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COMMISSION A2	**ROTATION OF THE EARTH**
	ROTATION DE LA TERRE
PRESIDENT	**Florian Seitz**
VICE-PRESIDENT	**Zinovy Malkin**
SECRETARY	**Alberto Escapa**
ADVISOR	**Richard Gross**
ORGANIZING COMMITTEE	**Jose Manuel Ferrándiz, Shuanggen Jin, Jolanta Nastula, Hadia Selim**
IAG Representative	**Robert Heinkelmann**
IERS Representative	**Daniela Thaller**
IVS Representative	**Oleg Titov**

COMMISSION A2 WORKING GROUPS

Div. A / Commission A2 WG	**Theory of Earth Rotation and Validation (IAU/IAG Joint WG, ended in July 2019)**
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 2018–2021

1. Activities of IAU Commission A2 during 2018-2021

by Florian Seitz (President) and Alberto Escapa (Secretary)

Earth rotation has been an elementary topic within the International Astronomical Union (IAU) since its foundation in 1919. During the past triennium, the Commission celebrated its 100^{th} anniversary and one century of Earth rotation research in the framework of IAU. Along with the creation of IAU during the Constitutive Assembly of the International Research Council in Brussels 1919, the *Standing Committee 19 on Latitude Variations* was created as one of the 32 constituent standing committees of IAU in order to study polar motion. In 1922 the Standing Committee 19 was transformed into *Commission 19 on Variation of Latitude*, and in 1964 it was renamed into *Commission 19 on Rotation of the Earth*. After restructuring the IAU in 2015, the designation was changed into *Commission A2 on the Rotation of the Earth*.

All along, the Commission has been bridging the disciplines of astronomy and geodesy, for which the Earth's rotation and its temporal changes are key quantities for various scientific questions and practical applications. Above all, the determination of Earth Orientation Parameters (EOP), comprising precession, nutation, polar motion and the Earth's spin at the highest level of accuracy is fundamental for the realization of precise celestial and terrestrial reference systems, time systems, and for positioning and navigation on Earth and in space. Temporal changes of Earth rotation on timescales from subdaily to decadal and secular reflect external influences and geodynamic processes. Thus, their analysis allows for inferences on the internal structure and interactions between the components of the Earth system and on the impacts of global change phenomena.

The Commission's objectives are to encourage collaboration in theoretical studies and observations of Earth rotation, the development of new observation techniques and of strategies and methods for improving the accuracy of Earth rotation changes and reference frames. It ensures the agreement and continuity of different (geodetic/astronomical) reference frames and their densifications, and it has been linking the astronomical community to international organizations that are responsible for providing EOP and terrestrial and celestial reference frames (ITRF/ICRF), such as the International Association of Geodesy (IAG), the International Earth Rotation and Reference Systems Service (IERS), and the technique services IVS (Very Long Baseline Interferometry), ILRS (Satellite Laser Ranging), IGS (Global Navigation Satellite Systems), and IDS (Doppler Orbitography and Radio positioning Integrated by Satellite). Through a multitude of dedicated symposia (among them various IAU Symposia and IAU Colloquia), workshops, and working groups (WGs), the Commission has been fostering research and discussion on Earth rotation and reference frames within the international scientific community over its history. Furthermore, the Commission has effected various IAU Resolutions on different aspects. By March 2021, Commission A2 counted 110 members. This information is accessible via Commission's web at `https://www.iau.org/science/scientific_bodies/commissions/A2/info/`.

During the past triennium, Commission A2 contributed to the organization of various symposia and dedicated sessions at scientific conferences. The *Journées 2019: Astrometry, Earth rotation and Reference systems in the Gaia era* held in Paris, France (October 7-9, 2019) were organized by jointly with Commission A1 and gathered 120 international scientists. The symposium comprised dedicated sessions on the Gaia mission, Earth rotation and geodynamics, ICRF and astrogeodesy, and space navigation and solar system dynamics. The presentations highlighted exciting investigations of high scientific relevance. During the meeting, Commission A2 celebrated its 100^{th} anniversary in the frame of a dedicated session, reviewing the enormous achievements in Earth rotation and reference systems/frames research over the past century and discussing prospective scientific challenges and potentials. Furthermore, Commission A2 members contributed to the organization of the EGU General Assemblies 2019, 2020 and 2021 in Vienna, Austria (Session G2.2: The International Terrestrial Reference Frame: Elaboration, Usage and Applications; Session G3.1/G3.3: Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation), the IUGG General Assembly 2019 in Montreal, Canada (Session G01: Reference Systems and Frames; Session G04: Earth Rotation and Geodynamics; Session G06: Monitoring and Understanding the Dynamic Earth With Geodetic Observations), and the AGU Fall Meetings 2018 (Session G004: Earth and Planetary Rotation: Theory, Observations, and Analysis) and 2019 (Session G11A/G23C: Reference Frames: Determination, Usage, and Application; Session G41A/G31B Fifty Years of Lunar Laser Ranging and Earth and Planetary Rotation). Furthermore, a proposal for an IAU Symposia on *Reference systems and their ties with the rotation of the Earth and other Solar System bodies* has been prepared in 2019 under the lead of Commission A2 jointly together with Commission A1 and the Inter-Division A-F WGCCRE to highlight the rotation of the Earth and other Solar System bodies in theory, modeling and analysis, as well as the definition and future consistent realization of reference systems.

After four years of operation, the Commission A2/IAG Joint Working Group (JWG) on Theory of Earth Rotation and Validation (JWG TERV) ended successfully in 2019. A summary of the JWG activities and results is provided below. Based on the findings of the JWG, Commission A2 drafted a resolution on the Improvement of the Earth's Rotation Theories and Models, submitted to IAU for adoption in 2021. Besides, Commissions A2 jointly with Commission A1 proposed a resolution to be adopted in 2021 in support of the Protection of Geodetic Radio Astronomy Against Radio Frequency Interference.

During the past triennium, Commission A2 promoted the creation of two new JWGs, namely the IAU Commission A2/IAG JWG on Improving Theories and Models of the Earth's Rotation (JWG ITMER), and the IAU Commission A2/IAG/IERS JWG on the Consistent Realization of TRF, CRF, and EOP (JWG CRTCE). Both JWGs started their operations in 2019; reports on their activities can be found below.

Based on the positive evaluation of the Commission's application for continuation by the IAU Executive Committee, Commission A2 Rotation of the Earth will continue its effort during the upcoming term 2021-2024.

2. Working group reports

2.1. *IAU/IAG Joint Working Group Theory of Earth Rotation and Validation*

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

The Joint Working Group (JWG) of the IAU Commission A2 and the International Association of Geodesy (IAG) on Theory of Earth Rotation and Validation (TERV) was kept in operation during the period between the 2018 IAU General Assembly (GA) and the next GA of the IAG/ International Union of Geodesy and Geophysics (IUGG) held in July 2019, in which the JWG was formally ended. That extra time allowed the JWG to complete its tasks successfully. The end-of-term reports of the JWG TERV and each of its three Sub-WGs (SWG) contain a partial extension of the 2018 reports to the IAU and were presented in that IAG/IUGG GA; they can be accessed at the JWG web site (`https://web.ua.es/es/wgterv/`). A summary of the presentations appears in the IAG Travaux 2015-2019 (Drewes and Kuglitsch, 2019, pp 292-301, `https://iag.dgfi.tum.de/en/iag-publications-position-papers/iag-reports-2019-online/`) as part of the IAG Commission 3 report, and an open access digest of the final JWG report is published in the IAG Symposia Series (`https://link.springer.com/chapter/10.1007%2F1345_2020_103`).

