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COMMISSION A2 — ROTATION OF THE EARTH

ROTATION DE LA TERRE

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IERS Representative — **Daniela Thaller**
IVS Representative — **Oleg A. Titov**

COMMISSION A2 WORKING GROUPS

Div. A / Commission A2 WG — **“Improving Theories and Models of the Earth’s Rotation” (IAU/IAG Joint WG)**
Div. A / Commission A2 WG — **“Consistent Realization of TRF, CRF and EOP” (IAU/IAG/IERS Joint WG)**

TRIENNIAL REPORT 2021–2024

1. Introduction

The Commission began its history with the birth of the IAU at the Brussels Conference in 1919, where Standing Committee 19 “Latitude Variations” was established. At the first IAU General Assembly in 1922, Standing Committee 19 became Commission 19 “Variation of Latitude”. Later, as the topic of the Commission was expanded to include observations and the theory of Earth’s rotation and interconnection between Earth’s rotation and geophysical phenomena, in 1964 it was renamed Commission 19 “Rotation of the Earth”. In 2015, Commission 19 was renewed as Commission A2 “Rotation of the Earth” (CA2) with the same functions. In 2021, CA2 was renewed for the next 6-year term.

Election of CA2 officers for the term 2021–2024 took place in April 2021. Alberto Escapa was elected as the new CA2 Vice-President. Three new CA2 OC members were elected: Laura Fernandez, David Salstein, and Jean Souchay. Second term CA2 OC members are Hadia Hassan Selim, Shuanggen Jin, and Jolanta Nastula.

Three non-voting Representatives to CA2 OC from other organizations were appointed by the new CA2 OC and confirmed by corresponding organizations: Robert Heinkelmann (IAG Representative), Daniela Thaller (IERS Representative), and Oleg Titov (IVS Representative).

Laura I. Fernandez was appointed by the CA2 OC as the new Commission Secretary.

As of March 20, 2024, the Commission consists of 114 members.

The CA2 webpage is
https://www.iau.org/science/scientific_bodies/commissions/A2/info/.

Earth's rotation is an interdisciplinary topic that bridges astronomy and geodesy. Precise knowledge of the Earth's rotation and its variations is needed for positioning and navigating objects on Earth and in space. And the analysis of Earth's rotation variations provides important information about interactions between the various components of the Earth system and about global change phenomena.

The objectives of CA2 according to its ToR are to:

1 Encourage and develop cooperation and collaboration in observation and theoretical studies of Earth orientation variations (the motions of the pole in the terrestrial and celestial reference systems and rotation about the pole).

2 Serve the astronomical community by linking it to the official organizations that provide the International Terrestrial and Celestial Reference Systems/Frames (ITRS/ITRF and ICRS/ICRF) and Earth orientation parameters (EOP): International Association of Geodesy (IAG), International Earth Rotation and Reference Systems Service (IERS), International VLBI Service for Geodesy and Astrometry (IVS), International GNSS Service (IGS), International Laser Ranging Service (ILRS), International DORIS Service (IDS).

3 Develop methods for improving the accuracy and understanding of Earth orientation variations and related reference systems/frames.

4 Ensure agreement and continuity of the reference frames used for studying Earth orientation variations with other astronomical reference frames and their densification.

5 Provide means of comparing observational and analysis methods and results to ensure accuracy of data and models and encourage the development of new observation techniques.

The Commission meets its objectives by fostering research and discussion on Earth's rotation and reference frames, by organizing topical symposia and workshops, and by forming relevant Working Groups.

This report is structured as follows. Section 2 briefly describes the main directions of the CA2 activities in 2021–2024, Section 3 includes reports of CA2 Working Groups, Section 4 contains reports of collaborations international organizations IAG, IERS, and IVS, national reports are collected in Section 5, and Section 6 concludes the CA2 report and overviews main directions of planned future CA2 activities. In the end of the report, bibliography of main publications on the CA2 topics is given.

2. Activities of the IAU Commission A2 during 2021–2024

Two IAU resolutions proposed with participation of CA2 were adopted bu the XXXI IAU General Assembly (Busan, Korea, August 16–27, 2021).

• IAU Resolution B1 proposed by IAU CA1 and CA2 in support of the protection of geodetic radio astronomy against radio frequency interference;

• IAU Resolution B2 on Improvement of the Earth's Rotation Theories and Models.
A. Escapa, R. Heinkelmann, J.M. Ferrándiz, F. Seitz, and R. Gross published an article in IAU Catalyst, March 2022, on these two IAU Resolutions including their detailed description and explanation.

Proposal on IAU Symposia "Advancing reference systems, ephemeris, and standards.

From the Earth and the Moon to solar system bodies" (August 2025, La Plata, Argentina) was initiated and promoted by CA2 and submitted to IAU in 2023.

The CA2 initiated and co-organized two Joint Working Groups.

Joint IAU-IAG-IERS WG "Consistent Realization of TRF, CRF and EOP" (JWG CRTCE, Chair: Robert Heinkelmann, Co-Chair: Manuela Seitz). The main objectives of this WG are:

- to compute multi-technique CRF-TRF solutions together with EOP in one step;
- to quantify the consistency of the current conventional reference frames and EOP;
- assess the consistency of reprocessed and predicted EOP.

Joint IAU-IAG WG "Improving Theories and Models of the Earth's Rotation" (JWG ITMER, Chair: José Ferrándiz, Co-Chair: Richard Gross). The main purpose of this WG is to propose consistent updates of the Earth's rotation theories and models, and their validation. The associated tasks will thus contribute to the implementation of the IAU 2018 Resolution B1 on Geocentric and International Terrestrial Reference Systems and Frames, the IAG 2019 Resolution 5 on Improvement of the Earth's Rotation Theories and Models, and the IAU 2021 Resolution B2 on Improvement of the Earth's Rotation Theories and Models.

Brief overview of the Working Groups activities in 2021–2024 are given below, full reports are provided at `https://www.iau.org/publications/iau/wg_reports/`.

CA2 representatives also participated in the IAU Division A Working Group "Multi-waveband International Celestial Reference Frame (optical+VLBI)".

During the past triennium, CA2 contributed to the organization of various meetings and dedicated sessions at many large scientific conferences:

- IAU XXXI General Assembly 2022,
- IUGG General Assembly 2023,
- AOGS 2022,
- REFAG 2022, Thessaloniki,
- EGU General Assemblies 2022, 2023, and 2024,
- AGU Fall meetings 2021, 2022, and 2023,
- IVS General Meetings 2022 and 2024,
- EVGA Meeting 2023,
- Journées 2023 "Time and General Relativity",

and others.

3. Working group reports

3.1. *IAU/IAG Joint Working Group "Improving Theories and Models of the Earth's Rotation"*

by José M. Ferrándiz (Chair) and Richard S. Gross (Co-Chair)

Overview

This JWG was started in 2019/2020 with the main purpose of proposing consistent updates of the Earth rotation theories and models as well as their validation. Tasks were designed so as to contribute to the implementation of the 2019 IAG Resolution 5 and the 2021 IAU Resolution B2 on Improvement of the Earth's Rotation Theories and Models, which mandate:

- to encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOP;
- that the definition of all the EOP, and related theories, equations, and ancillary models governing their time evolution, must be consistent with the reference frames and the resolutions, conventional models, products, and standards adopted by the IAG and its components;
- that the new models should be closer to the dynamically time-varying, actual Earth, and adaptable as much as possible to future updating of the reference frames and standards.

