhat better, with a median value of 0.56 mas for EDR3, vs. 0.67 for DR2 (Figure 19).

The values of uncertainty-normalized offsets are similar between DR2 and EDR3 (Figure 20). For both catalogs, the normalized offsets are not consistent with expectations for offsets due to errors, providing that the formal uncertainties are accurate. The similarity in the distribution between Gaia EDR3 and DR2 is consistent with these offsets, which

have been the subject of much study, being physically significant.

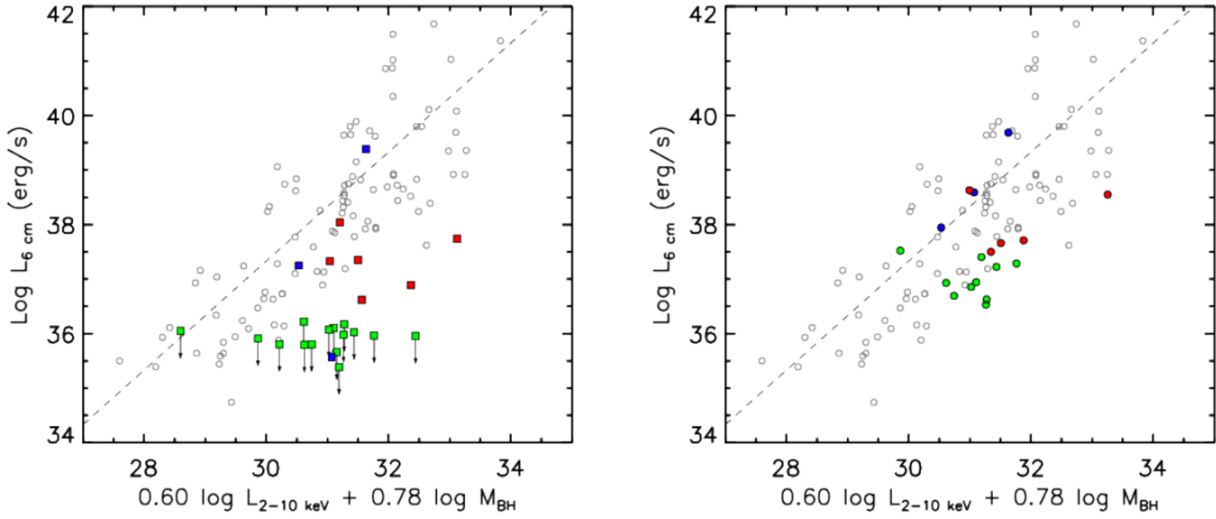


Fig. 18: Left: fundamental plane (projected along X-ray and black hole mass axis) versus C-band luminosity for VLBA-detected AGNs and upper limits. Right: for VLA-detected objects. From FRAMEX paper I (Fischer et al. 2020).

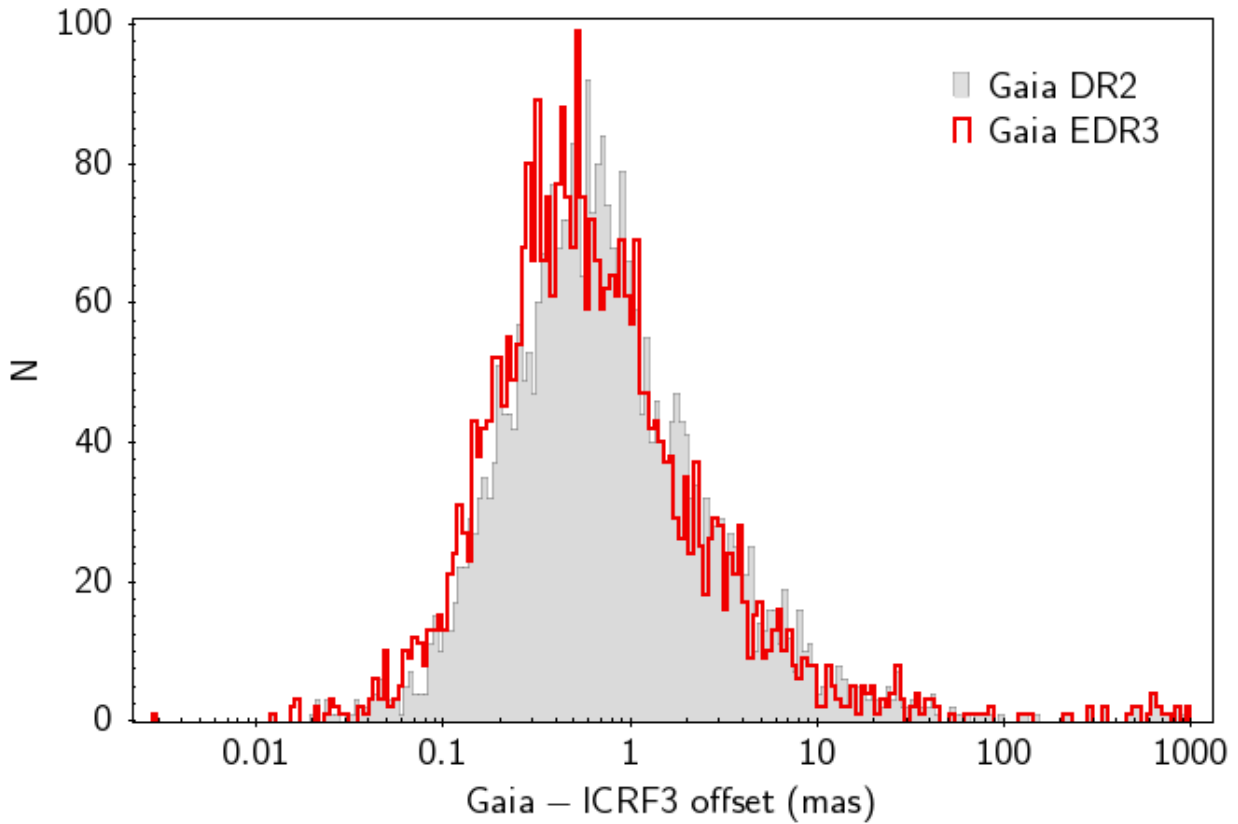


Fig. 19: Offsets between Gaia and ICRF3 for DR2 (gray shaded) and EDR3 (red line).

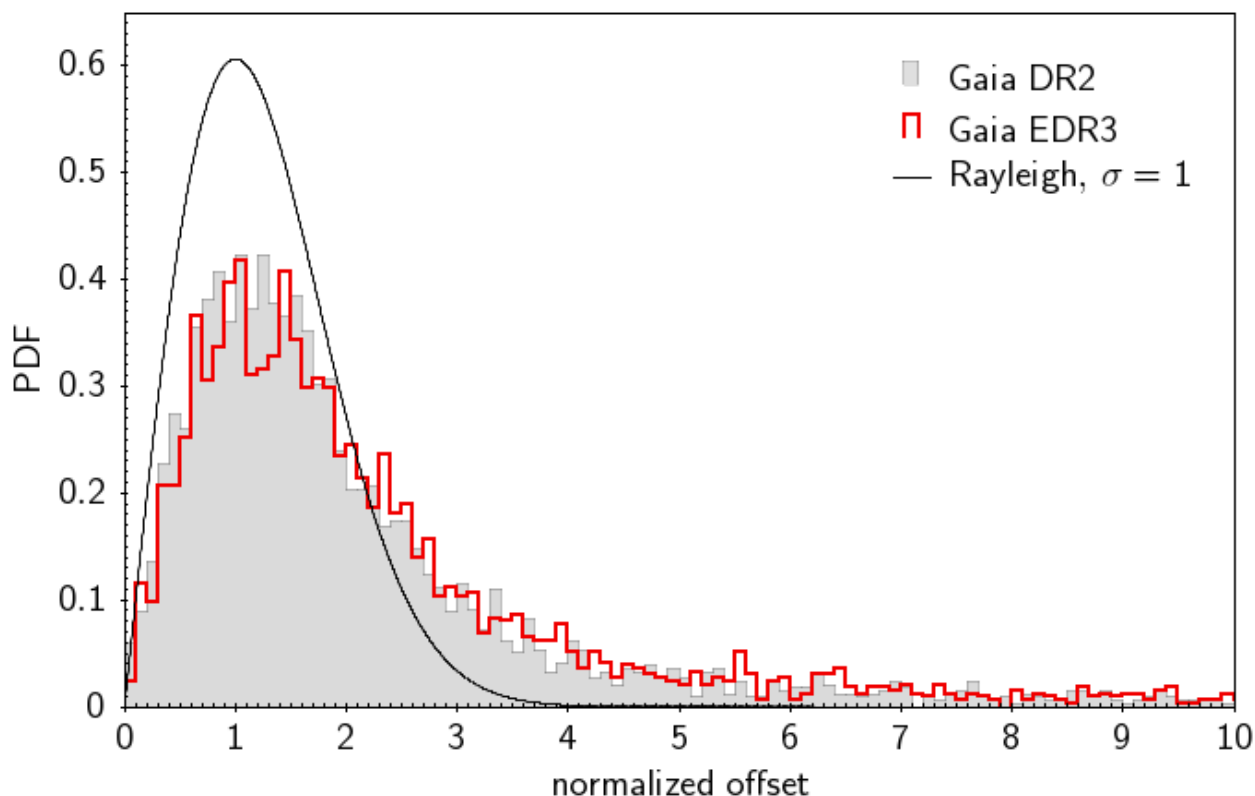


Fig. 20: *Uncertainty-normalized offsets.* A Rayleigh distribution with $\sigma = 1$ is expected if the coordinate errors are normally-distributed with errors corresponding to their formal errors (see, e.g., Makarov et al. 2019).

Note, however, that there is some variance in the offset significance for any given source in EDR3 vs. DR2. To quantify this, we made a table of the number of sources in DR2 and EDR3 meeting varying cuts on normalized offset (X_{cut} ; Table 6). For all thresholds, the number of sources in EDR3 is equal to or lower than those in DR2, suggesting that, overall, there are fewer objects in EDR3 with significant optical-radio offsets, although this change is small, of order a few percent. Above a normalized offset cut of 5, the two catalogs are in agreement to within 2%, suggesting that 5 is a good cut for a reliable sample of significant optical-radio offsets.

Analysis of the newly published Gaia EDR3 and ICRF3 data, as well as ongoing FRAMEx observations, is expected to produce significant new results of direct relevance to improving the evolving ICRF and its associated optical counterpart, the GCRF.

Table 6: *The number of objects in Gaia DR2 and EDR3 meeting some normalized offset threshold X_{cut} . Percent gives these numbers as a portion of the total catalog (3384 sources). Percent_change = $N_{\text{diff}} / N_{\text{DR2}} * 100$.*

X_cut	N_DR2	Percent	N_DR2_EDR3	Percent	N_diff	Percent_change
3	778	23	709	21	-69	-9
4	538	16	516	15	-22	-4
5	415	12	406	12	-9	-2
6	349	10	340	10	-9	-3
7	291	9	289	9	-2	-1
8	254	8	252	7	-2	-1
9	221	7	218	6	-3	-1
10	198	6	194	6	-4	-2
11	175	5	174	5	-1	-1
12	158	5	158	5	0	0
13	140	4	140	4	0	0
14	126	4	125	4	-1	-1
15	120	4	120	4	0	0
16	115	3	114	3	-1	-1
17	105	3	104	3	-1	-1
18	99	3	99	3	0	0
19	88	3	88	3	0	0
20	86	3	86	3	0	0

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3.5.5 ITRS Centre

This report summarizes the activities of the IERS ITRS Centre during the year 2019.