The activity of the JWG was crucial to unveil that a significant part of the unexplained variance of the determined EOP series is due to systematic errors, inconsistencies, and need of updating old model components. From all those findings and the research still in progress, it was possible to conclude that at least a partial update of the Earth rotation theory was needed and feasible within a reasonable time span. The IAG GA accepted the JWG conclusions and adopted Resolution 5 on Improvement of the Earth's Rotation Theories and Models (available at `https://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2019.pdf`), submitted on behalf of the JWG by its chair. The Resolution encourages the prompt improvement of the Earth rotation theory in regard to its accuracy, consistency, and ability to model and predict the essential EOPs; encourages consistency between reference frames and the definition of the EOPs including its theories, equations of motion, and models; and encourages the development of new models that are closer to the dynamically time-varying real Earth.

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

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

The IAU/IAG JWG on Improving Theories and Models of the Earth's Rotation (ITMER) was created by the IAG in July 2019 and approved formally as an IAU C. A2 WG in February 2020. According to its Terms of Reference, its main purpose is proposing consistent updates of the Earth rotation theories and models and their validation. The associated tasks will thus contribute to the implementation of the 2018 IAU Resolution B1 on Geocentric and International Terrestrial Reference Systems and Frames, and the 2019 IAG Resolution 5 on Improvement of the Earth's Rotation Theories and Models. The last resolution is the most specific for the JWG assignment and mandates: *(1) to encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOP, (2) 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, and (3) 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.*

Working in good coordination with the IAU/IAG/IERS JWG on the Consistent realisation of TRF, CRF, and EOP, with the team in charge of the update of the IERS Conventions, and also with the Bureau of Products and Standards of the IAG Global Geodetic Observing System (GGOS) is of paramount relevance and will be sought through common members and correspondents.

The initial activities of the JWG have been planned to fulfil its commitment of deriving supplementary models for the celestial pole offsets (CPO) evolution, in part of semi-empirical and semi-analytical nature, and able to increase significantly the explained variance of the current theories and models. According to the recommendations of the 2019 GGOS-IERS Unified Analysis Workshop, the prioritary tasks of building such models will include:

– updating the amplitudes of the leading nutations of the IAU2000 theory and testing shortened series for certain operational purposes;

– correcting the inconsistencies already known in the precession-nutation models;

– test the available FCN models (for explaining CPO variance) and help the relevant bodies considering whether the IERS should recommend FCN models or not.

To develop and publish a fully dynamically consistent theoretical approach to support those models will require the maintenance of the activity until the end of the 4-year IAG term.

Taking into account the different methods and expertise required for the treatment of the different kinds of EOP and that their theoretical treatment must be as consistent as their determination from observations, the functional structure of this JWG is similar to that of the discontinued JWG TERV, in the sense that the tasks are distributed among three Sub-WGs (SWG) working in parallel. These are: *(1) Precession/Nutation*, chaired by Alberto Escapa; *(2) Polar Motion and UT1*, chaired by Aleksander Brzezinski; and *(3) Numerical Solutions and Validation*, chaired by Robert Heinkelmann.

As for the JWG activities since its approval by the IAU, they have been seriously affected by the pandemic. This unexpectedly long situation has produced some delays in the development of the foreseen work and did not allow holding any in-person meeting of opportunity, due to the final cancelation of many of the relevant events (e.g., the Journées 2020 were postponed sine die after some attempts of delaying them, and the AGU 2020 did not host a specific Earth rotation session) or the change of others to a virtual format. Among the last ones, the EGU 2020 virtual session G3.1 (`https://meetingorganizer.copernicus.org/EGU2020/session/35334`) received contributions related to the background of the JWG ITMER terms of reference, i.e., developing the outcomes of the precedent JWG TERV. Similarly, the vEGU 2021 virtual session G3.3 (`https://meetingorganizer.copernicus.org/EGU21/sessionprogramme#G3`) on Earth rotation welcomes contributions in the ITMER scope. Both two were organised by the President and Secretary of the C. A2, jointly with other JWG members.

Finally, the JWG promoted a proposal of IAU Resolution on the improvement of Earth rotation models that was submitted by the Commission in February 2021.

2.3. *IAU/IAG/IERS Consistent Realization of TRF, CRF and EOP*

by Robert Heinkelmann and Manuela Seitz

The International Astronomical Union / International Association of Geodesy / International

Earth Rotation and Reference Systems Service (IAU/IAG/IERS) Joint Working Group (JWG) on the Consistent Realization of TRF, CRF and EOP was created by IAU Commission A2, IAG Sub-Commission 1.4 and IERS to continue the activity of the previous IAG Working Group on 'Consistent Realization of ITRF, ICRF, and EOP' that operated in the period 2015-2019.

The objectives of the JWG 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 will
– investigate the impact of different analysis options, model choices and combination strategies on the consistency between TRF, CRF, and EOP. It will
– 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 in cooperation with the IAU Division A WG on 'Multi-waveband Realizations of International Celestial Reference System',
– study the differences between EOP derived by VLBI solutions improved through Gaia (optical) data in cooperation with potential future IAU Division A WG(s) on VLBI – Gaia topics,
– study the effects on the results, when different data time spans are considered,
– compare the practically achievable consistency with the quality requirements deployed by IAG GGOS; and
– derive conclusions about future observing systems or analysis procedures in case the quality requirements cannot be met with the current infrastructure and approaches.

Members
We acknowledge the dedication of the JWG members and correspondents.

IAU members: Bizouard, Christian, de Witt, Aletha, Escapa, Alberto, Getino Fernández, Juan, Gordon, David, Gross, Richard, Heinkelmann, Robert, Jacobs, Christopher, Jin, Shuanggen, Krásná, Hana, Le Bail, Karine, MacMillan, Daniel, Malkin, Zinovy, Seitz, Manuela, Seitz, Florian, Souchay, Jean, Thaller, Daniela

IAU Associates: Bachmann, Sabine, Biskupek, Liliane, Collilieux, Xavier, Girdiuk, Anastasiia, Lambert, Sebastien, Mayer, David, Soja, Benedikt

DGFI-TUM computed a consistent realization of ITRS and ICRS based on VLBI observations only. The solution covers the full history of VLBI observations until November 2020. It includes 6180 sessions comprising 32 VCS sessions, 53 VCS-like sessions and 35 VGOS sessions those stations are linked by two mixed mode sessions to the legacy network. The VLBI sessions are consistently reprocessed according to the ITRF2020 standards. The most important changes w.r.t. VLBI obervation modelling are: the new secular pole model, gravitational deformation models for six VLBI antennas, the new subdaily pole model and ICRF3 a priori source positions. The combination of the sessions to a global TRF-CRF-EOP solution is performed on normal equation level. This solution will be the basis for the research on multi-technique realizations in future. First studies on a consistent multi-technique realization are performed, e.g. by Kwak et al. (2018, `https://doi.org/10.1007/s00190-018-1130-6`).

3. Organization reports

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

by Robert Heinkelmann and Harald Schuh

A highlight of the International Association of Geodesy (IAG) activities in the last period was its General Assembly held from July 8 to 18, 2019 in Montreal, Canada (`http://iugg2019montreal.com/`)in conjunction with the International Union of Geodesy and Geophysics (IUGG) (`http:`

//www.iugg.org/), which had its centennial celebration. Almost 4000 participants registered for the Montreal meeting and 465 participated in the IAG General Assembly. The interdisciplinary Scientific Program of the IUGG General Assembly consisted of 234 Symposia, 18 Workshops, and 558 Sessions. 4580 presentations were given. Among those, there were 437 invited talks. The IAG General Assembly consisted of three important parts: (i) an open Scientific Assembly, (ii) a Council Meeting of the duly accredited Delegates of the IAG Member Countries, and (iii) several business meetings of the IAG Executive Committee and the IAG Bureau.

The IAG Council approved several Resolutions (https://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2019.pdf), which might have some relevance for IAU:

1. The International Terrestrial Reference Frame (ITRF)
2. Third Realization of the International Celestial Reference Frame (ICRF)
3. Establishment of the International Height Reference Frame (IHRF)
4. Establishment of the Infrastructure for the International Gravity Reference Frame (IGRF)
5. Improvement of the Earth's Rotation Theories and Models

The next upcoming meeting is the IAG Scientific Assembly 2021 from June 28 to July 3, 2021, in Beijing, China and the next IAG General Assembly will be held during the 28th IUGG General Assembly in Berlin, Germany, from 11 to 20 July, 2023 (https://www.iugg2023berlin.org/).