This JWG reports to the IAU Commission A2 "Rotation of the Earth". The interaction with the IAU has also been naturally extended to IAU CA3, "Fundamental Standards" for the better fulfilment of our assignment, as it deals with astronomical standards in general. Besides, the JWG has sought to keep a close cooperation with IAG components, particularly its Global Geodetic Observing System (GGOS), the IERS, and other WGs dealing with Earth rotation topics and standards from specific perspectives, as well as with the IAU Commission A3. Continuous coordination has been facilitated through having common members and correspondents, in the main.

As for the outcomes, a proposal was presented at the 2022 IERS/GGOS Unified Analysis Workshop on concrete recommendations for achieving short-term feasible improvements to the precession and nutation models by means of supplementing theories with some specific corrections, containing among them a few nutation terms of planetary origin besides the lunisolar ones (`https://zenodo.org/record/7352364`). Also an article was published in IAU Catalyst (2022, Issue 1) explaining the meaning and scope of the two IAU GA 2021 resolutions B1 and B2 in a way that would be intelligible without the possession of specific technical knowledge.

Brief account of progress of research and outcomes

This concise summary highlights significant progress in Earth's rotation research, focusing on short-term improvements in precession-nutation models, advances in FCN modeling, effects of ancillary geophysical models on EOP, exploration of Earth's interior effects, consideration of time variations in Earth's parameters, and miscellaneous advancements contributing to a better understanding of Earth's rotation and prediction accuracy for EOP.

Short-term Improvement of Precession-Nutation Models. Deviations of the observed precession-nutation parameters from the current models, IAU2000 and IAU2006, are about 200 μas in terms of WRMS of CPO, far from the target of 33 μas set by GGOS/IAG. Correcting the linear precession terms of dX and dY, as well as the amplitudes of a reduced set of forced nutation terms allows a noticeable WRMS reduction till about 120–130 μas. Other known inconsistencies between the precession and nutation theories can be corrected at the same time, and the revision of the adopted value of the dynamical ellipticity H is in progress.

Advances in FCN Modeling. Free Core Nutation (FCN), arising from Earth's fluid core resonance, is a main source of the unexplained variance of the determined CPO. Using suitable models permits reducing the WRMS till about 80–90 μas. Two main approaches have been tested: the most common of fitting time-varying amplitudes to an FCN oscillation with fixed frequency or fitting constant amplitudes to a chosen set of frequencies in a band around the FCN one. Recent advancements propose novel approaches for better performance.

Effects of Ancillary Geophysical Models on EOP. Updates to Earth's rotation theories must consider changes in ancillary geophysical models to maintain consistency with data analyses in this and various fields. Recent investigations within the JWG framework revealed significant specific differences between current and past geophysical models, impacting nutation and LOD parameters. Efforts are underway to address these inconsistencies and refine the modeling of Earth's rotation parameters.

Exploring Effects of Earth's Interior on Rotation. Other studies investigated diverse challenging effects of the Earth's interior on nutations. While estimates suggest some effects arising from the core-mantle boundary may be undetectable at present, ongoing research aims to refine understanding and modeling of these intricate processes.

Time-variations of Earth's Dynamical Parameters and Rotation. Recent studies highlight the need for updated theories to accommodate time-varying Earth parameters to improve EOP models. Inconsistencies between observed and assumed variations in Earth's oblateness and principal axes of inertia require correction for better accuracy.

Second order solutions and miscellaneous. Various recent studies explore second-order contributions to nutations, investigate polar motion and LOD variations, and address the complex relationship between Earth's rotation and geophysical phenomena. These ongoing efforts promise a deeper understanding of Earth's rotation and more accurate EOP predictions.

3.2. *IAU/IAG/IERS Joint Working Group "Consistent Realization of TRF, CRF, and EOP" (CRTCE)*

by Robert Heinkelmann (Chair) and Manuela Seitz (Co-Chair)

IAU Commission A2 joint with IAG Sub-Commission 1.4 and IERS.

Member list (alphabetical order)

We acknowledge the dedication of the JWG members and correspondents:
IAU members: Christian Bizouard, Aletha de Witt, Alberto Escapa, Juan Getino Fernández, David Gordon, Richard Gross, Robert Heinkelmann, Christopher Jacobs, Shuanggen Jin, Hana Krasna, Karine Le Bail, Daniel MacMillan, Zinovy Malkin, Manuela Seitz, Florian Seitz, Jean Souchay, Daniela Thaller
IAU Associates: Sabine Bachmann, Liliane Biskupek, Xavier Collilieux, Anastasiia Walenta (née Girdiuk), Sebastien Lambert, David Mayer, Bendikt Soja

Objectives

The objectives of the Working Group are to

- quantify the consistency of the current conventional reference frames and EOP, as well as to
- assess the consistency of reprocessed and predicted EOP.

The JWG strives to achieve this purpose through the computation of multi-technique CRF–TRF solutions together with EOP in one step, which can serve as reference solutions for comparisons. The JWG is aimed to:
– investigate the impact of different analysis options, model choices and combination strategies on the consistency between TRF, CRF, and EOP,
– study the differences between multi-technique and VLBI-only solutions,
– study the possible contributions to EOP and frame determination by the LLR technique,
– study the differences between EOP derived by VLBI solutions at different radio wavelengths,

– study the effects on the results, when different data time spans are considered, and to
– compare the practically achievable consistency with the quality requirements deployed by IAG GGOS.

Progress

In the time period 2021-2023 progress has been achieved on the following topics:

Earth Orientation Parameters and station coordinates from Lunar Laser Ranging (LLR) (L. Biskupek, V.V. Singh, J. Müller, and M. Zhang). Since the operations of the infra-red system at OCA (Cote d'Azur Observatory, Grasse, France) started, the number of LLR normal points approximately doubled and the accuracy of the observations increased. IR-LLR also enables a better distribution of observations across the synodic month in comparison to e.g. green laser. RMS of Xp/Yp are specified to be 1.4/1.8 mas and 18.6 μs for ΔUT1 in the time frame 2000–2022. The determination of nutation terms significantly improved as well. In comparison to results based on data until 2018, repeatability improved by about a factor of two or three for the 13.6^d period, respectively.

K-band and Ka-band VLBI results improved significantly (A. de Witt, C. Jacobs, D. Gordon, and H. Krásná). Since the ICRF3, K-band based VLBI results improved in practically all aspects making this technology a very good comparison for EOP and reference frames. In 2022, the authors report four more years of data, an increase of recorded bandwidth by a factor of two, more than three times the number of observations, about 25% more radio sources than for ICRF3 leading to median scaled errors at the level of 48.4 μas (α) and 83.2 μas (δ). For EOP, the authors report formal errors of 0.1 mas for Xp and slightly more for Yp as well as 7.5 μs for ΔUT1 in the time frame after 2015. For Celestial Pole Offsets (CPO) about the same level of precision or slightly better than EOP 14 C04 is reported (Krásná et al. 2022). This means uncertainties comparable to those of S/X bands. Concluding high-frequency VLBI will in future provide very precise means of comparison for S/X and VGOS-derived geodetic VLBI results. Krśnét al. (2023a) carried out a study, which allowed to better understand the systematic differences between the available S/X and K-band observations, such as the need for an external ionospheric calibration by the K-band data, or the lack of a uniform global terrestrial network causing a non-optimal observation geometry.