Preparation for ITRF2020

After the release of the ITRF2020 Call for Participation (CfP) which was published at the end of 2018 (see: http://itrf.ign.fr/doc_ITRF/CFP-ITRF2020.pdf), the ITRS Centre continued the dialog with the 4 Technique Centres for the preparation of their inputs to the ITRF2020. The ITRS Centre emphasized the need for the TCs to implement the new recommended models which are annexed to the ITRF2020 CfP. The ITRS Centre has in particular attended most meetings of the analysis working groups of the Technique Centres (IDS, IGS, ILRS and IVS).

Hosting the Unified Analysis Workshop 2019

The ITRS Centre hosted the Unified Analysis Workshop 2019 at Institut de Physique de Globe de Paris, during 2–4 October, 2019. A number of the technique presentations addressed the preparation for the ITRF2020, including the implementation of updated models and analysis strategies.

IERS Technical Note 40

At the initiative of the ITRS Centre, and with the help of the IERS Central Bureau, an IERS Technical Note (# 40) was published in order to, primarily, acknowledge the activities of the ITRS Combination Centres at DGFI and JPL, beside the ITRS Combination Centre at IGN which is part of the ITRS Centre (Altamimi and Dick, 2020). It includes the description of both DTRF2014 and JTRF2014, as well as their inter-comparisons with respect to the official IERS solution, the ITRF2014. The Technical Note was also intended to include evaluations of the three solutions by the IERS Technique Centres (IDS, IGS, ILRS and IVS) who constantly provide input solutions to the ITRF. In addition to DGFI, JPL and ITRS Centre contributions, the Technical Note includes contributions from IDS, ILRS and IVS. A specific article by the ITRS Centre evaluates the two solutions DTRF2014 and JTRF2014 with respect to the ITRF2014 (see IGN ITRS Combination Centre Report, this issue).

Update of Chapter 4 of the IERS Conventions

Chapter 4 of the IERS Conventions has been re-written by the ITRS Centre team which includes the following updates (IERS ITRS Centre, 2019):

- A description of ITRF2014, with its associated equations, to model the nonlinear station motions due to seasonal signals and post-seismic deformation of stations subject to major earthquakes.
- A description of the mathematical model used in the ITRF combination.

- A revision of Table 4.1, listing the transformation parameters relating ITRF2014 to previous ITRFs.
- Improvements in wording and the removal of unnecessary paragraphs.

Resolutions on ITRS/ITRF

The ITRS Centre has prepared the text of an IUGG resolution on the ITRF which was adopted at the occasion of the IUGG General Assembly 2019 in Montreal, Canada, see: <http://www.iugg.org/resolutions/2019%20IUGG%20GA%20Resolutions.pdf>.

At its 9th Session, the UN-GGIM Committee of Experts supported the agreement of the Subcommittee on geodesy on the adoption of the International Terrestrial Reference System and the International Terrestrial Reference Frame as the standard for scientific, geospatial and operational geodetic applications. The ITRS Centre has significantly contributed to the text of that agreement, see Decision 9/104 of the 9th Session report available here: <https://ggim.un.org/meetings/GGIM-committee/9th-Session/documents/GGIM9-report-e.pdf>.

Participation to the activities of the UN-GGIM subcommittee on Geodesy

The ITRS Centre contributes actively to the activities of the UN-GGIM subcommittee on Geodesy and is chairing a Working group related to the geodetic infrastructure. The ITRS Centre has in particular attended the subcommittee related meetings in 2019, and contributed to the writing of the implementation plan of the Roadmap on the Global Geodetic Reference Frame for Sustainable Development, and two reference documents: draft Position Paper on Sustaining the Global Geodetic Reference Frame and draft Concept Paper on Establishing a Global Geodetic Centre of Excellence.

Maintenance of the IERS network

The ITRS Centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments. The IERS network database, which contains the descriptions of the sites and points, is continuously updated as DOMES numbers are assigned. DOMES number request form can be found on the ITRF web site <http://itrf.ign.fr>, and should be sent to domes@ign.fr. An updated list of all available DOMES number is available at . The IERS site information is available to the users through the ITRF website interface (see below). Several new stations, mainly GNSS permanent stations were added to the ITRF network and database.

ITRF web site

The ITRF web site, available at <http://itrf.ign.fr>, provides an interface to consult the IERS network database. Site and point information can be requested on line; it contains approximate coordinates of the sites, the list of their points as well as their descriptions, their DOMES numbers

and the list of ITRF versions in which they have been computed. Subsets of points can be selected and their ITRF coordinates can be requested at any epoch in any ITRF version if their coordinates are provided in the requested ITRF version.

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

Preparation for a new ITRF web site

The ITRS Centre has started an initial study analysis and preparation for a new design of the ITRF web site. It will be designed to provide more ITRF-related information to the users using more user-friendly interfaces. The new web site which was expected to be operational beginning 2016 experienced some delay, unfortunately, and will hopefully be available by early 2021.

Local ties of ITRF co-location sites

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

At the occasion of the ITRF2020 analysis, we expect new local tie SINEX files and corresponding reports to be submitted to the ITRS Centre. All past and new local surveys used in the ITRF2014 computation are now available via the ITRF website:

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

Publications

Altamimi, Z. and W. R. Dick (Eds.), (2020), Description and evaluation of DTRF2014, JTRF2014 and ITRF2014, IERS Technical Note 40, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie. 167 p., ISBN 978-3-86482-137-0, online: <https://www.iers.org/IERS/TN40>.

IERS ITRS Centre, 2019, Chapter 4 of the IERS Conventions (Terrestrial reference systems and frames), available at <https://iers-conventions.obspm.fr/chapter4.php>

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3.5.6 Global Geophysical Fluids Centre

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

Special Bureau for the Atmosphere

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

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

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

Operational atmospheric analyses are fields determined from observations during the epoch they are valid from the resident atmospheric analysis system in use at that time. Thus the systems, the main compo-

nents 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. For the NCEP reanalysis, files are given both in angular momentum units (aam files) as well as in effective angular momentum units related to Earth rotation (aamf files).

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

During 2019, the SBA updated fields from AAM; the updates were performed by Dr. Y. Zhou of the Shanghai Astronomical Observatory, China. Additional updates for the full 2019 datasets were calculated and are planned for 2020, and will be archived.

Special Bureau for the Ocean

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

available through the SBO website at <https://euler.jpl.nasa.gov/sbo> are produced primarily by general circulation models of the oceans that are operated by participating modeling groups and include oceanic angular momentum, center-of-mass, and bottom pressure. Through the SBO website, oceanic data can be downloaded and a bibliography of publications pertaining to the effect of the oceans on the solid Earth can be obtained. Additional information about the SBO can be found in an unpublished manuscript available through the SBO Publications website at https://euler.jpl.nasa.gov/sbo/sbo_publications.html and in the SBO chapter of IERS Technical Note 30, Proceedings of the IERS Workshop on Combination Research and Global Geophysical Fluids.

During 2019, 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 kf080i (data assimilating) runs of the ECCO/JPL ocean model are now available from 02 January 1993 through 30 March 2020. These values can be extended back to 06 January 1949 using the corresponding values from a 50-year-long simulation run of the ECCO/JPL ocean model whose results are also available through the SBO website.

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

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

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

Special Bureau for Hydrology

The Special Bureau for Hydrology (<http://www2.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) and GRACE

Follow-On (GFO) satellite gravity measurements. The web site contains TWS estimates from five numerical models, the NCEP (National Center for Environmental Prediction) reanalysis, the ECMWF (European Center for Medium Range Weather Forecasting) reanalysis, the CPC (Climate Prediction Center) Land Data Assimilation System (LDAS), the NASA's Global Land Data Assimilation System (GLDAS), and the NOAA LandWorld land dynamics model. Global gridded TWS changes estimated from GRACE time-variable gravity observations are also provided in our online data archive (at <http://www2.csr.utexas.edu/research/ggfc/dataresources.html>). The NASA GLDAS and GRACE data products are updated on a regular basis.

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

In addition, TWS change estimates from historical GRACE release-01 and release-04 products are also provided in our online data archive (at <http://www2.csr.utexas.edu/research/ggfc/dataresources.html>). Some other data sets available in the SBH online data archive include daily hydrological excitations of polar motion and length-of-day computed from the NCEP/NCAR Reanalysis and the list of global major artificial reservoirs and their capacities. We have updated the monthly GLDAS TWS estimates to extend the coverage from January 2002 to December 2019. The GRACE and GFO release-06 monthly TWS estimates with decorrelation filtering and 300 km Gaussian smoothing applied have been provided for the period April 2002 to April 2020.

Combinational Products

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

- UNB Vienna Mapping Function Service (<http://unb-vmf1.gge.unb.ca/Products.html>), M. Santos, University of New Brunswick, Canada.
- AAM analysis (and forecast) series from various atmospheric models (<http://files.aer.com/aerweb/AAM/>), D. Salstein, Atmospheric and Environmental Research, USA.
- Vienna Mapping Function Service, AAM analysis, Atmospheric loading and time-variable gravity (<https://vmf.geo.tuwien.ac.at/>), J. Boehm & M. Schindelegger, Technical University of Vienna, Austria.

- Time-variable gravity field and AM from various hydrology models and from GRACE (<http://www2.csr.utexas.edu/research/ggfc/>), J.-L. Chen, University of Texas at Austin, USA.
- Atmospheric, oceanic and hydrological loading, AM and time-variable gravity (<http://isdg.gfz-potsdam.de/esmdata/>), H. Dotschewski & R. Dill, GFZ, Potsdam, Germany.
- Atmospheric, oceanic and hydrological loading (<http://geophy.uni.lu/>), T. van Dam, University of Luxembourg, Luxembourg.
- Atmospheric, oceanic and hydrological loading and time-variable loading (<http://loading.u-strasbg.fr>), J.-P. Boy, EOST/IPGS, University of Strasbourg, France.

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

3.6 ITRS Combination Centres

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

In 2019, the ITRS Combination Centre at DGFI-TUM focused on the development and testing of a new version of the DOGS-CS software and the preparation of the reference paper for the DTRF2014 solution. A further important research task was to investigate and compare the consideration of non-tidal loading corrections at different levels of the Gauss-Markov model.

DOGS-CS software development

The software package DOGS (DGFI Orbit and Geodetic parameter estimation Software) is a geodetic analysis and combination software developed at DGFI-TUM. It provides the options of SLR and DORIS observation analysis and orbit computation (DOGS-OC), VLBI observation analysis (DOGS-RI) as well as the combination of any space geodetic techniques (DOGS-CS). The combination package of DOGS includes a large number of modular matrix manipulation tools which can be used very flexibly. The development of the new software version 501 comprises (i) the extension of the internal data formats. The new format allows for more precise parameter time-tags and thus for a higher resolution of parameters as well as for more precise parameter transformations. (ii) Furthermore, most of the meta data given in observation or SINEX files can now be handled by the new format. This guarantees a lossless transfer of meta data information from input data through the analysis / combination process to the final solution output (SINEX file). (iii) And finally the homogenization of all software parts w.r.t. the mentioned implementations and in general w.r.t. the usage of models and parameterizations is an important task. The programming process is still ongoing but a large part was finished in 2019 and software tests are performed to ensure the smooth running of the DTRF2020 computation.