During the last years, the cooperation between IAU CA2 and IAG has intensified. Most important are two Joint Working Groups:

1. Joint Working Group on "Theory of Earth Rotation and Validation" (https://web.ua.es/es/wgterv/iau-iag-joint-working-group-on-theory-of-earth-rotation-and-validation.html), Chairs: José Ferrándiz, Richard Gross, which is joint with IAG Sub-commission 3.3 "Earth Rotation and Geophysical Fluids"
2. Joint Working Group on the "Consistent realization of TRF, CRF, and EOP" (https://www.iers.org/IERS/EN/Organization/WorkingGroups/ConsistentRealization/consistentRealization.html) , Chairs: Robert Heinkelmann, Manuela Seitz, which is joint with IAG Sub-commission 1.4 "Interaction of Celestial and Terrestrial Reference Frames" and the International Earth Rotation and Reference Systems Service (IERS).

Both JWGs present own reports as part of this report.

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

by Wolfgang R. Dick, Brian J. Luzum, and Tonie van Dam

From 2018 to the present, the International Earth Rotation and Reference Systems Service continued to provide Earth orientation parameter (EOP) data, terrestrial and celestial references frames, as well as surface mass driven geodetic parameters to the scientific and other communities. The Earth Orientation Centre improved its software and applied several corrections to the 14 C04 EOP series. The Rapid Service / Prediction Centre transitioned their EOP solution to be consistent with the 14 C04 for polar motion, UT1-UTC, and celestial pole offsets. The IERS continued to ensure that the user community has the most up-to-date terrestrial reference frame by beginning preparations for the International Terrestrial Reference Frame 2020 (ITRF2020). The three ITRS Combination Centres (DGFI, IGN, JPL) improved their combination software for ITRF2020 and made first test analyses with preliminary data. The final re-analysis data from IDS, IGS, ILRS, and IVS are expected in April 2021. The ITRS Centre also participated in surveys of co-located sites. In collaboration with the IAU Division A Working Group on ICRF3, the ICRS Centre finalised the Third Realization of the International Celestial Reference Frame (ICRF3) which was adopted at the XXXth IAU General Assembly in Vienna, Austria in 2018. Comparisons were made between the ICRF3 and preliminary versions of the Gaia optical reference frame. 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 will be printed in 2022. 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 loading data in preparation for the ITRF2020 combination. The GGFC Special Bureau for the Oceans was transferred from JPL to GFZ at the beginning of 2021. The Central Bureau finished the main part of the work on a new system for the data management component of the IERS Data and Information

System. It became operational in 2018. 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 WG on Site Coordinate Time Series Format, responsible for the definition of a common exchange format for coordinate time series for all geodetic techniques, was dissolved in May 2020. At the same time the IAG/IAU Joint Working Group on the Consistent Realization of TRF, CRF, and EOP was also established as an IERS WG. It will compute 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. Currently, a new WG on the 2nd Earth Orientation Parameter Prediction Comparison Campaign is being established. It will re-assess the various EOP prediction capabilities by collecting and comparing operationally processed EOP predictions from different agencies and institutions over a representative period of time, with the aim to evaluate the accuracy of final estimates of EOP, to identify accurate (reliable) prediction methodologies, and to assess the inherent uncertainties in present-day EOP predictions.

The IERS Directing Board (DB) continued to meet twice per year. It has several new members, among them Tonie van Dam as the new DB Chair starting with 2021, replacing Brian Luzum after two terms (8 years) of his service. Robert Heinkelmann is the new Analysis Coordinator since 2019, replacing Tom Herring who served for two terms.

The following IERS publications and newsletters appeared: Z. Altamimi and W. R. Dick (eds.): Description and evaluation of DTRF2014, JTRF2014 and ITRF2014 (IERS Technical Note No. 40, 2020); IERS Annual Reports 2017 and 2018 (the report for 2019 is in preparation); IERS Bulletins A, B, C, and D (weekly to half-yearly); ca. 70 IERS Messages. The central IERS web site 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), October 2–4, 2019 in Paris. The final report provides a thorough summary of the workshop as well as conclusions and recommendations from the discussions (see GGOS website and IERS Annual Report 2019).

3.3. *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.- Dr. Axel Nothnagel (University of Bonn, then TU Wien) completed his eight-year tenure as IVS Chair in February 2021. Following IVS Directing Board elections, the new Board elected Dr. Rüdiger Haas (Chalmers University of Technology) as new chair effective March 1, 2021. In June 2020, Dr. Stuart Weston (Auckland University of Technology) became the IVS Network Coordinator replacing Ed Himwich (NVI, Inc./NASA Goddard Space Flight Center) in this function. There were three active committees: Observing Program Committee (chaired by D. Behrend), VGOS Technical Committee (chaired by G. Tuccari), and Committee on Training and Education (chaired by R. Haas). And on October 14, 2020, the Celestial Reference Frame Committee (chaired by A. de Witt) was formed as a fourth committee.

Observing program.- The IVS continued the observation of 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 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). In 2020, an operational VLBI Global Observing System (VGOS) session series was started running at a cadence of one session every other week.

ICRF3.- A new realization of the International Celestial Reference Frame (ICRF3) was released and approved by the XXII General Assembly of the International Astronomical Union (IAU) in 2018. The ICRF3 considers the tiny effect of Galactic Aberration in accordance with a recommendation from IVS Working Group 8, which was chaired by Dr. Dan MacMillan (NVI, Inc/ NASA GSFC) and studied this effect.

VGOS.- 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 IVS Data Center. The fledgling network started observing in operational IVS sessions 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.

4. National reports

4.1. *Report of activities during 2018–2021 in Australia*

by Oleg Titov, Jamie McCallum and Randall Carman

SLR

Geoscience Australia operate two permanent fixed Satellite Laser Ranging Systems, one in Western Australia at Yarragadee and one in the Australian Capital Territory at Mt Stromlo. Both stations consistently sit within the top ten of the International Laser Ranging Service rankings for performance - both quantitatively and qualitatively. Importantly, the two stations rank very highly for the number of normal points acquired on the geodetic missions, the basis for all ILRS data products. With the continued scarcity of SLR systems in the southern hemisphere (currently there are eight active stations south of the equator), the two Australian sites perform a very important role in balancing the network.

a) Yarragadee

NASA continues to provide engineering support to the MOBLAS5 system as part of an inter-governmental agreement and although many parts of the hardware are now 40 years old the legacy (10 Hz) system still out-performs all others, at least quantitatively.

- In 2018 the MOBLAS system at Yarragadee was improved markedly with the installation of an event timer in place of the old HP5370B time interval unit. As well as much better precision (3pS vs 12pS), using an event timer means the laser can fire at its maximum repetition rate (10Hz) instead of going down to as low as 1Hz for distant targets;
- In 2019 a pair of InSAR Radar Corner Cube Reflectors, were installed at the Observatory;
- Geoscience Australia has maintained 24x7 operations with a staff of 6-7;
- In 2020 the DORIS Beacon was upgraded to 4.0;
- The system is now partially remotely controllable, unlike the other 4 NASA MOBLAS systems. The operator can control the instrumentation from the adjacent comfortable VLBI operations room. Further off-site operations will be possible after further system upgrades planned for the next year.

b) Mt Stromlo

Geoscience Australia contracts out the maintenance and operations of the Mt Stromlo SLR facility to a private Australian company (currently EOS Space Systems hold both contracts). This facility, installed in 2004, is a monostatic system with a laser fire rate of 60Hz and is designed to operate in all-weather condition using a sealed telescope enclosure. This allows ranging operations at Mt Stromlo to be fully automated and the facility to be unmanned for significant periods. Throughout the reporting period, the facility has been operating almost continuously with data collection only impacted by overcast skies and occasionally smoke from nearby bushfires. The SLR facility shares the site with a number of fiducial pillars supporting GNSS instruments and four corner cube retro reflectors used for maintaining range data accuracy. The DORIS beacon was also upgraded to 4.0 during 2019. Geoscience Australia undertakes regular local colocation surveys to maintain the local ties of these fiducial points. Upgrades to the SLR facility, including improvements to automated target scheduling and data post-processing are planned for the next reporting period.