Multi-technique solutions on the observation level involving a variety of ties (J. Wang, M. Ge, S. Glaser, R. Heinkelmann, and H. Schuh). With the example of a GNSS–VLBI observation level combination, the authors demonstrate significant improvement for polar motion with weighted standard deviations of below 40 μas for Xp and a bit more than 40 μas for Yp. Whereas the WSTD of ΔUT1 of about 10 μs and CPO do not seem to benefit a lot from the combination with GNSS. The effects of tropospheric ties on the combination will remain in the focus of the studies.

VGOS results for EOP and reference frames (A. Walenta (née Girdiuk), D. Thaller. et al.). Preliminary results have been presented by the BKG IVS AC on the analysis of VGOS data for reference frames and EOP. As the report has been given before the release of ITRF2020, no prior VGOS VLBI station coordinates were available consistent with ITRF releases and therefore one could observe small but significant biases in results obtained by VGOS data. Already first benefits of VGOS could be demonstrated previous to ITRF2020 by the author team. In future, as more VGOS data will become available, these studies will be demonstrated with more statistical significance and employing ITRF2020 as prior information the VGOS to S/X inter-system biases will become considerably smaller.

DTRF2020 release (M. Seitz and F. Seitz). The ITRS realization of the ITRS Combination Centre at DGFI was finalized and released in 2023 (Seitz et al. 2023). In DTRF2020, the VGOS station network is combined with the legacy S/X network on normal-equation (NEQ) level based on common parameters (station coordinates of antennas observing in both modes, station velocities, EOP) mixed-mode sessions, special session linking the Onsala telescopes and local ties. Further innovations of DTRF2020 are: i) atmospheric, oceanic and hydrological non-tidal loading corrections, consistently modelled and provided by IERS GGFC, are reduced on NEQ level, ii) the DTRF2020 scale is realized from the VLBI and the GNSS scale contribution, iii) post-seismic deformation is considered.

ITRF2020 release (Z.Altamimi, P. Rebischung, X. Collilieux, L. Métivier, K. Chanard). ITRF2020 was published in June 2022. Similar to ITRF2014, consistent combined EOP series have been provided with ITRF2020 station coordinates. In addition to an enhanced combination strategy, GPS spurious draconitic signals have been filtered out from the input GNSS station coordinate series which benefited the ITRF2020 EOP. ITRF2020 orientation has been aligned to ITRF2014 to avoid introducing any significant bias and trend with the previous combined series of ITRF2014 and IERS EOP C04. More details can be found in Altamimi et al. (2023).

Consistent estimation of TRF, CRF and EOP. The IVS-AC at DGFI-TUM (M. Seitz and D. Thaller) worked on a consistent estimation of TRF, CRF, and EOP based in a first step on VLBI data only but including for the first time VGOS sessions. Comparisons with DTRF2020, ITRF2020, ICRF3, and EOP reference series show a good agreement. The work prepares a TRF/CRF/EOP solution which is based on the combination of all four space geodetic techniques that contributed to DTRF2020 and will be calculated in collaboration of ITRS Combination Centre and IVS AC at DGFI-TUM and the IVS Combination Center at BKG/DGFI-TUM.
The IVS-AC VIE (H. Krásná et al.) computes a consistent TRF, CRF and EOP from VLBI sessions on a regular basis (Krásná et al. 2023b). Two kinds of solutions are provided: the pure S/X solutions include only the legacy S/X 24-hour sessions provided through the IVS data centers, and the other solutions combine the S/X with VGOS sessions. These reference frames are substantial improvement of the official international terrestrial and celestial reference frames, since they include the latest VLBI sessions provided through the IVS data centers.

4. Organization reports

4.1. *Report of the International Association of Geodesy (IAG)*

by Daniela Thaller

The International Association of Geodesy (IAG) has a strong connection to IAU, in particular IAU Commission A2. During the past three years (2021–2024), IAG had its Scientific Assembly in 2021 (28th of June to 2nd of July; `http://www.iag2021.com/`) in Beijing (China), which was attended by 1516 researchers, with 945 being from China. This was a hybrid meeting with many attendees joining online. A session on "Earth rotation, low-degree gravitational change and mass transport in geophysical fluids" was organized within symposium 3 (Earth Rotation and Geodynamics), which received 10 abstracts and was well attended. In July 2023, IAG had its General Assembly in Berlin (Germany) in conjunction with the International Union of Geodesy and Geophysics (IUGG;

https://www.iugg2023berlin.org/). More than 5000 researchers registered for the Berlin meeting, with 572 attending the IAG General Assembly. Of particular interest for IAU were the IAG symposium “Earth Rotation and Geodynamics” as well as the symposium “Geophysical Constraints on the Earth’s Deep Interior Combining Modelling and Observations”, which was jointly organized by IAG, IASPEI (International Association of Seismology and Physics of the Earth’s Interior), IAGA (International Association of Geomagnetism and Aeronomy), and SEDI (Study of the Earth’s Deep Interior). These symposia received more than 50 abstracts.

During the IAG General Assembly in 2023, several resolutions were approved by the IAG (https://www.iag-aig.org/doc/651bd7f2e3cbf.pdf) and IUGG (https://iugg.org/wp-content/uploads/2023/09/2023_IUGG-GA-Resolutions.pdf) councils, which might have some relevance for IAU:

1. IAG resolution: Establishment of the International Terrestrial Gravity Reference Frame (ITGRF),
2. IUGG resolution 1: Improving Protection of Geodetic Observatories from Active Radio Services,
3. IUGG resolution 3: Sharing Geophysical Data across Borders,
4. IUGG resolution 5: Preservation and Dissemination of and Enhanced Access to Analogue Records.

The next upcoming meetings are the IAG Scientific Assembly 2025 from September 1st to 5th, 2025, in Rimini (Italy), and the next IAG General Assembly, which will be held during the 29th IUGG General Assembly in Incheon (Republic of Korea) from 12th to 22nd of July, 2027.

During 2023 an IAG term ended (2019–2023), which resulted in a change of the structure of IAG, including Commission 3 (Earth Rotation and Geodynamics). Structures within IAG Commission 3 with close connection to IAU Commission A2 are IAG Sub-Commission 3.3 “Earth Rotation and Geophysical Fluids” and JWG 3.1 “Improving theories and models of the Earth’s rotation” (2019–2023). The first was led by Jianli Chen (Hong Kong) and Michael Schindelegger (Germany). They were involved in organizing four dedicated sessions on the topics of Sub-Commission 3.3 at various meetings and assemblies. JWG 3.1 was coordinated by José Manuel Ferrándiz (Spain) and Richard Gross (USA) in cooperation with IAU Commission A2 (see separate report above for detail). In the new IAG term (2023–2027), Sub-Commission 3.3 is now chaired by Sigrid Böhm (Austria) and Christopher Dieck (USA). They will work towards the quantification of angular momentum exchange and mass transfer for the past, present, and future. José Manuel Ferrándiz is leading the new JWG 3.2 on “Consistent improvement of the Earth’s rotation theory” with Cheng-Li Huang (China), again in close collaboration with IAU.

Besides Sub-Commission 3.3 and JWG 3.2, several other (new) working groups within other IAG components are related to Earth rotation and are thus for interest for IAU:

- ICCT JSG T.42 on the “Theoretical developments and applications of combined methods for a better understanding of the Earth’s lithospheric formation, structure, and dynamics”, Chair: Robert Tenzer (Hong Kong),
- ICCT JSG T.46 on the “Deformation, rotation and gravity field modeling for Earth and space”, Chair: Yoshiyuki Tanaka (Japan),
- GGOS JSG 3 within the Focus Area “Artificial Intelligence for Geodesy – AI4G” on “AI for Earth Orientation Parameter Prediction”, Chair: Sadegh Modiri (Germany), Vice-chairs: Justyna Śliwińska (Poland) and Santiago Belda (Spain),

• IERS Working Group on the "Prediction of Earth Orientation Parameters (PEOP)", Chair: Jolanta Nastula (Poland), Co-Chair: Robert Dill (Germany).