The correction of non-tidal loading on different levels of Gauss-Markov model

In the DTRF2014 solution non-tidal loading (NTL) induced by atmospheric and hydrological mass load changes are considered. For the ITRS 2014 realization, the input data of the space geodetic techniques provided by the Technique Centres (TC) of the individual Technique Services did not include NTL corrections, as agreed between the ITRS Centre and the TC. Therefore, in DTRF2014, the NTL corrections are applied as daily or weekly mean values (depending on the temporal resolution of the input data series). In accordance to the DTRF computation strategy which is based on the combination of normal equation

systems (NEQ), the NTL corrections were applied by a reduction of the right hand side of the normal equations. This corresponds to a reduction of all observations of one station in one session-wise, daily or weekly solution by a mean loading correction. Comparing this approach with a correction of the observations right in the observation analysis, the largest impact on the solutions results from the difference in the temporal resolutions of the applied corrections. A further approach for considering NTL, applied by some groups performing analysis of time series, is the a posteriori correction of estimated station positions for NTL. Like the correction of the NEQ, this approach allows only for a limited temporal resolution of the NTL corrections. Beside this, the approach has to be used carefully, because the already finished parameter adjustment might have led – in the sense of residual minimization – to a partial distribution of observation residuals (including NTL effects) within the station network. At DGFI-TUM we investigated the impact of NTL on the DTRF2014 in detail. A further detailed study was performed by the IVS AC at DGFI-TUM for single VLBI sessions comparing the differences between the application of NTL at observation, normal equation and solution level. The results are presented in Glomsda et al. (2020). VLBI sessions are very suitable for these studies as they provide the lowest network densities of all techniques and the most changing network geometries. Both aspects make the VLBI solutions sensitive to the NTL correction approach.

Effects of NTL correction on DTRF2014 results

In order to investigate the impact of NTL corrections on the DTRF2014 we analysed time series of station positions as well as datum parameters. Figure 1 displays the change in the WRMS of station position residual time series when NTL corrections are applied. A significant decrease of the WRMS was achieved for the up-component of GNSS stations. The results might be explained by the facts that (i) the up component is naturally more affected by NTL than the horizontal components and (ii) GNSS shows a generally smaller scatter of station position time series compared to the other techniques, which leads to a larger effect of the applied corrections on the time series.

Second, it is very interesting to study the impact of NTL corrections on the time series of the datum parameters (origin and scale). Figure 2 shows the power spectra of VLBI scale parameter time series derived from an analysis by separately applying atmospheric, hydrological and oceanic NTL corrections as well as all components together. It comes out very clearly that in particular the application of hydrological NTL leads to a significant decrease of the annual signal in VLBI scale time series. Furthermore, the figure allows for a comparison of the results derived from the application of NTL at observation and at NEQ level. The results are very similar and underline the aforementioned result,

that the reduction of NTL at NEQ level corresponds to the reduction at observation level, except for the loss in temporal resolution. The latter affects the parameters with subdaily resolution like EOP rates, clock and tropospheric parameters more than station positions (see also Glomsda et al. (2020)).

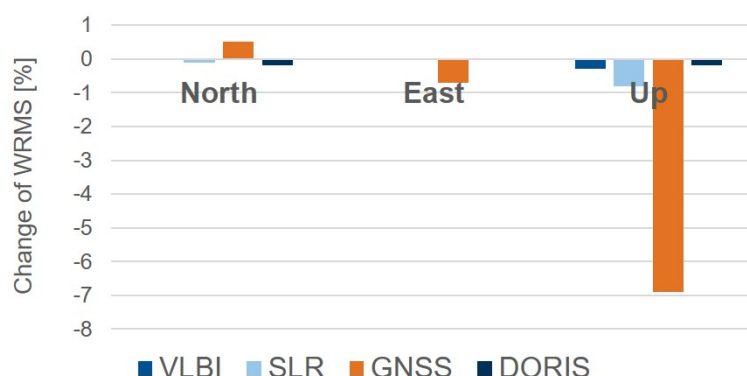


Fig. 1: Change of WRMS of station position time series due to the consideration of NTL corrections in DTRF2014 computation.

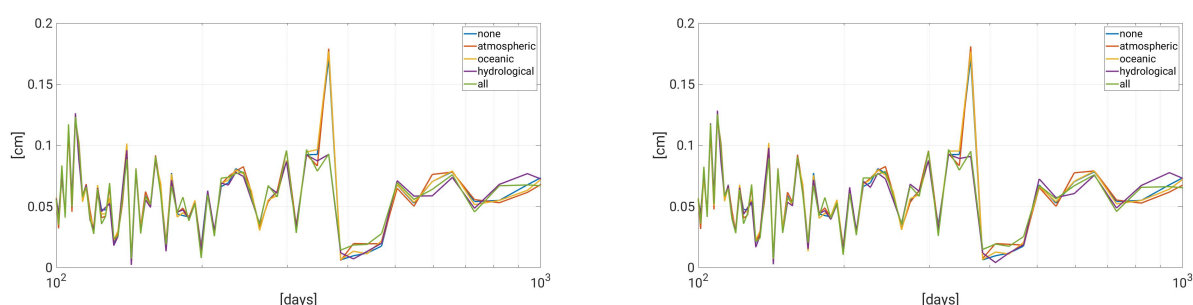


Fig. 2: Amplitude spectra of scale parameter time series derived from VLBI analysis with and without reducing atmospheric, hydrological and oceanic NTL at observation level (left panel) and NEQ level (right panel).

Consistent realization of ITRS and ICRS

For ITRF2020 it is planned for the first time, that the provided IVS input series contain besides station positions and EOP also positions of radio sources. This allows for a consistent determination of ITRF2020 and a celestial radio reference frame. The character of this first consistent solution, planned to be computed in addition to the ITRF2020 realization, is an experimental one. It will allow to formulate concrete scientific questions related to the common realization of ITRF and ICRS as well as to refine approaches for this new type of realization resulting from previous research, e.g., presented by Kwak et al. (2018). The importance of this scientific topic is underlined by the Resolution No. 3 of the International Union of Geodesy and Geophysics (IUGG) adopted by the General Assembly in 2011, wherein the IUGG urged “that highest consistency

between the ICRF, the ITRF, and the EOP as observed and realized by the IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS". An according resolution was adopted by the IAG (in 2019). As a consequence, an IAU/IAG/IERS Joint Working Group (JWG) on the Consistent Realization of TRF, CRF, and EOP was installed in 2020, in which the ITRS CC at DGFI-TUM is involved. More information about the JWG can be found on the IERS website <https://www.iers.org/IERS/WGConsistentRealization>.

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

This report summarizes the activities of the ITRS Combination Centre at IGN during the year 2019.

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 publications section, but also presented at international scientific meetings.

Investigation of the scale discrepancy between SLR and VLBI

The scale of ITRF2014 was defined in such away that it has zero scale and zero scale rate with respect to the arithmetic average of the implicit scales of SLR and VLBI solutions as obtained by the stacking of their respective time series. The resulting scale and scale rate differences between the two solutions (SLR and VLBI) are $1.37 (\pm 0.10)$ ppb at epoch 2010.0 and $0.02 (\pm 0.02)$ ppb/yr. The level of the scale agreement between SLR and VLBI confirms the ITRF2008 finding and is an indication of the persistent scale offset between the two technique solutions. These results suggest that there is still an urgent need for investigation on the causes of the scale discrepancy, e.g., range biases in case of SLR [Appleby et al., 2016] and possible effects due to VLBI antenna gravity deformations [Sarti et al. 2009, 2010]. The ILRS has initiated a pilot project on systematic errors including the range biases which will be estimated in the ILRS solution to ITRF2020. A preliminary SLR test solution was made available to the ITRS center by Cinzia Luceri from the Italian Space Agency (ASI) where estimated range biases were taken into account. Analyzing the time series of this SLR test solution showed a clear scale offset of about 1 ppb with respect to the ILRS solution which was used in the ITRF2014 as illustrated by Figure 1. We expect that this scale offset will greatly minimize the scale discrepancy between SLR and VLBI in the coming ITRF2020 solution.

Contribution to the IERS Technical Note 40

As reported in the ITRS Centre Report, this issue, an IERS Technical Note (# 40) was published in order to, primarily, acknowledge the activities of the ITRS Combination Centres at DGFI and JPL, beside the ITRS Combination Centre at IGN which is part of the ITRS Centre (Altamimi and Dick, 2020). The Technical Note includes in particular a specific article by the ITRS Centre which evaluates the two solutions DTRF2014 and JTRF2014 with respect to the ITRF2014 (Altamimi et

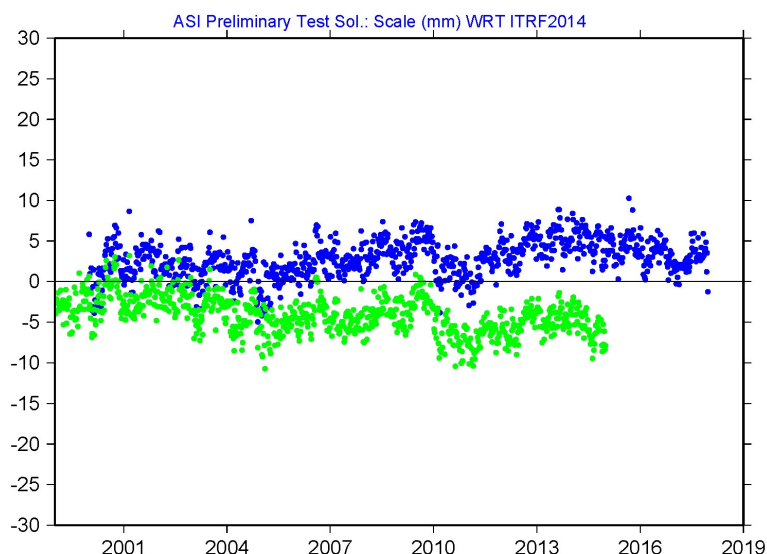


Fig. 1: Scale discrepancy between ASI preliminary solution (blue) where range biases are estimated and ILRS solution (green) used in the ITRF2014 computation

al., 2020). The article concludes in particular that (1) SLR and VLBI intrinsic and discrepant scales coexist in the DTRF and JTRF 2014 solutions, and (2) with respect to ITRF2014 and assuming that its scale is homogeneous, the scale offsets and rates between SLR and VLBI solutions embedded in DTRF2014 and JTRF2014 are respectively 1.32 and 1.21 ppb at epoch 2010.0 and 0.04 and 0.01 ppb/yr. These results are in almost perfect agreement with the results of ITRF2014 analysis.