VLBI

The AuScope array consists of three 12m telescopes spread across the Australian continent, sited in Hobart (Tasmania), Katherine (Northern Territory) and Yarragadee (Western Australia). Built as a geodetic array, they have been carrying out geodetic observations organised through the International VLBI Service (IVS) since 2011, using S/X receiver systems. The Hobart12 station was upgraded to a VGOS-style wideband receiver, sampler and recording system in mid-2017, with the Katherine station following in late 2019. The receivers use a QRFH feed with Stirling-cycle cryogenic systems, operating across the 2.2-13.5 GHz frequency range. Sampling is handled by 3-input DBBC systems, with available frequency ranges of 3-7, 6-10 and 9.5-13.5 GHz. Recording is carried out by 36-disk Flexbuff systems. Full VGOS compatibility is yet to be obtained but is expected to become available once upgrade of the DBBC3 systems is completed. Hobart12 and Katherine are regularly used in locally organised "mixedmode" observations together with the traditional S/X telescopes. Yarragadee continues as an S/X station, with the upgrade to the wideband system waiting on the availability of the fully compatible DBBC3 systems.

The Hobart26 telescope continues operations, supporting both astronomical and geodetic observing campaigns. The latter are normally organised through the IVS, utilising the existing S/X receiver. No major changes have been made to the system over the last few years although there have been a number of faults developing with some receivers and the cryogenic systems due to ageing hardware.

4.2. *Report of activities during 2018–2021 in Austria*

by Sigrid Böhm

Earth rotation variations are investigated at Technische Universität Wien (TU Wien), where the research division Higher Geodesy is analyzing VLBI and GNSS observations for the determination of Earth orientation parameters (EOP). Routine analysis of the VLBI observations is carried out with the in-house Vienna VLBI and Satellite Software (VieVS, Böhm et al. 2018) and results are presented at `https://www.vlbi.at/`. Special emphasis has been put on the scheduling of VLBI Global Observing System (VGOS) observations for an improved determination of Earth orientation parameters (Schartner et al. 2020). A more recent study deals with the suitability of VLBI baselines for UT1-UTC Intensive sessions (Schartner et al. 2021).

Other investigations focused on the integration of length-of-day values from GNSS and the comparison against UT1-UTC estimates from VLBI (Mikschi et al. 2019). And Böhm et al. (2019) combined normal equations from VLBI with those derived from ringlaser observations. Moreover, Böhm and Salstein (2020) studied the interrelation between climate change and Earth rotation speed on the basis of climate predictions for the 21st century provided by the Coupled Model Intercomparison Project Phase 6. In an upcoming Phd thesis Dzana Halilovic investigates the contribution of Galileo observations to determine precise Earth rotation parameters in a combined multi-GNSS estimation process.

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4.3. *Report of activities during 2018–2021 in Belgium*

by Veronique Dehant

Within the European Research Council (ERC) Project RotaNut (ERC Advanced Grant 670874, `https://rotanut.oma.be)` - Rotation and Nutation of a wobbly Earth, we have developed the appropriate codes and computed the geostrophic flow associated with harmonic forcing of a rotating cavity and show that a systematic axisymmetric flow in the bulk of the fluid appears.

We have computed the core flow considering Coriolis, viscous (represented by an Ekman number close to real Earth), and magnetic forces, in response to that forcing. To that aim, we have developed a code solving the Navier-Stokes in a fluid coupled with the mantle. The code is available for the scientific community (`https://bitbucket.org/repepo/kore/src/master/`). Our results demonstrate the roles of viscous and ohmic dissipations and where they occur in the core.

We have built a new nutation model for predictions, based on Earth interior parameters that have been determined from modelling and recent data.

We have applied our approach to other planets (Mars and Mercury) and to the icy moons.

In 2020, we have started the ERC Synergy Grant GRACEFUL (GRavimetry, mAgnetism, rotation and CorE FLow) project (Number 855677, `https://graceful.oma.be`).

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4.4. *Report of activities during 2018–2021 in China*

by Chengli Huang and Ben Chao

A triaxial three-layered Earth rotation theory and four rotational normal modes under this frame were presented (Guo & Shen, 2020). A new interpretation of the mechanism of eigen-mode excitation of Chandler wobble was proposed (Fang et. al., 2020). The relationship between FCN and geomagnetic jerks was also discussed (Cui et al, 2020).

The triaxiality actually adds extra degrees of freedom to the rotational eigen-mode system of the oblate Earth model. Chao (2017; see also Ding & Chao, 2018) derived the dynamics of the axial torsional libration (ATL) of the inner core in the triaxial mantle-inner core gravitational (MICG) system using the general multipole formalism, and related the ATL to the 6-yaer oscillation found in LOD. Shih & Chao (2020) derived the implications of the above to address the density anomaly of the LLSVP (large low shear velocity provinces) constructs in the lower mantle. Chao & Shih (2021, in preparation) proposed, based on the multipole formalism, the existence of a (hitherto unnamed) MICG tilt-over-mode-like nutation of the inner core due to the triaxiality (independent of the pressure-driven FICN of an oblate Earth model).

As to the studies of the LOD variations, a 8.6-year periodic signal with an increasing amplitude was firstly found in LOD and its close association with the occurrence of geomagnetic jerks and their possible physics were discussed (Duan & Huang, 2020a); the theoretical quality-factor Q value ($40 \sim 75$) of the 6-year oscillation was estimated by solving the MICG coupling equation under the action of the electromagnetic effects (Duan & Huang, 2020b; Duan et al., 2018). A stabilized AR-z spectrum method was applied efficiently for detection of the intra-decadal periodic signals especially the 6-year signal in LOD (Ding & Chao, 2018a, 2018b; Ding, 2019; Ding et al., 2021); the atmospheric effect on the semi-decadal oscillations in LOD was also studied (Yu et al, 2020). Ding & Chao (2018a) in particular reported a connection (which can hardly be taken as a coincidence) of the 6-year LOD variation with the global GPS deformation field, which was later corroborated by SLR observations of C_{22} and S_{22} Stokes coefficients (Chao & Yu, 2020), as well as in the geomagnetic field variations.

The celestial pole offsets with VLBI, LLR, and optical observations were analyzed and it was shown that LLR data can contribute to improve the precession model (Cheng et al., 2019). The link between ICRF and Gaia reference frame was studied (Liu J. et al., 2018a, 2018b).

The weekly terrestrial reference frame and EOP combined from VLBI/SLR/GNSS/DORIS solutions was realized independently by the SHAO team (Lian et al. 2018, 2019). For EOP predictions, the 1-90 day EOP predictions by the SHAO team are updated daily at website 202.127.29.4/xxq/ for public download. Several studies on the prediction method were conducted, e.g., a combined SSA and ARMA model is proposed for long-term prediction of polar motion (Shen et al., 2018)

A new and generalized theory of the figure of the Earth to full third order of ellipticity was proposed and applied successfully to reduce the deviation of the calculated value of the global dynamical flattening (H) from observation from 1.1% to 0.2% significantly (Huang et al., 2018; Liu C. et al., 2018).

A brand new optical telescope functioned with simultaneously observing three fields of view (originally) for in-situ observation of lunar physical libration was proposed. The ground-based verification test observation of EOP by its prototype telescope of 2nd generation located at Beijing Obs. has been conducted for more than 1 year, from which the principle and feasibility of this telescope for EOP and lunar libration are validated (Sun et al., 2021).