In addition to the change of the structure of IAG Commission 3, the Commission is now chaired by a new president and vice-president, which are Rebekka Steffen (Sweden) and José Manuel Ferrándiz, respectively. The new IAG president is Richard Gross (USA).

To further intensify the connection between IAU and IAG Commission 3, a representative of IAU will be part of the IAG Commission 3 steering committee as a non-voting member. Alberto Escapa (Spain) is proposed by IAU for this position.

4.2. *Report of the International Earth Rotation and Reference Systems Service (IERS)*

by Wolfgang Dick and Daniela Thaller

From 2021 to the present, the International Earth Rotation and Reference Systems Service continued to provide Earth orientation parameter (EOP) data, terrestrial and celestial reference frames (TRF/CRF), as well as surface mass driven geodetic parameters to the scientific and other communities.

The Earth Orientation Centre improved its software and implemented the new 20 C04 EOP series on February 14, 2023. This series is consistent with the new TRF (see below).

The Rapid Service / Prediction Centre transitioned their EOP solutions to be consistent with the 20 C04 for polar motion, UT1-UTC, and celestial pole offsets on June 29, 2023.

The IERS continued to ensure that the user community has the most up-to-date terrestrial reference frame by releasing the International Terrestrial Reference Frame 2020 (ITRF2020) in April 2022. For this, the three ITRS Combination Centres (DGFI-TUM, IGN, JPL) improved their combination software for ITRF2020 and conducted test analyses with preliminary data. The final re-analysis data from the International DORIS Service (IDS), the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), and the International VLBI Service for Geodesy and Astrometry (IVS) were provided in April 2021. DGFI-TUM and JPL released DTRF2020 and JTRF2020 in 2023. The ITRS Centre also participated in surveys of co-located sites and updated the list of local ties.

The ICRS Centre started to work on a future realization of the International Celestial Reference Frame. The main focus is on the consistency with the new VGOS concept.

Work on technical updates to the IERS Conventions (2010) was continued, with updates of existing content, expansion of models, and introducing new topics. Several chapters have been revised by the Conventions Centre. A new printed version of the Conventions is in preparation. This version will incorporate a new style so that the main document will be greatly reduced in length, which will enhance the usability of the conventions for the general practitioner.

The Global Geophysical Fluids Centre (GGFC) provided models and loading data for the ITRF2020 combination.

The Central Bureau finished the work on a new user management as part of the IERS Data and Information System. It became operational in 2022. Further security and privacy protection measures were implemented for the IERS web pages and for the IERS user management system. Tools for analysis and visualization of data products have been added or improved.

Members of the Working Group (WG) on Site Survey and Co-location participated in several local tie measurements. Automated monitoring with terrestrial instruments was further developed. Additional local tie surveys were collected following a call from the ITRS Centre, in preparation for ITRF2020. The WG on SINEX Format worked (with other IERS components) on modifications and revisions of the format, particularly for the provision of loading corrections and of SLR range biases in SINEX files. The IAG/IAU Joint Working Group on the Consistent Realization of TRF, CRF, and EOP works on the development of methods for computing multi-technique CRF-TRF solutions together with EOP in one step, which will serve as a basis to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. A new WG on the 2nd Earth Orientation Parameter Prediction Comparison Campaign was established in 2021. It re-assessed the various EOP prediction capabilities by collecting and comparing operationally processed EOP predictions from different agencies and institutions during the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC) from September 2021 to December 2022, evaluating the accuracy of final estimates of EOP, identifying accurate (reliable) prediction methodologies, and assessing the inherent uncertainties in present-day EOP predictions.

The IERS Directing Board (DB) continued to meet twice per year in person or virtually.

The following IERS publications and newsletters appeared: IERS Annual Reports 2019 (the triennial report for 2020 to 2022 is in preparation); IERS Bulletins A, B, C, and D (weekly to half-yearly); approximately 75 IERS Messages. The central IERS web site `https://www.iers.org` was updated and enlarged continually along with 10 other individual web sites of IERS components. The central web site provides also all IERS publications and products.

The IERS co-organized the GGOS/IERS Unified Analysis Workshop (UAW), held in Thessaloniki on October 21-23, 2022. The presentations and recommendations from the discussions are available (see the Workshops page at the IERS website).

4.3. *Report of the International VLBI Service for Geodesy and Astrometry (IVS)*

by Oleg Titov and Dirk Behrend

The International VLBI Service for Geodesy and Astrometry (IVS) continued to fulfill its role as a service within the IAU by providing necessary products for the densification and maintenance of the celestial reference frame as well as for the monitoring of Earth orientation parameters (EOP). Here we report on highlights of the service work during the report period focusing on governance, ICRF work, the observing program, and the next-generation VLBI system.

Governance. On March 25, 2021, Rüdiger Haas (Onsala Space Observatory, Chalmers University of Technology) succeeded Axel Nothnagel (TU Vienna) as Chairman of the IVS Directing Board. Dr. Haas is the fourth IVS Chair. In June 2020, Stuart Weston (Warkworth Observatory, Auckland University of Technology (AUT)) became the IVS Network Coordinator replacing Ed Himwich (NVI, Inc./NASA Goddard Space Flight Center) in this function. After AUT divested itself of Warkworth Observatory at the end of 2022, Dr. Weston was replaced by Alexander Neidhardt (Geodetic Observatory Wettzell, TU Munich) in January 2023. There were four active committees: Observing Program Committee (chaired by D. Behrend), VGOS Technical Committee (chaired by

G. Tuccari), Committee on Education and Training (chaired by N. Zubko), and Celestial Reference Frame Committee (chaired by A. de Witt).

Observing program. The IVS continued the observation of legacy S/X 24-hour, rapid-turnaround sessions (IVS-R1 and IVS-R4), which were run two times per week, for a total of 104 sessions per year. These sessions provided the full set of EOP parameters (i.e., polar motion, UT1–UTC, and nutation). Daily 1-hour S/X Intensive measurements were made for the operational estimation and dissemination of UT1–UTC values. A set of projects aiming to improve the International Celestial Reference Frame (ICRF) were running over this period. The networks included such astrophysical facilities as Very Long Baseline Array (VLBA) operated by the US National Radio Astronomical Observatory (NRAO) and the 65-meter radio telescope in China operated by the Shanghai Astronomical Observatory (SHAO).

ICRF. An IVS Celestial Reference Frame (CRF) Committee was established in 2021. Aletha de Witt (South African Radio Astronomical Observatory, SARAO) is Chair of the CRF Committee. Following discussions between the committee and several international bodies, including the Gaia Optical mission team, the next ICRF realization (ICRF4) is foreseen to be prepared within the next 3 years and approved by the IAU General Assembly in 2027.

VGOS. The rollout of the next-generation VLBI system, the VLBI Global Observing System (VGOS), has continued during the report period. Operational 24-hour VGOS sessions were regularly observed on a network of 10–12 stations. The session cadence was on a two-weekly basis augmented by periods of weekly observing. Further, a weekdaily (1-hour) VGOS Intensive series has been established, as well as VGOS Intensives on weekends. As of early 2024, the VGOS observing network consisted of 14 stations; the network is expected to grow in 2024 and 2025 to about 25 stations. As part of the modernization process, other infrastructure components of the VLBI processing chain have been further developed, including the VGOS correlation and post-processing capabilities as well as VGOS data analysis.