Publications

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3.6.3 Jet Propulsion Laboratory (JPL)

Introduction

The Jet Propulsion Laboratory is continuing to develop an approach to determining ITRF-like terrestrial reference frames based upon the use of a sequential filter/smoothing. Sequential filters are commonly used to estimate the parameters of some system when a stochastic model of the system is available and when the data contain noise. For the purpose of determining a terrestrial reference frame, the system consists of the positions and velocities of geodetic observing stations and associated EOPs along with their full covariance matrices. The data consist of time series of observed VLBI, SLR, GNSS, and DORIS station positions and EOPs along with the data measurement covariance matrices. In addition, measurements from ground surveys of the positions of reference marks of co-located stations are used to tie the technique-specific station networks to each other. The sequential filter/smoothing software 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. The sequential filter/smoothing 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 first generation sequential filter/smoothing software developed at JPL was based upon the use of a Kalman filter and had a fixed time step of one week (Wu et al., 2015). This Kalman filter and smoother for reference frame determination (KALREF) software was used to determine JTRF2014, JPL's realization of a terrestrial reference frame using the ITRF2014 input data sets (Abbondanza et al., 2017). During 2019, besides continuing to analyze the JTRF2014 solution, JPL also started to develop a second generation version of our sequential filter/smoothing software. The new software, known as SREF (Square-root Reference Frame filter), is based upon a square-root information filter and has a variable time step. The variable time step will allow input data to be processed at its observation epoch without the need to first compute weekly averages of it.

JTRF2014 Analysis

An article for IERS Technical Note 40 "Description and Evaluation of DTRF2014, JTRF2014 and ITRF2014" was written (Abbondanza et al., 2020). The article reviews the main steps that led to the construction of JTRF2014. The first part of the article recalls the main concepts underlying the determination of terrestrial reference frames through

Kalman Filtering and Rauch-Tung-Striebel smoothing as implemented in JPL's KALREF software. The second part of the article adopts a comparative approach and, elaborating on metrics associated with Earth orientation and Helmert transformation parameters, analyzes JTRF2014 in relation to ITRF2014 and DTRF2014.

JTRF2020 Preparations

Much of 2019 was spent developing SREF, JPL's second generation sequential filter/smoothen software. SREF is based on a more flexible and numerically stabler square-root information filter with a time-variable step. In addition, unlike KALREF, SREF includes a full process noise covariance matrix which will allow stochastic models of regional crustal deformation to be optionally included in the process noise model. And SREF includes the ability to optionally process radio source coordinates and precession/nutation parameters which will allow joint terrestrial/celestial reference frames to be determined. In the future, JPL plans to implement a dynamical model for daily EOPs as well as a postseismic displacement model for stations affected by great earthquakes. These future improvements will allow SREF to more accurately predict EOPs and station positions when observations of them are not available.

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3.7 IERS Working Groups

3.7.1 Working Group on Site Survey and Co-location

At the Unified Analysis Workshop in the fall of 2019, discussions were had and a determination made to spend time to refocus the working group on standard field procedures, error budgets, and sharing research on site survey improvements. The approved Terms of Reference are listed here and the accomplishments of full year 2019 follow.

Terms of Reference

The International Terrestrial Reference System is built upon multiple geodetic techniques; Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by satellite (DORIS), and Global Navigation Satellite Systems (GNSS). At locations where these techniques are co-located, it is vital to determine and understand the vectors between the reference points of each technique. These vectors are determined by local tie surveys conducted terrestrially with various procedures and geodetic instruments. The reference points should be collected and properly aligned to a global reference frame in order to produce relative and absolute coordinates.

As the science of local tie surveys has developed, so has technology and the expectation of higher precision and improved protocols. It is the desire of this working group to investigate the current and expected best practices available, along with documenting past efforts, both in the field and researched. This working group will share methodology of existing tie surveys, continued to develop and document recommended procedures, and also archive surveys completed by all agencies represented. In addition, efforts will be made to isolate systematic errors of the space geodetic techniques using surveying methods and investigate field procedures that could be completed during the course of a tie survey in order to provide the operator valuable feedback on potential physical errors found onsite. One critical example of this is quantifying thermal and gravitational deformation in VLBI sensors. It is the overall goal of the working group to encourage consistent field practice, terminology, and documentation throughout the community, with a continued eye on the future of tie surveys.

Objectives/Activities

- Enhance and improve knowledge of local tie surveys through applied field practice, research, and dissemination of materials developed.
- Investigate thermal and gravitational deformation

- Consider importance and inclusion of DoV observations
- Discuss overall error budget and precision (achieved/necessary)
- Continue to enhance guidelines on procedures
- Archive reports, tie vectors and raw data of tie surveys
- Gather, distribute, and maintain publications on related matters
- Coordinate with and solicit feedback from all geodetic techniques

Recent survey activities and presentations

The US National Geodetic Survey conducted an IERS local site survey at the National Radio Astronomy Observatory in Maui (GNSS and SLR), the Table Mountain Geophysical Observatory in Colorado (new GNSS, gravity), and Midway Naval Research Laboratory's OTF in Virginia (GNSS and SLR). Reports and SINEX files were provided to the IERS. In addition, NGS fully implemented the use of an absolute laser tracking system (Leica AT402) into the completed tie surveys, enhancing precision of terrestrial observations. Progress was made on technical memorandum documenting current NGS procedures which will be released and reflect upon IERS TN39.

Pesce, D., Saunier J. (2019) IGN Recent and Planned Local Site Survey Activities & Contribution to the EURAMET GeoMetre Project. Proceedings of the Unified Analysis Workshop 2019. http://ggos.org/media/filer_public/9f/b6/9fb60a43-3d60-4218-9f48-89ac81073b79/uaw_sitesurvey_2-saunier_ignrecentactivities.pdf

Fancher, K., Hippenstiel, R. (2019) US National Geodetic Survey - Recent and Planned Local Site Survey Activities. Proceedings of the Unified Analysis Workshop 2019. http://ggos.org/media/filer_public/ff/67/ff679767-62ec-4065-acfc-3394ae85d573/uaw_sitesurvey_1-hippenstiel_usnationalgeodeticsurvey.pdf

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Co-location survey: online reports http://itrf.ign.fr/local_surveys.php and <https://www.ngs.noaa.gov/corbin/iss/>

- Erickson, B., Breidenbach, S., Jordan, K. Maui co-location survey, June 2019
- Jordan, K., Hippenstiel, R., Erickson, B., Fancher, K. Stafford co-location survey, October 2019
- Jordan, K., Hippenstiel, R., Fancher, K. Table Mountain co-location survey, October 2019

Sten Bergstrand, Ryan Hippenstiel

3.7.2 Working Group on SINEX Format

General aspects

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

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

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

During the year 2019 there was no special meeting of the working group. All discussions on possible format revisions and additions have been done mainly based on personal communication in conjunction with international conferences and workshops, and partly via email.

Provision of loading corrections in SINEX

In preparation for the upcoming realization of the terrestrial reference system (which is planned to be ITRF2020), the need to provide loading corrections along with the SINEX solution came up. The ITRF2020 should be generated without correcting the station deformations caused by non-tidal loading effects. The IVS, however, corrects its operational solutions by atmospheric loading effects, and not all IVS analysis centers want to have two different processing chains in parallel. The IERS Directing Board agreed that the IVS can submit its contribution to the ITRF2020 with loading corrections applied if these corrections are provided within the SINEX file as well. Therefore, a procedure for SINEX was defined that allows to make the loading corrections undone for the entire normal equation systems provided by the IVS. The ITRS Center together with the IVS Analysis Coordinator and the IVS Combination Center developed a block for storing the corrections for non-tidal loading effects that were applied at the observation level was defined. This allows to un-do this correction when handling the normal equations provided in the SINEX file.

One outcome of the ILRS pilot project on "Station Systematic Error Modelling (SSEM)" was that future solutions provided by the ILRS will

**Provision of SLR range
biases in SINEX**

include the values (including their sigmas) for range and time biases that have been applied when generating the solution. This made it necessary to define a new block in SINEX to cover the SLR biases. The ILRS Analysis Coordinator together with the ILRS Analysis Standing Committee started to develop this block in 2019. A final decision of the format is foreseen for end of 2020 in order to be prepared for generating the contribution to ITRF2020.

Daniela Thaller on behalf of the SINEX WG

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

Introduction Unified Analysis Workshops are co-organized by the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS) and International Earth Rotation and Reference Systems Service (IERS). This was the 6th in a series of workshops that are held every two to three years for the purpose of discussing issues that are common to all the space-geodetic measurement techniques. Attendance at the Workshops are by invitation only with each IAG Service nominating 5–6 experts to attend and participate in the discussions. At the 2019 Workshop the discussions were focused on:

- Systematic Errors and Biases in DORIS Observations
- Systematic Errors and Biases in GNSS Observations
- Systematic Errors and Biases in VLBI Observations
- Systematic Errors and Biases in SLR Observations
- Gravity Models for Precise Orbit Determination
- Global Space Geodesy Infrastructure
- Standards, Conventions, and Formats
- Digital Object Identifiers for Geodetic Data Sets
- Global Unified Height System
- Reference Systems and Frames
- Site Survey and Co-location

This report summarizes the Workshop discussions and resulting recommendations.

DORIS Systematic Errors and Biases

Chairs:
Hugues Capdeville (CLS, France)
Petr Štěpánek (GOP, Czech Republic)

The session started with the presentation “South Atlantic Anomaly Compensation” by Guilhem Moreaux, describing the possible ways to compensate the instability of the DORIS onboard oscillator due to the South Atlantic Anomaly (SAA). This effect is important in particular for SPOT-5 and the Jason satellites and results in a bias of the estimated station coordinates in the South Atlantic-South America region. Then we followed with the topic “Scale in DORIS Solutions” presented by Petr Štěpánek, focusing on the long-term stability of the scale and on the systematic effects of low elevation measurement editing and

(down)weighting and related inventions in the proposed strategy for ITRF2020 reprocessing. Since the DORIS space segment is based on LEO satellites having various size, shape, orbit and other characteristics, another important topic is “Mitigation of Non-conservative Force Model Error for DORIS Satellites”, presented by Frank Lemoine. It is important to mitigate systematic errors due to imperfect non-conservative force modeling such as radiation pressure and atmosphere drag, and in particular a signal at draconitic periods for non-sun-synchronous satellites and seasonal variations. The recommendations resulting from the DORIS discussions are:

1. *South Atlantic Anomaly.* Various strategies have been developed including direct observation correction, estimating more frequency parameters, “renaming” the SAA stations for affected satellites, and deleting or downweighting the most affected data. Test campaigns during 2007 for Jason-1 and SPOT-5 and during 2017–2018 for Jason-2 and Jason-3 are recommended in order to specify the optimal strategy for reprocessing the DORIS data for the ITRF2020 submission.
2. *Scale.* Much better stability and consistency of the DORIS scale is being obtained now than was obtained in the solutions for the ITRF2014 submission. It is recommended that Analysis Centers should use their own modeling and preprocessing procedures instead of the data accessories found in the Doppler observation files. It is also recommended that corrected values of the antenna phase center offset (PCO) be used (Hy-2A) and that low elevation data should be downweighted.
3. *Non-conservative force modeling.* In order to mitigate the 117-day signal in DORIS geodetic products, it is recommended that quaternions be used for Jason satellites and to adjust $1\text{Cr}/\text{arc}$. It is also recommended that more recent albedo and infrared models be used. It is noted that the imperfection of available thermosphere models at DORIS satellite altitudes remains a limiting factor in determining the orbits of the DORIS satellites.
4. *IDS reprocessing schedule.* Tests of different processing strategies for the ITRF2020 submission are not yet finished so final recommendations are not yet available. But the deadline to deliver the AC solutions is September 2020. While the start of the IDS reprocessing campaign for ITRF2020 has not yet been determined, it is expected to start sometime during January to March 2020 with the oldest data being reprocessed first.