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4.5. *Report of activities during 2018–2021 in Czech Republic*

by Jan Vondrák

Several topics in Earth rotation were accessed at the Astronomical Institute during a stay of Hana Krásná as guest scientist. Krásná et al. 2019 published the first VLBI EOP estimates from an observing frequency independent of the traditional S/X band using the Very Long Baseline Array measurements at K band (24 GHz, 1.2 cm). Furthermore, in cooperation with TU München and DGFI (Germany) mechanism of error propagation from the subdaily universal time model into daily celestial pole offsets estimated by VLBI was provided by Panafidina et al. 2019.

Recently it was noticed that the observed changes of the amplitude and phase of the free modes (Chandler wobble, Free Core Nutation) are correlated with the rapid changes of the second time derivative of geomagnetic field, so called geomagnetic jerks (GMJ). These events occur irregularly, in intervals of several years, and last typically several months. Brzeziński's broad band Liouville equations are used to integrate the changes of Earth's orientation due to excitations by atmosphere and oceans, with GMJ effect added (Ron and Vondrák 2020). The agreement of the integrated Earth orientation with the observed values significantly improves when GMJ effect is considered. This approach enables us also to determine the parameters of the free modes (period, Q-factor) with improved accuracy.

The Earth System Modelling Group of GeoForschungsZentrum (ESMGFZ) in Potsdam started producing a new series of Effective Angular Momentum Excitation Functions with 3-hour resolution for the atmosphere and dynamic ocean. These data were used (Vondrák and Ron 2019) to integrate Brzeziński's broad-band Liouville equations in celestial frame and compare the results with IERS C04 solution of celestial pole offsets in the interval 1986.0-2018.4. A possible influence of GMJ was also inserted. Best-fitting FCN parameters (period T, Q-factor) were estimated. The best fit is obtained for combined atmospheric, oceanic and GMJ excitations, the preferred parameters of FCN being $T = 429.53 \pm 0.04$d, $Q = 21600 \pm 200$. New value of empirical prograde MHB Sun-synchronous correction $SSC_{new} = (0.1045 + 0.0193i)e^{il'}$, where l' stands for mean solar anomaly, is also derived. The same excitations were used to calculate their effect on polar motion (Ron et al. 2019). The fit with observations improves substantially, if the influence of GMJ is applied. We also considered excitations due to the continental hydrosphere and barystatic sea-level variations, but they do not improve the agreement between integrated and observed polar motion.

Different VLBI solutions and geophysical excitations are used to determine FCN parameters (Vondrák and Ron 2020a). Three variants of geophysical excitations and seven different VLBI solutions of celestial pole offsets (CPO) are used to determine FCN parameters (Vondrák and Ron 2020b), possible effect of GMJ is also considered. Best-fitting values of FCN parameters are estimated by least-squares fit to observed CPO, corrected for the differences between the FCN parameters used in IAU 2000 model of nutation and newly estimated ones. Different VLBI solutions lead to FCN parameters that agree on the level of their formal uncertainties, but different models of geophysical excitations change the results more significantly. The best fit is achieved when only GMJ excitations are used. FCN parameters from this solution are $T = 430.23 \pm 0.03$, $Q = 19600 \pm 130$; GMJ are very probably more important for exciting FCN than the atmosphere and oceans. Empirical Sun-synchronous correction, introduced in the present IAU 2000 nutation model, cannot be explained by diurnal atmospheric tidal effects.

Solar origin of interannual oscillation of Earth rotation, MSL and climate indices is investigated (Chapanov et al. 2020) by analysing long time series of length-of-day, MSL variations at Stockholm, temperature and precipitation over South-Eastern Europe, El-Niño Southern Oscillation (ENSO), Total Solar Irradiance (TSI), sunspot numbers SSN and North-South solar asymmetry (N-S SA).

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4.6. *Report of activities during 2018–2021 in France*

by Christian Bizouard

In France the Earth rotation changes is first of all the appanage of the Paris Observatory/SYRTE, with Christian Bizouard, director of the IERS Earth Orientation Center (EOC), Sébastien Lambert, Olivier Becker (technician/programmer in charge of operational activities of the EOC), Jean-Yves Richard (in charge of the multi-technique EOP solution at normal equation level), and Teddy Carlucci (system engineer). During that period, C. Bizouard supervised the Ph-D thesis of Ibnu Nurul-Huda, defended in December 2019; S. Lambert the 2 year post-doc of Maria Karbon (2019-2020). The Paris team is also responsible for the IERS Convention in partnership with USNO.

Meanwhile, many other French scientists are also concern by the Earth rotation variations. First, these are scientists devoted to the determination of the astro-geodetic products and mostly working at CNES and IGN: Zuheir Altamimi, David Coulot, Arnaud Polet, Paul Rebischung (IGN), Alexandre Couhert, Flavien Mercier (CNES),... or geophysicists: among the most active during the last years: Christelle Charnard, Laurent Métivier (IGN); Marianne Greff (IPGP); Séverine Rosat, Yves Rogister (IPGS); Nicolas Gillet (Grenoble Univ.).

Since 2018, the Earth rotation studies of Paris Observatory have been focused on the determination of the global rheological parameters.

First, the Paris team extensively studied the polar motion normal mode in the diurnal band - containing the nutation as a retrograde polar motion. The normal mode periods in about 380 days for the nutation band and 400 days for the prograde polar motion were fully elucidated in light of the dynamical response of the oceans, evaluated from our knowledge of the ocean tides (Bizouard et al., 2020, Nurul Huda et al., 2020, Nurul Huda, 2020). For the first time, the resonance effect of the fluid core was also observed on the polar motion normal mode.

Second, a Paris Observatory-CNES cooperation has been dedicated to the possible visco-elastic effect in polar motion at multi-decadal scale (Couhert et al., 2020).

In light of the relation between Earth Rotation and climate changes, Paris Observatory has participated in the Inter-Commission Committee on "Geodesy for Climate Research" (ICCC), created in 2019.

Besides, French specialists of magneto-hydrodynamics in the fluid core attempted to better explain the multi-decadal change in the length of day (Gillet et al., 2019). See reconstruction of decadal LOD trend on `https://geodyn.univ-grenoble-alpes.fr`. Since 2020, informal exchanges between Paris Observatory, IPGP, IPGS and Grenoble University have begun in order to better understand the Earth rotation acceleration observed since 2016, and recently highlighted by the fact that the annual average of the length of day became smaller than the day of 86400 SI.

In October 2019 the Paris Observatory team had the task to organize the colloquium "Journées 2019 Astrometry, Earth Rotation, and reference systems in the Gaia era". Christian Bizouard chaired the colloquium and edited the proceedings in September 2020 (see `https://syrte.obspm.fr/astro/journees2019/LATEX/JOURNEES2019.pdf` or `https://ui.adsabs.harvard.edu/abs/2020jsrs.conf.....B/toc`).

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4.7. *Report of activities during 2018–2021 in Germany*

by Florian Seitz

During 2018-2021, Earth rotation research in Germany covered a broad range of topics, spanning the improvement of theories, the advancement, data analysis and combination of geodetic space techniques as well as the scientific exploitation, interpretation and prediction of Earth rotation changes. Several institutions and universities were involved in the investigations and conducted major collaborative research projects.

Within the ESA study "Independent generation of Earth Orientation Parameters" (Contract Nr. 4000120430/17/D/SR) a consortium led by DGFI-TUM developed a strategy for the independent determination and prediction of highly precise EOP and implemented it into a dedicated software. Partners involved were the Technical University of Munich (TUM), the Federal Agency for Cartography and Geodesy (BKG), the GFZ German Research Centre for Geosciences (Section 1.3) and the Technical University of Vienna. EOP are combined from VLBI, GNSS, SLR and DORIS on the normal equation level. The approach generates a daily updated consistent series of final, rapid and predicted EOP. While the final part of the series has a latency of about three weeks and comprises data from all four techniques, the rapid part is computed from GNSS-Rapids and VLBI-Intensives at a latency below one day. The series is completed by predicted EOP until 90 days into the future (see below). The strategy guarantees for a smooth transition between final, rapid and predicted EOP. This means an important advantage compared to existing EOP series (Dill et al., 2020). Based on its own input solutions ESA aims to provide an independent operational EOP solution.