5. National reports

5.1. *Report of activities during 2021–2024 in Austria*

by Sigrid Böhm

The Austrian contributions to Earth rotation research are provided mainly by the research division of Higher Geodesy at Technische Universität Wien (TU Wien). The group conducts routine analysis of very long baseline interferometry (VLBI) observations in cooperation with the Federal Office for Metrology and Surveying (BEV) and presents products such as Earth orientation parameters and reference frames at `https://www.vlbi.at/`.

Recently, Krásná et al. (2023b) published a set of consistently derived VLBI celestial and terrestrial reference frames, VIE2022b. One focus area is the estimation of UT1–UTC from VLBI 1-hour Intensive sessions. In 2020, the Southern Intensives program was initiated to establish an Intensive baseline independent of the standard Intensives, solely observed on baselines in the Northern Hemisphere. Böhm et al. (2022) delivered the proof of concept of the Southern Intensives, and the sessions are now routinely observed as IVS-INT-S every week. The performance of the latest Southern Intensives was evaluated by Böhm and McCallum (2023) along with the EOP determination potential of the Australian mixed-mode sessions. The impact of inaccurate a priori pole and station coordinates on UT1–UTC estimated from VLBI Intensive sessions was examined globally in a simulation study by Kern et al. (2023). Arnab Laha, a guest scientist from India at TU Wien, investigated the influence of the terrestrial datum definition on estimating Earth orientation parameters from geodetic VLBI (Laha et al. 2023). An ongoing topic of interest is the interrelation between climate change and Earth rotation variations based on climate predictions for the 21st century provided by the Coupled Model Intercomparison Project Phase 6, where Böhm and Salstein (2023) presented the latest results on the future atmospheric excitation of length of day.

5.2. *Report of activities during 2021–2024 in Belgium*

by Véronique Dehant

In 2020, we have started the European Research Council (ERC) Synergy Grant project GRACEFUL – Gravimetry, mAgnetism, rotation and CorE FLow (Number 855677, `https://graceful.oma.be`). Our work at the Royal Observatory of Belgium was the continuation of the ERC Advanced Grant project RotaNut – Rotation and Nutation of a wobbly Earth (Number 670874, `https://rotanut.oma.be`). We have developed a fully coupled model with the appropriate code Kore able to compute the core flow considering a rotating Earth, with an inner core and a mantle and with a viscous (represented by an Ekman number close to real Earth) core, embedded in a magnetic field, and responding to tidal forcing. We are able to compute all core modes at all timescales, going from inertial waves, torsional Alfvén waves and magneto-Coriolis waves. In parallel, we have analysed Earth rotation observation to be used to constrain the model. We have applied our approach to other planets (Mars and Mercury) and to the icy moons. The publications can be found on the GRACEFUL website (`https://graceful.oma.be/publications`). The most important ones are included in the bibliography at the end of this report.

5.3. *Report of activities during 2021–2024 in China*

by Xueqing Xu, Chengli Huang, Fengchun Shu, and Jim Ray

Many advancements have been achieved in the theoretical foundation of the Earth's rotation. By dissecting the traditional Liouville equation, a full-band formula for Earth's rotation was developed (Fang et al. 2022). A linear operator method is proposed to compute the rotational modes of any asymmetric 3D planet with pure vector spherical harmonics and applied to study the lower degree normal modes of planets (Zhang & Huang 2023a). The PM and Earth's dynamic oblateness (ΔJ2) were analyzed using a state-space methodology known as Hankel Spectral methodology (HSA) (Shi & Ding 2023). An alternate method to the frequency domain yielded an estimate of 430.4 ± 2.0 mean solar days for the Chandler period (Li & Shen 2022).

Regarding the exploration of the Earth's interior, a finite spectral element method is proposed to compute the Earth's free core nutation and obtained a period of 434 sidereal days which is very close to the observation (Zhang & Huang 2023b). The model of equatorial Magnetic-Archimedes-Coriolis waves propagating at the Earth's core surface which relates with ΔLOD 8.5-year variation is studied, and analytical formulas regarding the physical parameters of the eMAC waves are provided (Duan et al. 2023). Using the frequency domain stepwise regression (FDSR) approach, the three interannual oscillations (at ∼5.9, ∼7.2, and ∼8.6 years) in ΔLOD are determined and considered as internal causes (Hsu et al. 2021). The inner core wobble (ICW), which is considered to have a roughly 8.5-year PM signal, is also thought to be contained in the ΔLOD series (An et al. 2023).

ENSO, AAM oscillations, and ΔLOD are predicted to be substantially correlated on interannual time scales. After evaluating the contributions of continental and oceanic AAM to the interannual variation in ΔLOD, it was discovered that the AAM motion term over the sea makes the largest contribution, especially during strong ENSO events (Xu et al. 2022a). The 2020–2022 triple-dip La Niña and 2023 El Niño events were detected in ΔLOD observations and predictions after the difference+FDSR approach was used to identify the components relevant to climatic oscillations (Xu et al. 2022b, Xu et al. 2023).

Several methods for improving EOP predictions were developed (Lei et al. 2023, Luo et al. 2022, Wang et al. 2023, Wu et al. 2023). Five institutions in China took part in the 2nd EOP PCC activity. Combination product of TRF+EOP from VLBI+GNSS+SLR+DORIS in Shanghai Astronomical Observatory (SHAO) was first achieved in 2018 and is continuing to improve.

Researches at Hubei Luojia Laboratory, School of Geodesy and Geomatics, Wuhan University in cooperation with the National Oceanic and Atmospheric Administration, USA, investigated the excitations of seasonal polar motions derived from satellite gravimetry and general circulation models and compared harmonic and inharmonic analyses (Liu et al. 2022), obtained a self-consistent estimate of the period and quality factor of the Chandler Wobble (Chen et al. 2023).

Four VLBI stations in China regularly participated in global observing programs organized by the IVS. Seshan25, Tianma65 and Kunming stations are hosted by SHAO, while Urumqi station is hosted by Xinjiang Astronomical Observatory. Seshan25 actively participated in IVS-R1 observing sessions for rapid EOP measurements, as well as IVS-INT3 intensive sessions for UT1 monitoring. As an example, Seshan25 contributed to 20 IVS-R1 sessions and 32 IVS-INT3 sessions in 2021.

Shanghai Correlator hosted by SHAO is one of IVS correlators. There were 202 IVS observing sessions in total correlated at Shanghai by the end of 2023. In the past 3 years, 68 database files were generated and submitted to the IVS data centers, 10 of which are derived from international VGOS observing sessions. However, most of those correlated sessions are focused on VLBI absolute astrometry dedicated to maintenance of the ICRF and ITRF.

Three VGOS antennas (Seshan13, Tianma13 and Urumqi13) built by SHAO have been included in the IVS station network. A series of UT1 test observations have been performed using Seshan13 and Urumqi13 VGOS antennas in 2023. The median formal error of UT1 estimates is approximately 10 microseconds. Further UT1 test observations between Shanghai, Yebes and Santa Maria were also planned. It is a near-term goal to establish an operational baseline used for the IERS EOP Rapid Service.

5.4. *Report of activities during 2021–2024 in France*

by Christian Bizouard and Yves Rogister

During the period 2021–2024 the French research devoted to the Earth rotation changes was mostly carried in four institutions: Paris Observatory, Université de Strasbourg and Université de Grenoble, Institut du Globe de Paris, and University of Lethbridge, Alberta.