GNSS Systematic Errors and Biases

Chair:

Michael Moore (Geoscience Australia)

The discussions held during the GNSS session were largely concerned with preparing the GNSS submission to ITRF2020. The IGS contribution to ITRF2020 will use multi-GNSS observations (GPS+Glonass+Galileo) to define the reference frame and will include estimation of scale for the first time. The IGS submission to ITRF2020 will then become part of the IGS operational products at a time to be decided by the participating Analysis Centers. In the meantime, ITRF2014 will be maintained as the basis for the operational products. It is anticipated that improvements in orbit modeling, through updates to the solar radiation pressure models, will help reduce draconitic signals currently present in GNSS time series. Finally, geodetic troposphere products are valuable, especially from reprocessing runs, so please keep these results and make them available.

VLBI Systematic Errors and Biases

Chair:

John Gipson (NASA/GSFC, USA)

The discussions held during the VLBI session were also largely concerned with preparing for ITRF2020:

1. *Models.* The IVS contribution to ITRF2020 will include four new models, two of which are specific to VLBI and two of which are in common with other techniques. The two VLBI-specific models are galactic aberration which causes a change in the apparent source position due to rotation of the solar system about the galactic center, and gravitational deformation of the VLBI antennas which causes a change in the path length and which therefore affects the VLBI observable. The two models in common with the other techniques are the new pole tide model and the new high frequency EOP model.
2. *Timetable.* Currently, all IVS analysis software has been modified to use the four new models. The IVS Combination Center will organize the vetting of the submissions by distributing a list of trial sessions. It is expected that on or about December 1, 2019, the IVS Combination Center will begin to accept trial solutions using the new models. After the trial solutions are vetted by the IVS Combination Center, the Analysis Centers will submit two sets of solutions: one using the old ITRF2014 models and the other using the new ITRF2020 models. Then on or about January 1, 2020 the IVS Analysis Centers should stop submitting solutions using the old ITRF2014 models and should only submit solutions using the new ITRF2020 models. During January 2020 the IVS Analysis Centers will reprocess prior years with the new ITRF2020 models.

In the autumn of 2020, all solutions will be redone, if necessary, using updated gravitational deformation models.

3. *Gravitational deformation.* Currently, the IVS has models for only six of the roughly 60 IVS (and cooperating) antennas. The IVS Directing Board recommends that all IVS antennas have surveys done in order to determine the effect of gravitational deformation. Several groups are already planning on performing these surveys in 2020. If they are completed and the results analyzed by the fall of 2020 then the IVS will redo its submission for ITRF2020 using all available models.
4. *IVS submission.* The IVS SINEX files submitted for ITRF2020 will include radio source position information. The IVS submission will also include results from new broadband VGOS stations. While station loading effects will be included a priori in the IVS processing as is done in routine operations, the SINEX files submitted for ITRF2020 will be modified so that the loading effects can be removed a posteriori. Finally, we expect the IVS submission to ITRF2020 to be more robust than previous submissions because it will be based on results from several new VLBI analysis packages.

SLR Systematic Errors and Biases

Chairs:

Cinzia Luceri (e-Geos/ASI, Italy)

Erricos Pavlis (JCET/UMBC, USA)

The discussions held during the SLR session concerned improvements to the analysis of SLR data, preparations for ITRF2020, and possible new ILRS products. José Rodríguez gave a talk on upgraded center-of-mass modeling for geodetic SLR targets. The signature of the targets in SLR measurements has been the subject of research for many years and has been identified as a significant source of error, affecting primarily the scale of the SLR-determined TRF. Our current understanding of this was reviewed and areas for further investigation were identified. The status and initial results of the ILRS Station Systematic Error Modeling (SSEM) Pilot Project was presented by Cinzia Luceri and the steps needed to apply these results to the development of the ILRS contribution to ITRF2020 were outlined. A description of the various tasks undertaken to prepare for the development of the ILRS contribution to ITRF2020 and their current status was presented by Erricos Pavlis. The timeline for the completion of all outstanding tasks as agreed by the ILRS Analysis Centers during their meeting on October 1, 2019 was presented. Mathis Blossfeld gave a talk on the development of a future product based on multiple SLR targets. Over the past year the ILRS Analysis Standing Committee has discussed the development of new products beyond those used for TRF development. These new

products would be based on an expanded number of targets and would exploit existing and future data. In particular, the benefits of delivering accurate estimates of low degree harmonics of the gravitational field and the relative value of the available targets was described. Finally, Krzysztof Sosnica proposed a model for correcting SLR data for horizontal tropospheric refraction gradients. The importance of including horizontal gradient corrections for tropospheric refraction during the reduction of SLR data for geodetic products was illustrated. An analytical model for this was developed and applied in the analysis presented at the meeting. The repercussions of this correction on various estimated parameters were quantified.

Gravity Models for Precise Orbit Determination

Chairs:

Erricos Pavlis (JCET/UMBC, USA)

Jean-Michel Lemoine (CNES, France)

Michael Moore (Geoscience Australia)

IGS was the first to raise the question about a uniform approach to modeling gravity, tides, and temporal variations from a single source for all satellite techniques. A first attempt to address their concern during their Potsdam 2019 Analysis meeting showed that all satellite techniques are interested in a single point of service, but with different preferences for each technique and sometimes each Analysis Center. The purpose of this session was to examine what each technique does now operationally and during ITRF reprocessing events, and to find out who in the community is willing to provide (or already provides) such a service. John Ries gave a presentation on the GRACE/GRACE-FO products and the SLR-derived supplements which is the basis for what is done within the ILRS. His presentation outlined the rationale and approach in replacing the lowest degree harmonics in GRACE/GRACE-FO products with estimates obtained from the analysis of SLR data on multiple spherical targets. Erricos Pavlis summarized the approach devised by JCET to develop a forecast of low degree harmonics for use in operational analysis by the ILRS Analysis Centers. The sources of the underlying information were detailed and the steps followed were given. Providing the results on a publicly accessible server in the near future was requested and agreed to. Rolf Dach gave a presentation on COST-G, the new Product Center of the International Gravity Field Service (IGFS). COST-G is the evolution of the EGSIM project and it is operationally combining Swarm gravity field solutions on a quarterly schedule with a latency of 3 months from solutions contributed by AIUB, ASU, IfG and OSU. GRACE-FO combinations are foreseen but are not yet done. The generation of gravity field combinations with short latency (e.g., daily products with 5-day latencies, as in the case of EGSIM) is not foreseen. Jean-Michel Lemoine gave a presentation

on the gravity models used at CNES. CNES develops a wealth of gravitational products from the analysis of GRACE/GRACE-FO and SLR data from LAGEOS, LAGEOS -2, Starlette, Stella, and Ajisai, including degree-1 terms, dealiasing products, tidal models, etc. The forecasting and post-casting of such SLR and GRACE-based results was also presented. Mean-field models such as EIGEN-GRGS.RL04.MEAN-FIELD are updated on roughly an annual basis; there is no possibility of a monthly service for such products at the moment. The last presentation, given by John Moyard, focused on an alternate way of describing mass variations observed by DORIS to answer the question: Is it possible to improve TOPEX/POSEIDON orbit performance by identifying some corrections on the geopotential using DORIS missions? The developed procedure uses mascons with EIGEN-GRGS.RL04.MEAN-FIELD as the underlying mean field.

Global Space Geodesy Infrastructure

Chair:

Michael Pearlman (CfA, USA)

In this session, updates were given from the space geodesy techniques and reports were given from the major network players on the current state of the network and its components, current issues limiting performance, current improvements underway, and projected capability over the next 5 and 10 years.

1. *DORIS*. There is a very comprehensive network of DORIS ground stations. The 4th generation DORIS beacon is currently under deployment (since June 2019) which allows larger distance between the beacon and the antenna (50m vs 15m previously) thanks to a signal amplifier at the foot of the antenna. Three new DORIS co-located sites were installed in 2018: with GNSS at Mangilao, Guam island; with SLR at San Juan, Argentina; and with VLBI and GNSS at Ny-Alesund, Svalbard. A network densification (10 additional stations) is being discussed with CNES and IGN.
2. *VLBI*. VGOS is transitioning to an operational status. Bi-weekly, 24-hour sessions will be increasing to weekly sessions as resources permit. The VGOS network is increasing from 6 to 25 stations in the next 2 years. The IVS will begin VGOS intensive observations two times-a-week in late 2019–2020. A 14-station S/X network has been shown to give EOP precision similar to that given by GNSS at biweekly cadence.
3. *SLR*. Significant increase in network capability can be expected over the next 3 years. Unfortunately, there are still large geographic voids in the network. The network will continue to have a mix of new technology and legacy equipment. But progress is being made in dealing with systematics.

4. *GNSS*. The GNSS community is a broad-based, well organized, resilient community exerting strong control, including quality control, of a complicated system. This is achieved by involving their members in all aspects of the process. It is recommended that regular communication channels among the different techniques be established in order to ensure that no co-location opportunities are lost or delayed and that issues impacting each other's infrastructure can be discussed in a timely fashion.
5. *PSMSL*. The Permanent Service for Mean Sea Level (PSMSL) will issue the PSMSL dataset with a digital object identifier (DOI). This is likely to be done on an annual basis. PSMSL is setting-up a GNSS-Interferometric Reflectometry (GNSS-IR) data portal to preserve, archive and distribute sea level data from GNSS-IR. PSMSL will be making available software to automatically quality control near real-time sea level data which can be used to produce mean sea level data and which will improve data flow to PSMSL.

Co-locating techniques is key to determining the terrestrial reference frame. But many co-located (core) sites will not be at ideal locations or have ideal observing conditions. While the original goal was to have 32 well-distributed core sites, 32 sufficiently "good" locations may not exist or may not be in accessible locations. While new technology stations are being deployed, many are not being co-located with other techniques. Since core site deployment will occur over many years, we will have a mix of new and legacy technologies for many years to come. As a result, co-location (non-core) sites will continue to play a vital role in our data products well into the future. The quality of our products will result from observations acquired by a mix of core sites, co-location sites, and different technologies. As a result, it will be important to adhere to proper operational and engineering procedures and to make the best use of data once it leaves the field. Fortunately, many groups are taking the initiative to join the effort, build new stations, or upgrade existing stations. There are many DORIS-GNSS co-locations, and we should not forget about the co-locations that currently exist in space. Analysts will need to be creative in order to make the best use of this mix of data. In summary, this is a challenging program with very important scientific and societal benefits. There is a great opportunity here to participate in the analysis and scientific interpretation of our data. We need to engage students and young scientists in our enterprise. Ultimately, our success will depend on the partnerships that we develop.