GFZ Section 1.3 started to rigorously introduce effective angular momentum functions (EAM), including its 6-day forecast, from global geophysical fluid models into EOP predictions. The approach combines and predicts completely in the space of EAM functions. From the sum of model-based EAM (atmospheric/oceanic/hydrological/sea-level angular momentum) and its difference to the geodetic angular momentum (GAM derived from EOP solutions), the residual (non-modeled) Earth rotation excitation can be estimated. The GAM residual is extrapolated by least-squares harmonic analysis and auto regression model until the end of the 6-day EAM forecasts, and in a second step the total angular momentum function (GAM residual + modelled EAM) is extrapolated up to 90 days into the future. This 90-day EAM predictions is the basis to calculate 90 day EOP predictions by means of the Liouville equation (Dobslaw & Dill, 2018; Dill et al., 2019). The 90-day EOP prediction could be improved significantly especially for short-term forecast horizon up to some weeks. In order to further improve the EAM prediction-skills, the EAM products from GFZ Section 1.3 were analysed (Ron et al., 2019) and compared to independent EAM solutions, e.g. from GRACE (Śliwińska et al., 2020). Especially for length of day (LOD) variations, the influence of the global mass balance has to be taken into account (Dill & Dobslaw, 2019; Dobslaw et al., 2020). To validate and improve final EOP, EOP solutions IERS C04, JPL Space2018, and ESA were contrasted against the independent model-based EOP solution from GFZ's EAM time series (Dill et al., 2020).

The new prediction method of GFZ Section 1.1 for the celestial pole offsets (CPO) developed by Belda et al. (2018, 2019) based on previous joint FCN models improves the prediction by about 40%, from short to long periods. A novel prediction method for polar motion (PM) and LOD was developed by Modiri et al. (2018, 2019a, 2020) as presented by Schuh et al. (2018). They applied Copula-based analytical methods for the analysis of PM and LOD data, in combination with deterministic methods, such as singular spectrum analysis. This new hybrid prediction method is competitive with the prediction approaches presented for the EOP Prediction Comparison Campaign depending on the EOP and the prediction length, factors that are taken into account for the final design of the procedures. Furthermore, GFZ Section 1.1 has intensified the cooperation with University of Alicante on the revision and improvement of accuracy/consistency of Earth rotation theories and models. The study of several minor effects on Earth rotation, derived from geophysical properties not considered so far, has been initiated (Ferrándiz et al., 2019, 2020b; Modiri et al., 2019b,c; Fodor et al., 2020). Models were proposed to improve the consistency between the IAU2000 nutation theory and the IAU2006 precession model, and their performance was assessed (Ferrándiz et al., 2018, 2019, 2020a). GFZ Section 1.1 was also investigating the interconnection between the celestial pole motion (CPM) and the geomagnetic field (GMF) in order to augment the current CPM prediction. They used the CPM time series from VLBI and the latest GMF data to explore their correlation (Modiri, 2019c). Preliminary results reveal various significant common features in the CPM and GMF variations, which show the potential to improve the understanding of the interaction of GMF and Earth rotation.

In a joint effort, the TUM and the Ludwig-Maximilians-Universität Munich have further developed and used the large ring laser ROMY (Rotational Motion in Seismology) operated at the Geophysical Observatory in Fürstenfeldbruck, Germany, to reconstruct the full Earth rotation vector. The instrument is composed of four triangular active ring lasers, mounted on the sides of a tetraeder with side length of 12m, each measuring the orientation change with respect to inertial space using the Sagnac effect. First experiments could reconstruct the full Earth rotation vector with sub-arcsecond resolution. Based on experience with the large and ultra-stable single-component ring laser "G" at the Geodetic Observatory in Wettzell, Germany, an improvement of the resolution of ROMY by three orders of magnitude using planned active stabilization is expected (Gebauer et al., 2020; Igel et al., 2021). Further studies at the TUM assessed the potential of DORIS observations for LOD determination using improved orbit models (Stepánek et al., 2018), and the analysis of the propagation of errors in the subdaily Earth rotation model into VLBI-based CPO estimates and into GNSS orbit orientation (Panafidina et al., 2019, 2020). At DGFI-TUM, Göttl et al. (2018, 2019) studied the effect of mass changes within the cryosphere on long-term changes of Earth rotation.

Infrared (IR)-based Lunar Laser Ranging (LLR) measurements resulted in a strongly increased amount of highly accurate LLR data from 2015 on. At Leibniz University Hannover, two new projects were started for LLR data analysis. One is funded in the context of the Cluster of Excellence 'Quantum Frontiers' since 2018, the second was initiated by the new DLR Institute for Satellite Geodesy and Inertial Sensing in 2019. A major objective focuses on the benefit of high-precision IR LLR data for determining parameters related to the lunar interior, relativity, reference frames and EOP. The work on model improvements was intensified (Singh et al., 2020; Hofmann et al., 2018) to fully exploit the potential of IR LLR data. Including IR data in LLR analysis allowed an improved determination of relativistic parameters (Biskupek et al., 2021; Zhang et al., 2020; Hofmann & Müller, 2018). Also, better EOP determination from IR LLR data could be demonstrated.

The contributions to the 2020 ITRS realization was a major activity at the IVS AC at BKG and the IVS Combination Center operated jointly by BKG and DGFI-TUM. A full re-analysis of all VLBI sessions was carried out. The final combined IVS contribution to the 2020 ITRS realization contains station coordinates and the full set of EOP. In addition, an experimental IVS combined solution is being generated to investigate the impact of additionally estimating radio source positions. BKG also developed a procedure to provide a combined low-latency series of EOP with regular spacing of 24 hours. For this, VLBI Intensive sessions analyzed at BKG's IVS AC are combined with GNSS Rapids generated by the IGS AC CODE of which BKG is a member (Lengert et al., 2021).

At the Institute of Geodesy and Geoinformation, University Bonn, the working group on "Geodetic Earth System Science" continued the work within project SCORE (Simulating Oceanic Contributions to Earth Rotation), funded by the Austrian Science Fund since 2017. SCORE aims at improved numerical modeling of ocean-induced Earth rotation variations on sub-seasonal to daily time scales based on a range of ocean forward models (Schindelegger et al., 2021). Results from 2D and 3D models indicate that horizontal resolution is an important factor for better representing the wind-driven modal variability in the Southern Ocean, which projects strongly onto intraseasonal PM variability.

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4.8. *Report of activities during 2018–2021 in Poland*

by Jolanta Nastula, Aleksander Brzeziński, Justyna Śliwińska, and Krzysztof Sośnica

A comprehensive review of the research on Earth rotation and geodynamics in Poland during 2015-2018 was given by Bogusz et al. (2019).

Polish researchers have been involved in the studies concerning improvement of the determination of Earth rotation parameters (ERP) and geocenter coordinates from measurements done by the satellite techniques including Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). Kosek et al. (2020) performed detailed analysis of the geocenter motion determined by GNSS, SLR, DORIS, and in addition by Gravity Recovery and Climate Experiment (GRACE), focusing on seasonal terms. They estimated mean amplitudes of the annual oscillation to be at the level of 2 mm for the X coordinate, 2.4–3.6 mm for the Y coordinate and 2.8–5.6 mm for the Z coordinate, and about two times smaller amplitudes of the semi-annual term. However, the estimated seasonal signals are not stable in time and there are considerable differences between the determinations from different techniques. Zajdel et al. (2020) and (2021) analyzed the daily and sub-daily series of ERPs derived from GPS, GLONASS, and Galileo observations. The orbital signals are distinguishable in all system-specific ERPs at the periods that arise from the resonance between the Earth's rotation and the satellite revolution period, e.g., 8.87 h, 34.22 h, 3.4 days for Galileo; 7.66 h, 21.29 h, 3.9 days, 7.9 days for GLONASS; 7.98 h (S3 tidal term), 11.97 h (S2 tidal term), and 23.93 h (S1 tidal term) for GPS. The GPS-derived sub-daily ERPs suffer from the overlapping periods of the diurnal and semidiurnal tidal terms and the harmonics of the GPS revolution period. Sośnica et al. (2018, 2019) derived ERPs using SLR data to geodetic LAGEOS satellites, as well as the active GNSS satellites: Galileo, GLONASS, BeiDou, GPS, and QZSS. Bury et al. (2021) combined GNSS and SLR observation to Galileo satellites and found that the bias of the Length of Day (LOD) parameter is 20% lower for the combined solution when compared to the microwave-only solution. Bury et al. (2019) employed the Galileo metadata to construct the a priori box-wing model for Galileo satellites. On the top of the a priori model, a small set of empirical parameters must be estimated to account for mismodeled forces and variable external conditions to derive high-quality ERPs and geocenter coordinates.