Paris Observatory (C. Bizouard, Y. Cheng, S. Lambert). C. Bizouard supervised the PhD thesis of Y. Cheng, started in 2020 and devoted to the hourly determination of Earth rotation parameters by processing GNSS observations, associated with GPS and Galileo constellation (Cheng et al. 2023). The obtained results have been analyzed in light of the geophysical and tidal excitation. In particular C. Bizouard and Y. Cheng have revised the diurnal and semi-diurnal effect of ocean tides on polar motion, UT1 and nutation (Bizouard & Cheng 2024). In parallel, C. Bizouard and Y. Cheng (Bizouard & Cheng 2023) showed that the quaternion soffer synthetic expressions for describing the rotation transformation between terrestrial and celestial reference systems. In 2021–2022, C. Bizouard pursues the study of the Earth global rheology from Earth rotation changes. Nurul Huda et al. (2021) estimated the polar motion resonance parameters in the prograde diurnal band, concluding to a resonance period of 400 days; in Bizouard et al. 2022 the removal of oceanic axial excitation in addition to the atmospheric one was proved to be crucial for estimating the admittance coefficients of the zonal tidal terms in the length of day. In collaboration with L. Zotov and other Russian and Chinese scientists, C. Bizouard investigated the presence of climatic signals in polar motion trend (Zotov et al. 2022a). S. Lambert investigated the possible influence of the pole tide on the volcanic activity of the Campi Flegrei (Lambert & Sottili 2023).

Université de Strasbourg et Université de Grenoble (Séverine Rosat, Nicolas Gillet). Rosat & Gillet (2023) confirmed the presence of interannual oscillations of period about 5.9 and 8.5 years in the Earth's length of day. In 2022, S. Rosat in collaboration with other scholars, mainly of Royal Observatory of Belgium, reviewed the relations between the Earth rotation changes and the deep Earth's interior (Rekier et al. 2022).

University of Lethbridge, Alberta (Y. Rogister and B. Seyed-Mahmoud)) Seyed-Mahmoud and Rogister (2021) have theoretically investigated the rotational modes of simple Earth models. In particular, they specified the distinction between the spin-over mode and the tilt-over mode, used analytical formulas and numerical methods to compute the Free Core Nutation, the Chandler Wobble, the Free Inner Core Nutation and the Inner Core Wobble, and questioned the validity of the approximations usually made to represent the displacement field of the free wobble or the free nutation of the inner core.

In September 2023, the Observatoire de la Côte d'Azur(OCA) and Paris Observatory team had the task to organize the colloquium "Journées Systémes de Référence Saptio-temporels 2023 Time and General Relativity", that was chaired by A. Fienga and C. Bizouard.

5.5. *Report of activities during 2021–2024 in Germany*

by Liliane Biskupek, Jürgen Müller, Florian Seitz, Peter Steigenberger, Daniela Thaller, and Maik Thomas

During the past term, the collaborative ESA study "Independent generation of Earth Orientation Parameters" (Contract Nr. 4000120430/17/D/SR) was successfully concluded. This study was performed by a consortium led by DGFI-TUM and involved the Federal Agency for Cartography and Geodesy (BKG), the GFZ German Research Centre for Geosciences (Section 1.3) and TU Wien. It resulted in a prototype software to combine and predict Earth Rotation Parameters (ERP) with seamless transition between final, rapid and predicted states (Kehm et al. 2023). In the framework of the recently started project

"Pro- and Retrospective Highly Accurate and Consistent Earth Orientation Parameters for Geodetic Research within the Earth System Sciences" (PROGRESS, funded by the German Research Foundation DFG), DGFI-TUM, the TUM chair of Satellite Geodesy, and GFZ are exploring further enhancements to EOP combination and prediction procedures.

DTRF2020, the ITRS realization of the ITRS Combination Centre at DGFI-TUM, was released in 2023 (Seitz et al. 2023). The realization includes reference frame and consistently estimated EOP parameters (terrestrial pole coordinates and rates, UT1–UTC, LOD, nutation offsets) between 1980 and 2021. The IVS Analysis Center at DGFI-TUM started with the analysis of intensive legacy VLBI and VGOS sessions, which will, beside the regular 24h sessions, also contribute to the operational combined IVS products. Furthermore, DGFI-TUM was involved in machine-learning-based ERP prediction studies led by ETH Zürich (Kiani Shahvandi et al. 2023).

GFZ section "Earth system modelling" worked mainly on the improvement of the Effective Angular Momentum (EAM) functions and their forecasts provided publicly available with daily updates on `http://esmdata.gfz-potsdam.de:8080/repository`. Forecasted atmospheric wind terms were improved by eliminating artificial signals using a machine learning algorithm (Dill et al. 2021). Using the GFZ EAM analysis and forecast data as essential input into our GFZ EAM Predictor (Dill et al. 2019) we successfully participated in the 2nd EOPPCC (Śliwińska et al. 2023). The quality of our short-term EOP prediction depends heavily on the quality of the available initial values given by rapid EOP solutions. Improvements of rapid EOP were achieved by geophysically informed machine learning (Kiani Shahvandi et al. 2023) and a consistent combination of geodetic satellite techniques (Kehm et al. 2023). We started to quantify time variable EAM forecast errors for future prediction algorithms (Dill et al. 2023).

BKG is regularly generating Earth Orientation Parameters (EOP) through the activities as Analysis Center of the IVS, as Combination Center of the IVS (Hellmers et al. 2022), and as Analysis Center of the ILRS. The VLBI-based EOP products include all 24-hour sessions as well as 1-hour Intensive sessions.

New developments are undertaken to generate a VLBI-internally combined EOP series including 24-hour sessions together with 1-hour sessions and providing EOP estimates in regularly spaced intervals, i.e. at midnight epochs (Klemm et al. 2023). Furthermore, combined EOP series from VLBI and GNSS are also developed (Lengert et al.2022, Klemm et al. 2024) and will be generated in a daily operational mode soon. The inclusion of BKG's ILRS DAILY solution into the combination started in 2024.

Along with the second EOP Prediction Comparison Campaign (EOP-PCC) from the IERS, BKG delivered a series of predictions for all five EOP (Modiri et al. 2024). The predictions are internally tested with different input series of EOP as training data, e.g., single-technique series (GNSS, VLBI, SLR) and our combined EOP series.

The successful realization of infrared-based Lunar Laser Ranging (LLR) measurements in the past years resulted in a strongly increased amount of highly accurate LLR data, where a better coverage of the retro-reflectors on the Moon and the lunar orbit could be achieved. And, more normal points per night could be observed which has been very beneficial for determining Earth orientation parameters from LLR. At Leibniz University Hannover, Germany, dedicated studies have been run to quantify the benefit of the new data for EOP determination, i.e. nutation coefficients as well as ΔUT and the pole components (Biskupek et al. 2022, Biskupek et al. 2024, Singh et al. 2022). In very good nights, ΔUT accuracies come close to VLBI determinations. From the other parameters of the Earth-Moon system, a new relativistic test addressing the equivalence of active and passive gravitational mass should be mentioned (Singh et al. 2023). A further study was related to Differential Lunar Laser Ranging (DLLR) as planned at the Table Mountain Observatory in the USA which would especially be beneficial to better determine parameters related to the lunar rotation, orientation and its interior (Zhang et al. 2022, Zhang et al. 2024).