Standards, Conventions, and Formats

Chairs:

Nick Stamatakos (USNO, USA)

Detlef Angermann (DGFI-TUM, Germany)

The IERS Conventions describe the reference systems realized by the IERS, in addition to developing and maintaining the models and procedures used to support this endeavor. The reference systems and procedures of the IERS are based on the resolutions of international scientific unions. It is highly recommended that planned major updates and changes to the IERS Conventions (from 2010 version) be discussed at the UAW meeting so that the several component members of the IERS and IAG/GGOS are aware of these upcoming changes, can identify potential impacts to their respective component, and have influence on the realization of these proposed changes in the IERS Conventions text and associated software. The discussions held during the session and the recommendations made were largely concerned with revising the IERS Conventions:

1. *Review of Section 1.1.* An IAG resolution in 1983 recommended that the zero-tide system be used for both gravity field parameters and for the figure of the Earth (geometry). And an IAG resolution in 2015 on the IHRF recommended that the mean-tide system be used to support oceanographic and hydrologic modeling. But the current practice is to use a tide-free system for geometry (ITRF), a zero-tide system for gravity, and a mixed system for physical heights derived from leveling. It is recommended here that the inconsistency concerning the treatment of the permanent tide be resolved within the IAG in order to support GGRF developments and user needs.
2. *Review of Section 1.2.* Because a consistent set of numerical standards does not exist within the IAG, it is recommended that: (1) the numerical standards that are used, including time and tide systems, be clearly documented for all geodetic products; and (2) a new Geodetic Reference System (GRS20XX) be developed that is based on best estimates of the major ellipsoidal parameters.
3. *Review of Chapter 5.* During the presentation of Nick Stamatakis, guiding principles for the simplification of the IERS Conventions were given. It was suggested that the revision of Chapter 5 could be used as a test of the implementation of these guiding principles. It is recommended that: (1) users be encouraged to provide their comments on these guiding principles; and (2) chapter contributors use these guiding principles when revising their chapters.
4. *Review of Nutation Models.* Issues affecting the accuracy and consistency of the presently available precession-nutation models were discussed during the presentation of José Ferrándiz. It is recommended that: (1) the amplitudes of the leading nutation terms of the IAU2000 theory be updated and a shortened series for certain operational purposes be tested; (2) the inconsistencies

found in the precession-nutation models be corrected; (3) the available FCN models be tested and consideration be given to the question of whether or not the IERS should recommend an FCN model to use; and (4) the tasks of the joint IAU/IAG Working Group on Improving Earth Rotation Theories and Models be prioritized in order to get results in two years.

5. *Review of High Frequency EOP Models.* John Gipson gave a report on the activities of the ad hoc IERS Working Group on high-frequency EOP models. Following a series of extensive tests, it was found that the Gipson and the Desai & Sibois models were the two that performed the best amongst all those tested. It is recommended that the Desai & Sibois / Egbert TPX08 model be used in the IERS Conventions.
6. *Review of IAA Solutions.* Dmitry Pavlov reviewed the characteristics of the VLBI, LLR, and GNSS solutions determined at the Institute of Applied Astronomy (IAA) of the Russian Academy of Sciences (RAS). He recommended that: (1) a simpler formulation for ocean loading, including the use of the HARPOS format, be considered; and (2) LLR data be used in EOP combinations.

Digital Object Identifiers for Geodetic Data Sets

Chairs:

Allison Craddock (NASA/JPL, USA)

Kirsten Elger (GFZ, Germany)

In this session, Martin Sehnal gave a broad-scope overview of DOIs for geodetic datasets, Kirsten Elger built on Martin's overview with expert examples and suggested strategies that were revisited during the panel discussion, and Pierre Fridez gave a case study of how one of our contributing organizations currently implements DOIs. The panel discussion addressed the development of future-focused strategies for using DOIs in current and emerging geodetic technologies. The discussions held during the session regarded: (1) the need to identify what the community needs from consistent usage of DOIs for data in terms of being able to discover data, permanently cite data, and acknowledge the data providers; (2) the need to formulate a strategy for assigning DOIs to data in the face of the opportunities and risks for doing this; and (3) the need to identify our goals for implementing DOIs for geodetic data sets such as having a consistent method for data citation across all IAG Services, to support those who are providing the data, and to provide quantitative support detailing the use of geodetic data sets and other resources. The GGOS Working Group on this is planning to meet at AGU 2019 and EGU 2020 to discuss these and other aspects of assigning DOIs to geodetic data sets.

Global Unified Height System

Chair:

Laura Sánchez (DGFI-TUM, Germany)

IAG Resolution No. 1 released during the IUGG 2015 General Assembly outlines 5 conventions for the definition of the International Height Reference System (IHRs). The definition is given in terms of potential parameters: the vertical coordinates are geopotential numbers ($-\Delta W_P = C_P = W_0 - W_P$) referring to an equipotential surface of the Earth's gravity field realized by the conventional value $W_0 = 62\,636\,853.4 \text{ m}^2\text{s}^{-2}$. The spatial reference of the position P for the potential $W_P = W(\mathbf{X})$ is given by coordinates $\mathbf{X}$ of the International Terrestrial Reference Frame (ITRF). This Resolution also states that parameters, observations, and data shall be related to the mean tidal system/mean crust. At present, the main challenge is the realization of the IHRs; i.e., the establishment of the International Height Reference Frame (IHRF): a global network with regional and national densifications, whose geopotential numbers referring to the global IHRs are known. According to the GGOS objectives, the target accuracy of these *global* geopotential numbers is $1 \times 10^{-2} \text{ m}^2\text{s}^{-2}$. In practice, the precise realization of the IHRs is limited by different aspects; for instance, there are no unified standards for the determination of the potential values W_P ; the gravity field modelling and the estimation of the position vectors $\mathbf{X}$ follow different conventions; the geodetic infrastructure is not homogeneously distributed globally, etc. This may restrict the expected accuracy of $1 \times 10^{-2} \text{ m}^2\text{s}^{-2}$ to some orders lower (from $10 \times 10^{-2} \text{ m}^2\text{s}^{-2}$ to $100 \times 10^{-2} \text{ m}^2\text{s}^{-2}$). The objective of this session was to summarize advances and present challenges in the establishment of the IHRs/IHRF. Special care was given to the collocation of ITRF and IHRF reference stations and the harmonization of the standards applied in the determination of geometric and physical coordinates.

Reference Systems and Frames

Chairs:

Zuheir Altamimi (IPGP-IGN, France)

Richard Gross (NASA/JPL, USA)

Manuela Seitz (DGFI-TUM, Germany)

The terrestrial reference frame (TRF) is the foundation for virtually all space-based, airborne and ground-based Earth observations. Through its tie to the celestial reference frame (CRF) by time-dependent Earth orientation parameters, it is also fundamentally important for interplanetary spacecraft tracking and navigation. The TRF determined by geodetic measurements is the indispensable foundation for all geo-referenced data used by science and society. It plays a key role in modeling and estimating the motion of the Earth in space, in measuring change and deformation of all components of the Earth system, and in providing the ability to connect measurements made at the same place at differ-

ent times, a critical requirement for understanding global, regional and local change. Providing an accurate, stable, homogeneous, and maintainable terrestrial reference frame to support numerous scientific and societal applications is one of the essential goals of the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS). This session was a forum for discussing the ways and means of improving the TRF, including understanding the inconsistencies of the current TRFs and the possibility of jointly determining them with the CRF. The recommendations resulting from the discussions held during this session are to:

1. urge the IGS to preserve the alignment of its operational products (orbit, clocks, EOP) to ITRF2014 until ITRF2020 is published;
2. urge the IVS to provide the atmospheric loading (atml) corrections (if applied) to the right-hand side of the normal equation in the SINEX files, i.e. $A^T P(-\delta Y_{atml})$;
3. urge the ILRS to provide the range bias estimates with covariance in their weekly SINEX files;
4. encourage the IDS to mitigate IDS-specific systematic errors that impact the TRF parameters (origin and scale);
5. and invite the GGFC to provide a unified loading model including all contributions (atmosphere, hydrology, and ocean) for all ITRF2020 sites.

Site Survey and Co-location

Chairs:

Sten Bergstrand (RISE, Sweden)

Zuheir Altamimi (IPGP-IGN, France)

The connections between geodetic stations on a geodetic site are key components to a reliable combination of different techniques and a crucial component of a Global Geodetic Observing System on an observational level. Local ties are geometric vectors measured between reference points of different instruments, including the full covariance information in both temporal and spatial domain. These ties are obtained with surveying and monitoring instruments such as theodolites, total stations, laser trackers, invar rods and communicated through a coordinate system realized through GNSS antennas. Where available, the discrepancies between the analytic results and the corresponding ties exceed the expected uncertainty of the surveys. These discrepancies indicate the presence of unknown or underestimated uncertainties or unresolved systematic errors of the different techniques. This session was intended to identify the needs that can elevate the contribution of site surveying in the next ITRF. The recommendations resulting from the discussions held during this session are to:

1. re-form/re-activate the IERS Working Group on Site Survey and Co-location, set objectives for the working group, clarify reporting expectations, engage the IAG Services in the working group, hold annual meetings, disseminate knowledge of antenna deformation measurements, issue guidelines, liaise with the tide gauge community, and distribute publications related to the activities of the working group;
2. understand deflection-of-vertical (DoV) contributions to local tie measurements;
3. work on GNSS weakness on small scale;
4. and prioritize surveying more sites rather than surveying sites more often.

Richard Gross, Robert Heinkelmann, Zuheir Altamimi

Appendices

Appendix 1: IERS Terms of Reference

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

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

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

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

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

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

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

The IERS accomplishes its mission through the following components:

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

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

TECHNIQUE CENTERS (TC)

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

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

PRODUCT CENTERS (PC)

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

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

ITRS COMBINATION CENTER(S)

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

RESEARCH CENTER(S)

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

IERS ANALYSIS COORDINATOR (AC)

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

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

CENTRAL BUREAU (CB)

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

DIRECTING BOARD (DB)

The Directing Board consists of the following members:

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

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

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

- Representatives of IAU, IAG/IUGG and GGOS.

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

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

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

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

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

WORKING GROUPS

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

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

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

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

IERS ASSOCIATE MEMBERS

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

IAG General Secretary
 IAU General Secretary
 IUGG General Secretary
 President of IAG Commission 1
 Chair of IAG Subcommittee 1.1
 Chair of IAG Subcommittee 1.2
 Chair of IAG Subcommittee 1.4
 President of IAG Commission 3
 Chair of IAG Subcommittee 3.1
 Chair of IAG Subcommittee 3.2
 Chair of IAG Subcommittee 3.3
 President of IAU Division A
 President of IAU Commission A1
 President of IAU Commission A2
 President of IAU Commission A3

**IERS
CORRESPONDENTS**

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

October 6, 2015

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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 e-mail: zuheir.altamimi@ign.fr
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(Status as of 1 November 2023)

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Product Centres

Earth Orientation Centre	Earth Orientation Centre Observatoire de Paris Christian Bizouard 61, Avenue de l'Observatoire 75014 Paris France phone: +33-1-4051-2335 e-mail: services.iers@obspm.fr, christian.bizouard@obspm.fr <i>Primary scientist and representative to the IERS Directing Board:</i> Christian Bizouard
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(Status as of 1 November 2023)