The research on application of the Ring Laser Gyroscope (RLG) for direct and continuous measurement of changes in Earth rotation has been continued in the triennium 2018-2021. Tercjak et al. (2020) performed detailed analysis of the effects that change the terrestrial orientation of the RLG platform, including solid Earth tides, ocean tidal loading and non-tidal loading phenomena (atmospheric pressure loading and continental hydrosphere loading). They also discussed differences between data reduced with tiltmeter observations and those reduced with modeled signal, and potential causes of the discrepancies. Gebauer et al. (2020) reported on the construction and operation of a four-component, tetrahedral laser gyroscope array called ROMY, located at the Geophysical Observatory Fürstenfeldbruck near Munich, Germany. The paper demonstrated that with the use of this single instrument, reconstruction of the full Earth rotation vector can be achieved with sub-arcsecond resolution over more than six weeks.

The role of continental water in polar motion (PM) excitation, described with hydrological angular momentum (HAM), was assessed using different terrestrial water storage (TWS) estimates: from GRACE mission, from Global Land Data Assimilation System (GLDAS) hydrological models, from climate models provided by Coupled Model Intercomparison Project Phase 5 (CMIP5) (Śliwińska et al., 2019). Various HAM series were evaluated by comparison with hydrological signal in observed PM excitation called geodetic residuals (GAO). The results confirmed that for seasonal and non-seasonal spectral bands, GRACE observations provide the highest consistency between HAM and GAO. HAM from GLDAS models provided more satisfactory results than HAM from CMIP5 data. A detailed study of the contribution of different TWS components to the HAM showed that soil moisture dominates.

The GAO, computed as differences between the observed excitation of PM (geodetic angular momentum GAM) and joint atmospheric plus oceanic excitation (atmospheric angular momentum AAM and oceanic angular momentum OAM, respectively), were determined (Wińska & Śliwińska, 2019). Various estimates of GAO, computed for different AAM and OAM models, were analyzed and compared with HAM determined from the Land Surface Discharge Model (LSDM). They were assessed on decadal, interannual, seasonal and non-seasonal time scales. It was shown that the agreement between GAO and HAM was highly dependent on AAM and OAM models. Errors in these models affected the resulting GAO series and had a strong impact on the Earth's angular momentum budget.

A summary of the 15-year operation of the GRACE mission and the use of its data to analyze changes in PM excitation induced by changes in the global mass distribution was presented (Nastula et al., 2019). The gravimetric excitation series were computed using ΔC21 and ΔS2 derived from various GRACE solutions. A noticeable correlation was found between GRACE-based excitation functions and the corresponding GAO in the non-seasonal part of spectrum. However, differences among excitation functions computed using various hydrological models remained considerable.

The study provided by Śliwińska and Nastula (2019) evaluated the gravity field solutions based on high-low satellite-to-satellite tracking (hl-SST) of low-Earth-orbit (LEO) satellites: GRACE, Swarm, TerraSAR-X, TanDEM-X, MetOp-A, MetOp-B, and Jason 2, by converting them into HAM. The HAM series were then compared with the GAO and the HAM obtained from the GRACE ITSG 2018 solution. The findings indicated a large impact of orbital altitude and inclination on the accuracy of derived HAM. The HAM series obtained from Swarm data were found to be the most consistent with GAO. Visible differences were found in HAM obtained from GRACE and Swarm orbits and provided by different processing centres. The main reasons for such differences were likely to be different processing approaches and background models. The findings of this study provided important information on alternative data sets that may be used to provide continuous PM excitation observations, of which the Swarm solution provided by the Astronomical Institute, Czech Academy of Sciences, was the most accurate.

The PM excitation estimates were computed from two most recent releases of GRACE monthly gravity field models, RL05 and RL06, and converted into prograde and retrograde circular terms by applying the complex Fourier transform (Nastula & Śliwińska, 2020). HAM series were analysed in four spectral bands: seasonal, non-seasonal, non-seasonal short-term, and non-seasonal long-term. The general conclusions arising from the conducted analyses of prograde and retrograde terms were consistent with the findings from the equatorial components of PM excitation studies drawn in previous research. In particular, it was shown that the new GRACE RL06 data increased the consistency between different solutions and improved the agreement between GRACE-based excitation series and reference data. The level of consistency between HAM and GAO was dependent on the oscillation considered and was highest for long-term variations. The study revealed that both prograde and retrograde circular terms of PM excitation can be determined by GRACE with similar accuracy.

Śliwińska et al. (2020a) evaluated the newest generation of GRACE temporal models provided by Center for Space Research (CSR), Jet Propulsion Laboratory (JPL), GeoForschungsZentrum (GFZ), Institute of Theoretical Geodesy and Satellite Geodesy (ITSG) of the Graz University of Technology, and Centre National d'Etudes Spatiales (CNES) by conversion of ΔC21 and ΔS21 coefficients of geopotential into the equatorial components (χ_1, χ_2) of gravimetric excitation (called GSMAM) and compared with GAO. Various spectral bands (linear trends, seasonal and non-seasonal changes, oscillations with periods of 1000–3000, 450–1000, 100–450, and 60–100 days) were considered. GSMAM and GAO were also analyzed in four separated time periods which were characterized by different accuracy of GRACE measurements. The level of agreement between GSMAM and GAO depended on the frequency band considered and was highest for interannual changes with periods of 1000–3000 days. It was found that the CSR RL06, ITSG 2018 and CNES RL04 GRACE solutions provided the best agreement with GAO for most of the oscillations investigated.

Śliwińska et al. (2020b) computed the first estimates of hydrological plus cryospheric signals in PM excitation (hydrological plus cryospheric angular momentum, HAM/CAM) obtained from the new GRACE Follow-On (GRACE-FO) mission, and compared with GRACE results. Three different GRACE/GRACE-FO data types were used, namely ΔC21 and ΔS21 coefficients, gridded TWS anomalies derived from coefficients of geopotential, and TWS anomalies obtained from mascon solutions. The comparison and evaluation of different methods of HAM/CAM estimation as well as the test of the compatibility between CSR, JPL, and GFZ data were provided. Analysis of data from the first 19 months of GRACE-FO showed that the consistency between GRACE-FO-based HAM/CAM and observed hydrological/cryospheric signals in polar motion is similar to the consistency obtained for the initial period of the GRACE mission, worse than the consistency received for the best GRACE period, and higher than the consistency obtained for the terminal phase of the GRACE mission.

The predictions of celestial pole offsets (CPO) developed by JPL were evaluated by Nastula et al. (2020). The approach taken by JPL was based upon the use of a Kalman filter and smoother to provide smoothed and predicted CPOs to the interplanetary spacecraft tracking and navigation teams. For assessing the quality of JPL's nutation predictions, the time series of dX, dY provided by JPL were compared with the predictions obtained from the IERS Rapid Service/Prediction Centre, and with precise observations of the Earth Orientation Parameters. The results confirmed that the approach developed by JPL can be used for the successful nutation prediction. In particular, it was shown that after 90 days of prediction, the estimated errors were 43% lower for dX and 33% lower for dY than in the case of the official IERS products, and an average improvement was 19% and 22% for dX and dY, respectively.