Modernized navigation messages of Global Navigation Satellite Systems include Earth rotation parameters. Steigenberger et al. (2022) evaluated the quality of ERP transmitted by the US-American GPS, the Chinese BeiDou, the Japanese QZSS and the Indian regional navigation satellite system. They found a consistency with the IERS C04 series of 0.3–1.0 mas for polar motion and about 0.13 ms for ΔUT1 allowing for autonomous GNSS-based spacecraft navigation without external data.

5.6. *Report of activities during 2021–2024 in Poland*

by Jolanta Nastula

Studies on geophysical interpretation of polar motion excitation at CBK PAN and PW in Warsaw

The impact of continental water storage and the cryosphere on the excitation of polar motion (PM) was investigated using various data products from the GRACE and GRACE-FO missions, as well as climate models. This influence was assessed through the analysis of time series data related to hydrological and cryospheric angular momentum (HAM/CAM) derived from both GRACE/GRACE-FO and CMIP6 sources (Nastula et al. 2022; Śliwińska et al. 2021a, 2021b, 2022a; Śliwińska and Nastula 2023; Wińska 2022; Partyka et al. 2023).

In 2021, these studies were described in the paper by Śliwińska et al. (2021a), where the analysis was extended to include trends, seasonal, and non-seasonal changes. A comparison with results from satellite laser ranging (SLR) was also provided. It was demonstrated that the hydrological and cryospheric angular momentum (HAM/CAM) series computed from GRACE/GRACE-FO mascon solutions exhibited higher consistency with the hydrological signal in geodetically-observed PM excitation (geodetic residuals, GAO) than the same series based on data from other sources, particularly regarding seasonal fluctuations. A detailed analysis of PM excitation derived from mascon data provided by different data centres proved that the choice of mascon solution has no noticeable impact on the level of compliance between HAM/CAM and GAO (Śliwińska et al. 2021b). A summary of the research on the use of different types of GRACE and GRACE-FO data products to determine HAM/CAM was included in the PhD thesis of Justyna Śliwińska.

In Śliwińska et al. (2022a), several combined HAM/CAM series were computed from GRACE and GRACE-FO solutions using the three cornered hat (TCH) method, which allowed to minimize the noise in the combined series. Individual combined series were calculated as a weighted average of single solutions, in which the determined noise had an inverse relationship with the weights. A validation of combined series with the GAO as a reference showed that the proposed approach allows for increased compliance with GAO compared to exploiting single GRACE/GRACE-FO solutions.

Historical simulations from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) were utilized to verify whether climate models offer plausible data for determining HAM (Nastula et al. 2022). Climate-based HAM series were compared with

GAO, GRACE-based HAM/CAM and HAM obtained from the Land Surface Discharge Model (LSDM). Overall, the agreement between GAO and HAM derived from CMIP6 was less than the previous agreement established with the GRACE scores, and the level of consistency varied depending on the model and oscillations considered. Nevertheless, some CMIP6 models may produce reliable HAM data, especially for annual variations.

Various datasets were used by Wińska (2022) to determine the geophysical excitation of PM. Wińska (2022) focused on interannual oscillations in PM excitation calculated using different atmospheric and ocean models, GRACE/GRACE-FO data, and LSDM. Interannual oscillations in PM excitation were retained using the Multi-Singular Spectrum Analysis method. The primary finding of the research indicates that adding hydrological considerations to the coupling of atmospheric and oceanic excitations enhances the consistency between geophysical and geodetic excitation in the interannual spectral band. However, the models still need some amelioration to reduce non-negligible differences between geodetic and geophysical estimates of PM excitation.

Additionally, we examined the usefulness of the daily gravity field models based on observations from the Gravity Recovery and Climate Experiment (GRACE) mission developed by the Institute of Geodesy at Graz University of Technology (ITSG) in determining hydrological angular momentum (HAM). The study focused on non-seasonal time scales. ITSG data have a daily temporal resolution, enabling us to detect oscillations with higher frequencies than the more commonly used monthly data. In general, the ITSG daily gravity field models have proven useful in determining equatorial components of HAM at non-seasonal time scales (Partyka et al. 2023).

We assessed the impact of various corrections applied to the GRACE Level-3 data on the computed series of hydrological and cryospheric angular momentum (HAM/CAM). The application of these corrections mainly enhances the consistency between HAM/CAM and GAO, especially for $\chi1$ and $\chi2$ in the non-seasonal spectral band and for $\chi1$ in the seasonal spectral band (Śliwińska and Nastula 2023).

Second Earth Orientation Parameters Prediction Comparison Campaign (2^{nd} EOP PCC) at CBK PAN in Warsaw

Advanced geodetic and astronomical tasks, such as precise positioning and navigation, require forecasted Earth Orientation Parameters (EOP). Between 2021 and 2022, the Second Earth Orientation Parameters Prediction Comparison Campaign (2^{nd} EOP PCC) was launched (Śliwińska et al. 2022b, Kur et al. 2022). The Campaign aimed to compare various EOP forecast methods implemented by different institutes worldwide. The CBK PAN was the lead organiser and coordinator of this international initiative. There were 18 registered institutions from nine countries, and over 60 people regularly delivered predictions, based on 58 different approaches (Śliwińska et al. 2022b). The campaign started on 1 September 2021, and finished on 28 December 2022, with 7327 predictions submitted within 70 weeks. The work with 2^{nd} EOP PCC results focused on universal time (UT1–UTC) and Length-of-Day (LOD) predictions, received between 1 September 2021 and 29 May 2022. Forecasts were preliminarily evaluated against the EOP 14 C04 solution delivered by the International Earth Rotation and Reference Systems Service (IERS) using mean absolute error (MAE) as the prediction quality measure. Similarly, we compared forecasts from the IERS delivered by the U. S. Naval Observatory (USNO) and a selected campaign participant (GeoForschungsZentrum Potsdam, GFZ), to assess the impact of both input data and the computation methodology on predictions. This preliminary evaluation of both UT1–UTC and LOD data showed that nine months after the start of the 2^{nd} EOP PCC, MAE values for the 10th day of prediction were determined as 0.36–3.13 ms for UT1–UTC, and 0.07–0.28 ms for LOD, depending on the prediction method. It was also confirmed that IERS/USNO predictions are of very good quality and can be wholeheartedly recommended for operational applications.

5.7. *Report of activities during 2021–2024 in Russia*

by Zinovy Malkin and Leonid Zotov

Theoretical research related to the Earth's rotation, as well as EOP observations and data processing are carried out in several institutes in Russia. More than 20 Russian permanent VLBI, GPS, SLR and DORIS stations are included in the IVS, IGS, EPN,and IDS networks and are used for deriving IERS products such as EOP and ITRF. Russian experts in the Earth rotation and related topics participate in several working groups and committees of the IAU, IAG, and specific space geodesy services.

The Institute of Applied Astronomy (IAA) supports 3-station VLBI network QUASAR consisting of three observatories: Svetloe, Zelenchukskaya, and Badary (Shuygina et al. 2019). Each station is equipped with 32-meter and 13-meter radio antennas (RT32 and RT13, respectively) that participate in the domestic and global observing programs for determination of EOP. The IAA EOP observing program include 24-hour sessions on 3-station network providing full set of EOP, and 2-hour single-baseline sessions for rapid determination of UT1 with a delay and resolution of a few hours. All three QUASAR stations are also equipped with GNSS receivers and SLR units that contribute to IGS and ILRS, respectively. IAA is working on regular processing the observations collected on global IVS, IGS, and ILRS networks and submits obtained EOP, TRF, and CRF products to IERS and IVS.