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

Central IERS web site	https://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 https://www.iers.org/IERS/products .
Earth orientation data	Rapid data and predictions Web access: https://maia.usno.navy.mil/products/eo-products Monthly earth orientation data Web access: https://hpiers.obspm.fr/eop-pc/index.php?index=bulletins ftp access: hpiers.obspm.fr - directory iers/bul/bulb_new Long term earth orientation data Web access: https://hpiers.obspm.fr/eop-pc/index.php?index=eoptable ftp access: hpiers.obspm.fr - directory iers/eop Leap second announcements Web access: https://hpiers.obspm.fr/eop-pc/index.php?index=bulletins ftp access: hpiers.obspm.fr - directory iers/bul/bulc Announcements of DUT1 Web access: https://hpiers.obspm.fr/eop-pc/index.php?index=bulletins ftp access: hpiers.obspm.fr - directory iers/bul/buld
Conventions	Web access: IERS Conventions 2010: https://iers-conventions.obspm.fr/
International Celestial Reference Frame	Web access: https://hpiers.obspm.fr/icrs-pc/newwww/ https://crf.usno.navy.mil
International Terrestrial Reference Frame	Web access: https://itrf.ign.fr/
Geophysical fluids data	Web access: http://loading.u-strasbg.fr/GGFC/

Publications**IERS Messages**

<https://www.iers.org/IERS/Messages>

IERS Bulletins

<https://maia.usno.navy.mil/ser7/ser7.dat> (Bulletin A)

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

<https://www.iers.org/IERS/Bulletins>

IERS Technical Notes

<https://www.iers.org/IERS/TechnicalNotes>

IERS Annual Reports

<https://www.iers.org/IERS/AnnualReports>

IERS Components**Directing Board**

Web page: <https://www.iers.org/IERS/DB>

Analysis Coordinator

Web page: <https://www.iers.org/IERS/AC>

Central Bureau

Web page: <https://www.iers.org/IERS/CB>

Product Centres**Earth Orientation Centre**

Web site: <https://hpiers.obspm.fr/eop-pc/>

Rapid Service/Prediction Centre

Web site: <https://maia.usno.navy.mil/>

Conventions Centre

Web site: <https://iers-conventions.obspm.fr/>

ICRS Centre

Web site: <https://hpiers.obspm.fr/icrs-pc/newwww/>

ITRS Centre

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Global Geophysical Fluids CentreWeb site: <http://loading.u-strasbg.fr/GGFC/>**Special Bureaus:*****Special Bureau for the Oceans***Web site: <https://isdg.gfz-potsdam.de/ggfc-oceans/>***Special Bureau for Hydrology***Web site: <https://www.polyu.edu.hk/lsgi/ggfc/>***Special Bureau for the Atmosphere***Web site: <https://www.aer.com/science-research/earth/earth-mass-and-rotation/special-bureau-atmosphere/>***Special Bureau for Combination***Web site: <http://geophy.uni.lu/>**Technique Centres****International DORIS Service (IDS)**Web site: <https://ids-doris.org/>**International GNSS Service (IGS)**Web site: <https://igs.org/>**International Laser Ranging Service (ILRS)**Web site: <https://ilrs.gsfc.nasa.gov/>**International VLBI Service (IVS)**Web site: <https://ivscc.gsfc.nasa.gov/>**ITRS Combination Centres****Deutsches Geodätisches Forschungsinstitut (DGFI)**Web site: <https://dtrf.dgfi.tum.de/en/>**Institut Géographique National (IGN)**Web site: <https://itrf.ign.fr/>**Jet Propulsion Laboratory (JPL)**Web page: <https://www.jpl.nasa.gov/site/jsgt/jtrf/>**Working Groups****Working Group on Site Survey and Co-location**Web site: <https://www.iers.org/IERS/WGSiteSurvey>**Working Group on SINEX Format**Web site: <https://www.iers.org/IERS/WGSINEX>**IAG/IAU/IERS Joint Working Group on the Consistent Realization of TRF, CRF, and EOP**Web page: <https://www.iers.org/IERS/WGConsistentRealization>**Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign**Web site: <http://eoppcc.cbk.waw.pl/>

Appendix 5: Acronyms and abbreviations

The following acronyms and other abbreviations are used in this report. For more acronyms related to IERS see <http://www.iers.org/Acronyms>.

AAM	Atmospheric Angular Momentum	ASU	Astronomický ústav Akademie věd České republiky (Astronomical Institute of the Czech Academy of Sciences)
AC	Analysis Centre		
AC	Analysis Coordinator		
ACC	[IGS] Analysis Center Coordinator	ATML	atmospheric loading
AGGO	Argentinian-German Geodetic Observatory	AU	Australia
		AUS	Geoscience Australia
AGN	Active Galactic Nuclei	AWG	Analysis Working Group
AGU	American Geophysical Union	B4G	4th generation DORIS beacon
AIUB	Astronomical Institute, University of Bern	BEV	Bundesamt für Eich- und Vermessungswesen
AIWIS	WISE catalogue	BKG	Bundesamt für Kartographie und Geodäsie / Federal Agency for Cartography and Geodesy
AM	angular momentum		
ANTEX	Antenna Exchange (format)	BNO	GGOS Bureau of Networks and Observations
AOD	atmospheric and oceanic dealiasing	BPS	GGOS Bureau for Products and Standards
AOV	Asia-Oceania VLBI Group for Geodesy and Astrometry	BVID	Bordeaux VLBI Image Database
ApJS	Astrophysical Journal Supplement	c	century
APOLLO	Apache Point Observatory Lunar Laser-ranging Operation	CA	California, USA
APSG	Asia-Pacific Space Geodynamics	CASA	NRAO Common Astronomy Software Applications
AR	Annual Report	CATREF	Combination and Analysis of Terrestrial Reference Frames
AR	autoregressive		
as	arcsecond	CB	Central Bureau
ASAP	as soon as possible	CC	Combination Centre
ASC	Analysis Standing Committee	CC	Conventions Centre
ASI	Agenzia Spaziale Italiana	CCD	Charge-Coupled Device

CDDIS	NASA Crustal Dynamics Data Information System	C/P	Combination and Prediction
CEOS	Committee on Earth Observation Satellites	CPO	celestial pole offset
CERGA	Centre d'Etudes et de Recherches Géodynamiques et Astronomiques	CRC	Combination Research Centre
CETEs	[IERS Conventions] Chapter Editors-in-Chief and Technical Experts	CRD	Consolidated Laser Ranging Data Format
CfA	Harvard-Smithsonian Center for Astrophysics	CRF	Celestial Reference Frame
CfP	Call for Participation/Proposals	COST-G	International Combination Service for Time-variable Gravity Fields
CGPM	Conférence générale des poids et mesures (General Conference on Weights and Measures)	CSR	Center for Space Research, University of Texas
CGS	Centro di Geodesia Spaziale, ASI	CSTG	Commission on International Coordination of Space Techniques for Geodesy and Geodynamics
CIVISA	Centro de Informação e Vigilância Sismovulcânica dos Açores	CSV, csv	comma-separated values [format]
CLS	Collecte, Localisation, Satellites	CTIO	Cerro Tololo Inter-American Observatory
CN	China	CU	[DPAC] Coordination Unit
CN	centre of [observation] network	d	day
CNES	Centre National d'Etudes Spatiales	DB	Directing Board
CNSA	China National Space Administration	DC	Data Center
CODE	Centre for Orbit Determination in Europe	DC	District of Columbia, USA
CoG	centre of gravity	Dec, DEC	declination
CoM	centre of mass	deg	degree
CoP	centre of phase	Dep.	Department
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate	DGFI	Deutsches Geodätisches Forschungsinstitut
CPC	Climate Prediction Center	DGFI-TUM	Deutsches Geodätisches Forschungsinstitut at Technische Universität München
CPF	Consolidated [Laser Ranging] Prediction Format	DIM-ACAV	Domaine d'intérêt majeur en astrophysique et conditions d'apparition de la vie
		DIODE	Détermination Immédiate d'Orbite par Doris Embarqué
		DIS	IERS Data and Information System

DIS	ISO Draft International Standard	EMR	Energy, Mines and Resources Canada (replaced by NRCan)
DOGS	DGFI Orbit and Geodetic parameter estimation Software	ENVISAT	Environmental Satellite
doi, DOI	Digital Object Identifier	EO	Earth orientation
DOMES	Directory Of MERIT Sites (originally; now of more general use)	EOC	Earth Orientation Centre
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)	EOP	Earth Orientation Parameters
DOR-O-T	DORIS Online Tools	EOST	École et Observatoire des Science de la Terre
DoV	deflection of vertical	ERP	Earth Rotation Parameters
DPAC	Data Processing and Analysis Consortium [of the Gaia mission]	ES	Spain
DR	Data Release	ESA	European Space Agency
DST	Deep South Telescope	ESOC	European Space Operations Center, ESA
DTRF	ITRS realization by DGFI	EU	European Union
DUT1	= UT1–UTC	Eumetsat	European Organisation for the Exploitation of Meteorological Satellites
E	East [position/coordinate/direction]	EURAMET	European Association of National Metrology Institutes
EAM	Effective Angular Momentum	EVGA	European VLBI [Group] for Geodesy and Astrometry
EAPS	[MIT] Department of Earth, Atmospheric and Planetary Sciences	e-VLBI	Electronic transfer VLBI
EC	Executive Committee	FITS	Flexible Image Transport System [format]
ECCO	Estimating the Circulation and Climate of the Ocean	FR	France
ECMWF	European Centre for Medium-Range Weather Forecasts	FR	full rate
EDC	EUROLAS Data Center	FRAMEx	Fundamental Reference AGN Monitoring Experiment
EGSIEM	European Gravity Service for Improved Emergency Management	FRIDA	Fundamental Reference Image Data Archive
EGU	European Geosciences Union	FTP, ftp	File Transfer Protocol
EGV	Essential Geodetic Variable(s)	FTPS, ftps	File Transfer Protocol Secure
		GA	General Assembly
		GA	Geoscience Australia
		GB	Governing Board

Gb	gigabit	GRB	gamma-ray burst
GCRS	Geocentric Celestial Reference System	GRG	DORIS Analysis Center at CNES/CLS (formerly LCA)
GEO	Group on Earth Observations	GRGS	Groupe de Recherches de Géodésie Spatiale
GFO	GRACE Follow-On	GRS	Geodetic Reference System
GFZ	GeoForschungsZentrum Potsdam	GSC	GSFC Analysis Center
GGCE	Global Geodetic Center of Excellence	GSFC	Goddard Space Flight Center
GGFC	Global Geophysical Fluids Centre	GSI	Geospatial Information Authority of Japan (formerly: Geographical Survey Institute)
GGIM	= UN-GGIM	GTRF	Galileo Terrestrial Reference Frame
GGOS	Global Geodetic Observing System	GTRS	Geocentric Terrestrial Reference System
GHz	gigahertz	HartRAO	Hartebeesthoek Radio Astronomy Observatory
GIOVE	Galileo In-Orbit Validation Element	HEO	High Earth Orbiter
GIQC	Gaia Initial Quasar Catalog[ue]	HF	high frequency
GLDAS	NASA's Global Land Data Assimilation System	HF-EOP	High Frequency EOP
GLONASS	GLObal'naya NAvigatsionnaya Sputnikovaya Sistema [Global Orbiting Navigation Satellite System, Russia]	hr	hour, hours
GLOUP	GLObal Undersea Pressure	http	Hypertext Transfer Protocol
GM	General Meeting	HTTPS, https	Hypertext Transfer Protocol Secure
GM	geocenter motion	HY	HaiYan / Haiyang / Hai Yang [satellite]
GMU	George Mason University	IAA	Institute of Applied Astronomy, St. Petersburg
GNSS	Global Navigation Satellite System	IAG	International Association of Geodesy
GOP	Geodetic Observatory Pecny	IAU	International Astronomical Union
GPS	Global Positioning System	IBGE	Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics)
GRACE	Gravity Recovery and Climate Experiment	ICESat	Ice, Cloud, and land Elevation Satellite
GRACE-FO	GRACE Follow-On	ICG	International Committee on Global Navigation Satellite Systems
GRAIL	Gravity Recovery and Interior Laboratory		