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4.9. *Report of activities during 2018–2021 in Russia*

by Zinovy Malkin

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 (Pasynok et al. 2020). The VNIIFTRI also produces combined EOP solution using individual EOP series computed at VNIIFTRI and other Russian institutes. The accuracy of operational UT1–UTC combination was significantly improved after including data from new RT13 antennas installed at the QUASAR VLBI network. Over the next year, the next generation laser station "Tochka" with sub-millimeter measurement accuracy is expected to be installed at VNIIFTRI sites Mendeleevo and Irkutsk (Ignatenko and Emelyanov 2020).

Several groups in Russia have been working on EOP data processing, theoretical investigations of the Earth's rotation and studied the interconnection between Earth rotation variations and other geophysical and cosmo-physical processes. Perepelkin et al. (2019) showed that the motion of the Earth's pole contains an oscillation process associated with the precession of the Lunar orbit, which coincides in frequency and phase with a change in the angle of the Lunar orbit plane's inclination to the Earth's equator. Malkin (2020a) investigated statistics of the IVS observations and evaluated the progress in the accuracy of VLBI-based EOP over time during past 40 years. The Sternberg Astronomical Institute of the Moscow State University is working on developing software for computing EOP, station and radio source coordinates from VLBI data analysis. Pulkovo Observatory supports regular computation of several CPO and FCN series publicly available at `http://www.gaoran.ru/english/as/persac/`. Leonid Zotov's habilitation dissertation (Zotov 2019) was devoted to detailed study of links between the rotation of the Earth and geophysical processes. Zotov et al. 2019 discussed the decadal variations in the Chandler wobble amplitude and their possible reasons. Zotov et al. 2020 investigated the 6-year, 20-year, and 60-year LOD variations. Sidorenkov et al. 2020 studied the interconnection between the decadal instabilities in Earth's rotation and the motion of the lithospheric plates over the asthenosphere. Several groups have been working on improvement and accuracy assessment of the EOP prediction (Tolstikov 2019, Barkin 2020, Krylov 2020, Malkin 2020b, Skurikhina 2020).

The history of the Earth's rotation studies and the IAU Commission 19/A2 was considered by Malkin et al. (2019, 2020).

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4.10. *Report of activities during 2018–2021 in Spain*

by Alberto Escapa and José Manuel Ferrándiz

In this term the IVS recognized the University of Alicante VLBI Analysis Centre (UAVAC) as Associated AC. UAVAC has cooperated with the Universities of Alicante, León, Valladolid, and Centre of Defence of the Spanish Air Force Academy in developing research within the scope of Commission A2. The main outcomes refer to the modeling of precession/nutation due to the mass redistribution; to the second order terms, in the sense of perturbation theory; to the Oppolzer terms of planetary origin; to the background of Earth rotation theories as regard to the consistency with terrestrial reference frames (Ferrándiz et al. 2020c); to the testing precession-nutation models (Ferrándiz et al. 2020b) and obtaining corrections to the Celestial Intermediate Pole Offsets (CPO) from fits to VLBI observed Earth orientation parameters (EOP) and to their prediction. These last two topics in close cooperation with the VLBI group of GFZ Department 1 ((further details can be found at the Germany national report).

The effects on precession (Baenas et al. 2019, 2020) of the redistribution of mass resulting from the lunisolar attraction on the deformable Earth have been computed using the Hamiltonian approach for a two-layer Earth model composed of a fluid core and an anelastic mantle. The first reference concluded a series of previous papers and confirms definitely that the precession of a rigid-Earth model cannot be taken as a good approximation to the actual one anymore, given the current accuracy levels. The derived analytical nutation amplitudes were evaluated assuming different Earth rheologies by means of the Love number formalism: first, using the IERS Conventions (2010) standard models of Love numbers for solid tides and oceanic loading; and then with the Love numbers by Williams and Boggs (2016), accounting for the direct oceanic tide contribution. Our results show significant variations with respect to the values utilized in the construction of IAU2000 nutation and IAU2006 precession models, and thus should be taken into account in the revision of those models. Moreover, they suggest that IERS models concerning solid and oceanic tides should be updated, as showed other authors.

With respect to the second order theory of the non-rigid Earth, we have clarified neatly how such mathematical terms were incorporated in IAU2000 nutation model (Escapa et al. 2020). It was concluded that second order terms are not consistently treated in that IAU model. In addition, IAU2000 nutation lacks the influence of the Earth structure (normal modes) in Poisson and Oppolzer terms, simply because it was not considered in the REN2000 rigid model used in the convolution of the transfer function. In Getino et al. (2021), we constructed a second order Hamiltonian analytical theory for the rotation of a Poincaré Earth. It required introducing of a set of non-singular complex canonical variables that makes easier the second order integration. In a first stage, we focused on Poisson terms. Contrary to first order theories, a part of such terms does depend on the Earth structure. The resulting numerical amplitudes, not incorporated in IAU2000 nutation model, exceed the microarcsecond (μas) level for a few terms, with a very significant contribution in obliquity of about 40 μas for one term. Besides, structure dependent amplitudes are largely amplified with respect to the rigid model ones due to the fluid core resonance, in a way that is not recoverable by any known transfer function method.

In regard to the planetary block of the IAU2000 theory, it was assumed that the associated Oppolzer terms were smaller than 5 μas and thus were neglected. We have checked that approximation (Ferrándiz et al. 2018) by computing the corresponding nutation amplitudes both of direct and indirect origin. Our results show that planetary Oppolzer terms for the non-rigid Earth are not really negligible as for the rigid case. Some terms reach amplitudes larger than 10 μas, therefore significantly above the current level of uncertainty of individual harmonic constituents, estimated by many authors as 2-3 μas. These quantities may seem small, but they are not when compared to the whole set of 1768 planetary terms of IAU2000A. Hence, they should be considered as corrections to IAU2000 model and taken into account in the future developments of Earth nutation models.

Some other side topics of importance have been considered like, for example, a discussion about the tide-system used in the dynamical ellipticity given value (Escapa et al. 2020) or the extension of the Lie-Hori perturbation method to compute forced nutations in presence of dissipative torques (Baenas et al. 2020). Finally, let us point out that the contributions from Spanish A2 members to the operation and outcomes (Ferrándiz et al. 2020a) of two IAU/IAG JWG on Earth rotation have been described in Sections 2.1 and 2.2.

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4.11. *Report of activities during 2018–2021 in USA*

by Richard Gross, Rui Ponte, and David Salstein

During 2018–2021, 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`.

During the past triennium, JPL also continued to investigate the effect of global-scale mass transport on polar motion (Adhikari et al. 2018), finding that mantle convection may be another important driver of secular polar motion in addition to glacial isostatic adjustment and surface mass transport.

Activities at AER relate to maintaining the Special Bureau for the Atmosphere of the Global Geophysical Fluids Center of the International Earth Rotation and Reference Systems Service. To that end, AER put atmospheric angular momentum (AAM)/Earth rotation excitation data from the US National Centers for Environmental Prediction onto `https://www.aer.com/science-research/earth/earth-mass-and-rotation/special-bureau-atmosphere/`, with the assistance of Y. Zhou at the Shanghai Astronomical Observatory. There are also links to other sets on the bureau site, including a connection to the United Kingdom Meteorological Office set through the NCEP link. In addition, AER is analyzing AAM from results of climate model simulations from the Coupled Model Intercomparison Project, and have noted resulting potential increases in AAM throughout the course of the 21st century from a number of potential scenarios. (Salstein 2020; Boehm and Salstein 2018).

Other activities at AER involved the calculation of ocean angular momentum (OAM) quantities based on state estimates produced by the consortium for Estimating the Circulation and Climate of the Ocean (ECCO). As described in Quinn et al. (2019), new OAM series have been estimated and archived at the Special Bureau for the Oceans (`https://isdc.gfz-potsdam.de/ggfc-oceans/`).

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