The National Research Institute for Physical-Technical and Radio Engineering Measurements (VNIIFTRI) is the responsible agency for the Russian state EOP service and for maintenance and dissemination of the Russian national time scale. The VNIIFTRI is working on processing VLBI, SLR, and GHSS data collected on global and Russian domestic networks. The results of processing are delivered to IERS. The VNIIFTRI also produces combined EOP solution using individual EOP series computed at VNIIFTRI and other Russian institutes. Computation of daily EOP predictions are continued at the Sternberg Astronomical Institute of the Moscow State University.

Malkin (2021) and Lambert & Malkin (2023) investigated various methods for mitigation of the impact of outliers on results of comparison of different CRF realizations. Malkin and Tissen (2022) compared several statistics that can be used for accuracy assessment of the EOP predictions. Yao et al. (2022) investigated the effect of Galactic aberration on Earth orientation parameters. Some researches were devoted to analysis of the FCN variations and their interconnection with the geomagnetic field (Modiri et al. 2021, Malkin et al. 2022).

A comparison of the GRACE and SLR-derived trends in 2-degree Stokes coefficients and the tendencies in LOD and PM confirmed a consistency between the climatological mass redistribution on the Earth with the PM drift (Zotov et al. 2022a). Several studies were performed devoted on analysis of the behavior of the Chandler wobble during last decades, including the CW amplitude and phase variations, and its possible connection with variations of the speed of Earth's rotation and other geophysical phenomena observed near simultaneously with decreasing of the CW amplitude and significant phase drift. (Zotov et al. 2022b, Zotov 2022, Malkin 2023, Zotov et al. 2023).

5.8. *Report of activities during 2021–2024 in Spain*

by Alberto Escapa and José Manuel Ferrándiz

In this term Earth rotation studies have continued at the Universities of Alicante, León, Valladolid, and Centre of Defence of the Spanish Air Force Academy at San Javier, Murcia. There has been a significant increment of the activity from the University of Alicante VLBI Analysis Centre (UAVAC) because of the support of the regional government of Valencia via a Prometeo grant (PROMETEO/2021/030); it is now routinely offering operational products labelled as "uavyyyyx"(Karbon et al. 2023b) together with research products like global solutions for all the EOP and consistent reference frames as well, among them a celestial one derived using new strategies for the selection of sources (Karbon et al. 2023b). UAVAC has also kept a close partnership with the Spanish IGN (Instituto Geográfico Nacional) and RAEGE (Red Atlántica de Estaciones Geodinámicas y Espaciales/Rede Atlântica de Estações Geodinâmicas e Espaciais). In addition, the IGN has started a new IVS Associated Analysis Centre and the RAEGE network has two VGOS stations in full operation, namely those at Yebes Observatory (Spain) and Santa Maria de Açores island (Portugal).

One of the main outcomes of the UAVAC has been testing the effects of using the corrections for precession and forced nutations (Ferrándiz & Escapa 2022) proposed for assessment at the 2022 IERS/GGOS Unified Analysis Workshop (UAW) in the derivation of solutions from VLBI data, not only session-wise but also global. The reduction of the WRMS of CPO when the corrected precession-nutation theories are used as aprioris to derive CPO-like parameters instead of the conventional IAU2000 and IAU2006 is remarkable, since it decreases from about 190 μas as owned by conventional CPO to about 130 μas for the modified ones, without any FCN model (Ferrándiz et al. 2022, Ferrándiz et al. 2023). Supplementing the corrections with a suitable FCN model allows a further reduction of the CPO-like variables till around 80 μas, though FCN is not to be used as a "theory" for its physical character and that experiment is mainly intended to get more insight into the repeatability and presumed accuracy of solutions (Belda et al. 2023).

The UA team also took part in the Second EOP Prediction Comparison Campaign (EOPPCC2) as a part of the international group "BAG" (from BKG, Alicante, GFZ) whose weekly submissions were in charge of GFZ members. The UA hosted the final 2nd Workshop of the EOPPCC2 held in March 1-2 2023 in a mixed format in-person in Alicante and virtual.

On the theoretical side, we have gone on with developing analytical models to compute the effects of the redistribution of mass resulting from the lunisolar attraction on the Earth rotation (Escapa et al. 2022). We have applied our Hamiltonian formalism to re-evaluate the secular change in the length of day (Baenas et al. 2021). By doing so, our approach allows a consistent and integrated computation of the tidal redistribution contributions to precession, nutation, and length of day. It also offers the advantage, related to its analytical character, that can be evaluated for different Earth rheological and oceanic models by means of frequency-dependent Love number formalism. Within these researches, we have also revised (Escapa et al. 2023) the Earth's dynamical ellipticity constant as given in IAU2006/2000 precession-nutation model, which was derived from the precession model. The resulting value is updated to the last Hamiltonian developments, considering both second-order and redistribution effects, and, for the first time in an astronomical context, makes explicit the used tidal system in its computation (zero-frequency).

We are also working in the extension of a a second order Hamiltonian analytical theory for the rotation of a Poincaré Earth to consider Oppolzer terms in addition to Poisson terms (Getino et al. 2021). Such kind of contributions, whose derivation is very complex, cannot be obtained through the conventional transfer function approach used in IAU2000 nutation (Escapa et al. 2021), although very likely they contribute at the μas level, hence not negligible nowadays.

Finally, Spanish CA2 members have contributed to the operation and outcomes of the two IAU/IAG JWGs of the Commission formerly described, especially to the JWG on Improving Theories and Models of the Earth's Rotation (ITMER).

5.9. *Report of activities during 2021–2024 in USA*

by Richard Gross

During 2021–2024, JPL continued to support the tracking and navigation of interplanetary spacecraft by acquiring and reducing very long baseline interferometry, global navigation satellite system, and lunar laser ranging data and, by using a Kalman filter and smoother, to combine these with other Earth orientation measurements in order to produce optimal estimates of past variations in the Earth's orientation and to predict its future evolution. Export versions of the combined and predicted Earth orientation parameters are available at `https://keof.jpl.nasa.gov`.

6. Closing remarks and outlook

The Commission A2 has a more than 100-year history of active involvement in the IAU. Starting with investigations of latitude variations, now it has extended its activities to many key topics related to the investigation of all aspects of the theory and observations of Earth's rotation and maintenance and improvement of terrestrial and celestial reference systems and frames. The CA2 continues to play an important role in the IAU's activity of coordinating international cooperative efforts to promote progress in these directions. It works in close cooperation with international unions such as the IUGG and IAG and thus provides the necessary link between these organizations and the IAU. CA2 collaborates with several international services, IERS and IVS in the first place, and co-organized several joint working groups with IAG and IERS. This work will continue.

In addition to the traditional and regular CA2 activities, the major topics of interest for the next 3-year period will be:

- Theoretical studies on Earth's Rotation, in particular, in the framework of a new IAU/IAG JWG "Consistent Improvement of the Theory of Earth Rotation (CITER)";
- Improvement of the IAU precession-nutation model, in continuation of and based on the results obtained in the frameworks of IAU/IAG JWGs on Earth Rotation TERV (2013–2020) and ITMER (2020–2024);
- Improvement of EOP prediction accuracy, in particular, in the framework of a new IAU/IAG/IERS JWG "Prediction of Earth Orientation Parameters (PEOP)".

The Commission will continue to work closely with the astronomical and geodetic societies, services, committees and commissions as it has been in the past, to encourage and promote progress in observing and understanding the Earth rotation, and related reference systems and frames.

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