ICRF	International Celestial Reference Frame	INASAN	Institute of Astronomy of the Russian Academy of Sciences
ICRS	International Celestial Reference System	INFN	Istituto Nazionale di Fisica Nucleare [National Institute for Nuclear Physics]
ICSU	International Council for Science (now: ISC)	Int.	Intensive [VLBI session]
ID	Identification/Identifier	IPGP	Institut de Physique du Globe de Paris
IDF	International DOI Foundation	IPGS	Institut de Physique du Globe de Strasbourg
IDS	International DORIS Service	IR	infrared
IERS	International Earth Rotation and Reference Systems Service	IRIS	International Radio Interferometric Surveying
IfE	Institut für Erdmessung [Institute of Geodesy], University of Hannover	IRNSS	Indian Regional Navigation Satellite System
IfG	Institute of Geodesy of the Graz University of Technology	ISBN	International Standard Book Number
IGFS	International Gravity Field Service	ISC	International Science Council (formerly: ICSU)
IGMA	ICG Monitoring and Assessment Task Force	ISO	International Organization for Standardization
IGN	Institut National de l'Information Géographique et Forestière (formerly: Institut Géographique National)	ITRF	International Terrestrial Reference Frame
IGS	International GNSS Service (formerly: International GPS Service)	ITRS	International Terrestrial Reference System
IGS-RTS	IGS Real-Time Service	IUGG	International Union of Geodesy and Geophysics
IHRF	International Height Reference Frame	IVS	International VLBI Service for Geodesy and Astrometry
IHRF	International Height Reference System	IWLR	International Workshop on Laser Ranging
IIUL	integrated IGS Ultra LODs	Jason-CS	Jason Continuity of Service [mission]
ILRS	International Laser Ranging Service	JCET	Joint Center for Earth Systems Technology, GSFC
INA	Institute of Astronomy of the Russian Academy of Sciences		

JGS	Japan satellite navigation Geodetic System	mas	milliarcsecond(s)
JMA	Japan Meteorological Agency	Mb	megabit
JoG	Journal of Geodesy	MCC	Russian Mission Control Centre
JP	Japan	MD	Maryland, USA
JPL	Jet Propulsion Laboratory	MeO	Métrologie Optique [Grasse SLR/LLR system]
JTRF	ITRS realization by JPL	MEO	Medium Earth Orbit
JWG	Joint Working Group	MGEX	Multi-GNSS [Global] Experiment, Multi-GNSS Extension
KALREF	Kalman filter for Reference frames	MHz	megahertz
keV	kiloelectronvolt	MIT	Massachusetts Institute of Technology
kHz	kilohertz	MJD	Modified Julian Day
LAGEOS	Laser Geodynamics Satellite	mJy	milli-Jansky
LAREG	Laboratoire de Recherches en Géodésie	MLRO	Matera Laser Ranging Observatory
LARES	Laser Relativity Satellite	MOBILE	Mass variation observing system by high low inter-satellite links
lat	latitude	MOU	Memorandum of Understanding
LDAS	Land Data Assimilation System	MPIfR	Max-Planck-Institut für Radioastronomie / Max Planck Institute for Radio Astronomy
LEO	Low Earth Orbit(er)	MPIOM	Max Planck Institute for Meteorology Ocean Model
LLR	Lunar Laser Ranging	ms	millisecond(s)
LMT	Large Millimeter Telescope	msec	milliseconds
LoD, LOD	Length of Day	N	number
lon	longitude	N	North [position/coordinate/direction]
LQAC	Large Quasar Astrometric Catalog[ue]	N, E	north, east
LRO	Lunar Reconnaissance Orbiter	NASA	U.S. National Aeronautics and Space Administration
LS	least-squares	NAVGEN	[U.S.] Navy Global Environmental Model
LSST	Large Synoptic Survey Telescope	NCAR	U.S. National Center for Atmospheric Research
ITPI	weighted square-sum of the residuals		
MA	Massachusetts, USA		
mag	magnitude		

NCEP	U.S. National Centers for Environmental Prediction	NVSS	NRAO VLA sky survey
NEQ	normal equation	OAM	Oceanic Angular Momentum
NERC	Natural Environment Research Council, UK	OBS	observation
NGS	U.S. National Geodetic Survey	Obs.	Observatory, Observatoire
NH	Northern Hemisphere	OC	Operations Center
NIR	near-infrared	OCN	ocean [loading]
NISAR	NASA-ISRO Synthetic Aperture Radar [satellite]	OHIG	O'Higgins [station]
NMA	Norwegian Mapping Authority [Statens kartverk / Kartverket]	OP, OPA	Observatoire de Paris
N.N.	nomen nominandum [the name is to be announced]	OSU	School of Earth Sciences of the Ohio State University
NNR	No-net-rotation, No Net Rotation	OTF	Optical Test Facility
No., Nos.	Number, Numbers	PAO	Public Affairs Official
NOAA	U.S. National Oceanic and Atmospheric Administration	PC	Product Centre
NOFS	[U.S.] Naval Observatory Flagstaff Station	PCO	phase center offset
NP	SLR normal point(s)	PhD	Doctor of Philosophy / philosophiae doctor
NRAO	U.S. National Radio Astronomy Observatory	PI	Principal Investigator
NRCan	Natural Resources, Canada (formerly: EMR)	PLATO	Performance Simulations & Architectural Trade-Offs
NRL	Naval Research Laboratory	PM	Polar Motion
NRT	Near Real-Time (products)	PNT	positioning, navigation and timing
ns	nanosecond(s)	POD	Precise [or Precision] Orbit Determination
NSGF	NERC Space Geodesy Facility	POE	Precise Orbit Comparison
NSOAS	National Satellite Ocean Application Service	POLAC	Paris Observatory Lunar Analysis Center
NT	non-tidal	PP	Pilot Project
NT-L	non-tidal loading	ppb	parts per billion (10^{-9})
		PPP	Precise Point Positioning
		PRC	People's Republic of China
		ps	picosecond(s)
		PSMSL	Permanent Service for Mean Sea Level

PUL	Pulkovo Observatory	SBCP	Special Bureau for Combined Products / Special Bureau for the Combination Products
PZ-90	Parametry Zemli 1990 goda (Earth's Parameters of 1990)	SBH	Special Bureau for Hydrology
PZT	Photographic Zenith Tube	SBO	Special Bureau for the Oceans
QC	quality control	s/c	spacecraft
QSO	Quasi-Stellar Object [quasar]	SDev	standard deviation
QZSS	Quasi-Zenith Satellite System	SDSS	Sloan Digital Sky Survey
RA, R.A.	right ascension	SERC	STEM [Science, Technology, Engineering and Mathematics] Education Research Centre, University of Canberra
RB	range bias	sec	second(s) [of time]
R&D	Research and Development	SH	Southern Hemisphere
RDV	Research and Development (sessions) with the VLBA	SHOM	Service hydrographique et océanographique de la Marine [Naval Hydrographic and Oceanographic Service]
Rep	representative	SIC	Satellite Identification Code
RINEX	Receiver INdependent EXchange format	SINEX	Solution (Software/technique) INdependent EXchange Format
RMS	Root Mean Square	SIO	Scripps Institution of Oceanography
RRFID	USNO Radio Reference Frame Image Database	SIRGAS	Sistema de Referencia Geocéntrico para Las Américas
RS/PC	IERS Rapid Service/Prediction Center	SLR	Satellite Laser Ranging
RT	real-time	SMBH	supermassive black hole
RT-AC	Real-Time Analysis Center	SOFA	Standards Of Fundamental Astronomy
RT-CC	Real-Time Combination Center	SOKENDAI	Graduate University for Advanced Studies
RTCM	Radio Technical Commission for Maritime Services	SPOT	Satellite Pour l'Observation de la Terre
RTS	IGS Real-Time Service	SREF	Square-root Reference frame Estimation Filter
RU	Russian Federation	SRP	solar radiation pressure
SAA	South Atlantic Anomaly		
SARAL	Satellite with ARGOS and ALTIKA		
Sat.	satellite		
SB	Special Bureau		
SBA	Special Bureau for the Atmosphere		

SSALTO	Segment Sol multi-mission d'ALTimétrie, d'Orbitographie et de localisation précise	TUW	Technische Universität Wien (Vienna University of Technology)
SSEM	Station Systematic Error Monitoring	TVG	time-variable gravity
STD	standard deviation	TUGO-m	Toulouse Unstructured Grid Ocean model
SWIFT	Solar Wind Imaging Facility Telescope	TWS	terrestrial water storage
SWOT	Strengths, Weaknesses, Opportunities, and Threats [analysis]	TX	Texas, USA
SWOT	Surface Water Ocean Topography [mission]	UAW	[GGOS/IERS] Unified Analysis Workshop
SYRTE	Systèmes de Référence Temps-Espace [department]	UBAD	USNO Bright-Star Astrometric Database
T2L2	Time Transfer by Laser Link	UBSC	USNO Bright Star Catalog
TAI	Temps Atomique International (International Atomic Time)	UCAR	University Corporation for Atmospheric Research
TB	terabyte	UCL	University College London
TB	time bias	UH	University of Hawaii
TBD, tbd	to be defined	UK	United Kingdom
TC	Technical Committee	UKIRT	United Kingdom Infrared Telescope
TC	Technique Centre	UKMO	Met Office (formerly: UK Meteorological Office)
TEC	Total Electron Content (Total Electron Count)	UMBC	University of Maryland, Baltimore County
TECU	TEC Unit	UN	United Nations
TIGO	Transportable Integrated Geodetic Observatory	UNAVCO	University Navstar Consortium
TN	IERS Technical Note	UNB	University of New Brunswick
TOW	Technical Operations Workshop	UN-GGIM	Global Geospatial Information Management Initiative of the UN
TRF	Terrestrial Reference Frame	URAT	USNO Robotic Astrometric Telescope
TT	Terrestrial Time	URL	Uniform Resource Locator
TU	Technical University	US, U.S.	United States [of America]
TUM	Technische Universität München (Technical University of Munich)	USA	United States of America
		USNO	United States Naval Observatory
		UT, UT0, UT1	Universal Time

UTAAM	NCEP [or NOAA] AAM analysis and forecast data	VT	VGOS Test
UTC	Coordinated Universal Time	w.r.t.	with respect to
UTGPS	Universal Time-like quantity using Global Position System	WDS	ICSU World Data System
VCS	VLBA Calibrator Survey	WG	working group
VGOS	VLBI Global Observing System	WGS84	World Geodetic System 1984
VISTA	Visible and Infrared Survey Telescope for Astronomy	WISE	Wide-field Infrared Survey Explorer
VLA	Very Large Array	WMAGN	Washington Multiple-AGN Catalog
VLBA	Very Long Baseline Array, NRAO	WP	Work Package
VLBI	Very Long Baseline Interferometry	WRMS	Weighted Root Mean Square
VMF	Vienna Mapping Function	WSCS	weighted smoothing cubic spline
VO	VGOS operational series	yr	year
		ZPD	zenith path delay