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COMMISSION A2 — ROTATION OF THE EARTH

ROTATION DE LA TERRE

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COMMISSION A2 WORKING GROUPS

Div. A / Commission A2 WG	**Theory of Earth Rotation and Validation (IAU/IAG Joint WG)**

TRIENNIAL REPORT 2015–2018

1. Introduction

Earth 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. The analysis of Earth rotation variations provides important information about interactions between the various components of the Earth system and about global change phenomena. Commission A2 was created to support and coordinate scientific investigations on Earth rotation and related reference frames.

The objectives of Commission A2 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 organizations that provide the International Terrestrial and Celestial Reference Systems/Frames and Earth orientation parameters (EOPs): the International Association of Geodesy (IAG), the International Earth Rotation and Reference Systems Service (IERS), the International VLBI Service for Geodesy and Astrometry (IVS), the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), and the 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 ways 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 rotation and reference frames, by organizing topical symposia and workshops, and by forming relevant Working Groups.

The 100th anniversary of the IAU and of Commission A2 will be July 28, 2019. The Constitutive Assembly of the International Research Council was held in Brussels during July 18-28, 1919. On the last day, July 28, the Assembly adopted a Statute creating the IAU. So, July 28, 1919 has been taken to be the birth date of the IAU (see https://www.iau.org/about/90years/) and July 28, 2019 will be its 100th anniversary. Along with creating the IAU, 32 Standing Committees were also created on July 28, 1919. One of these was Standing Committee 19 on Latitude Variations. In 1922 all the Standing Committees became Commissions. So, Standing Committee 19 on Latitude Variations became Commission 19 on Variation of Latitude. In 1964 this was renamed Commission 19 on Rotation of the Earth. In 2015 this became Commission A2 on Rotation of the Earth. So, July 28, 2019 also marks the 100th anniversary of Commission A2.

2. Scientific meetings organized during 2015–2018

Geodesy, Astronomy, and Geophysics in Earth Rotation

18-23 July 2016; Wuhan, China; http://main.sgg.whu.edu.cn/gager2016/

This joint science symposium, organized by Commission A2 (Rotation of the Earth) of the International Astronomical Union (IAU), Commission 3 (Earth Rotation and Geodynamics) of the International Association of Geodesy (IAG), and the International Earth Rotation and Reference Systems Service (IERS), and hosted by Wuhan University, Shanghai Astronomical Observatory and the Institute of Geodesy and Geophysics, was a forum for assessing our current ability to observe the Earth's time varying rotation, for assessing our current understanding of the causes of the observed variations, for assessing the consistency of Earth rotation observations with global gravity and shape observations, for exploring methods of combining Earth rotation, gravity, and shape observations to gain greater understanding of the mass load acting on the surface of the solid Earth, and for identifying improvements in the global geodetic observing system needed to further our understanding of the Earth's variable rotation.

Journées des Systèmes de Référence et de la Rotation Terrestre

25-27 September 2017; Alicante, Spain; https://web.ua.es/journees2017/index.html

In the interest of enhancing the interactions between astronomy and geodesy, the Journées are devoted to the study of the space-time celestial and terrestrial reference systems and their evolution with time with the emphasis on the rotation of the Earth. The scope of the Journées range from concepts and theoretical solutions to observational techniques and data analysis. The sub-title of this meeting was "Furthering our Knowledge of Earth Rotation" and the discussions helped to develop the tasks of the IAU/IAG Joint Working Group on "Theory of Earth Rotation and Validation" among others. The topics discussed at the Journées included:

1. Theory of Earth rotation variations: precession/nutation, polar motion, LOD/UT1

2. Observation methods of Earth rotation variations

3. Celestial and terrestrial reference systems and frames

4. Modeling of Earth rotation variations: solar system dynamics and global geophysical fluid mass transport

5. Relativity and new concepts in Earth rotation theory

Reference Systems and Frames
27 August 2018; Vienna, Austria; http://astronomy2018.univie.ac.at
Reference systems and frames are fundamental to positioning and navigating objects in space and on the Earth. Celestial reference frames are used to measure the passage of time, for navigation, and for studying the dynamics of the solar system. Most recently, celestial reference frames have become essential for studying the dynamics of more distant objects and for studying geophysical phenomena on the Earth. Terrestrial reference frames provide the fundamental framework and metrological basis for Earth observations. Since terrestrial reference frames are attached to the Earth, transforming the position of objects between the celestial and terrestrial reference frames requires knowledge of the Earth's changing rotation. Celestial reference frames, terrestrial reference frames, and the Earth's rotation therefore form an interconnected trio. Reference frames, either celestial or terrestrial, are represented by the positions of defining objects. For celestial reference frames these are the positions of radio sources or stars. For terrestrial reference frames these are the positions of fundamental observing stations on the ground. Reference frames need to be maintained and updated as observing systems improve and as the defining objects change their appearance and positions. This scientific meeting during the XXXth General Assembly of the IAU is a forum for discussing celestial and terrestrial reference systems and frames, the Earth orientation parameters that connect them together, and the fundamental standards needed to determine the reference frames and Earth orientation parameters.

3. Scientific meeting being organized during 2019

The Earth's Time Varying Rotation: A Centennial Celebration
7–11 October; Brussels, Belgium
A Symposium on "The Earth's Time Varying Rotation: A Centennial Celebration" is being planned for 7–11 October 2019 in Brussels, Belgium. The Symposium is being organized to celebrate the centennial anniversary of Standing Committee 19/Commission 19/Commission A2. The Centennial Symposium will be a forum for reviewing the scientific achievements of the Commission during the last 100 years; for discussing the observations, theory, modeling, and analysis of the Earth's time varying rotation including precession, nutation, wobble, UT1, and length-of-day; for discussing new and emerging technologies to observe the Earth's rotation; for discussing time scales and space-geodetic tests of relativity; for discussing the use of Earth orientation parameters to connect the terrestrial and celestial reference frames to each other; and for discussing the standards that are required to ensure that Earth orientation parameters and terrestrial and celestial reference frames are consistently determined.

4. Working group report

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

by José Manuel Ferrándiz and Richard Gross

The International Astronomical Union / International Association of Geodesy (IAU/IAG) Joint Working Group (JWG) on Theory of Earth Rotation and Validation (TERV) was created by IAU Commission A2 and IAG Commission 3 to continue the activity of the previous IAU/IAG Joint Working Group on Theory of Earth Rotation (IAU/IAG JWG ThER) that operated in the period 2013–2015. Its purpose is to promote the development of theories of Earth rotation that are fully consistent and that agree with observations, and that may contribute to providing predictions of the Earth orientation parameters (EOPs) with the demanding accuracy and stability targets required to meet the scientific and societal needs of the near future, namely, 30 μas and 3 μas/yr as recommended by IAG's Global Geodetic Observing System (GGOS).

The JWG is organized in three partially overlapping sub-working groups (SWG) that operate independently but in coordination with each other in order to guarantee consistency, which is one of the JWG essential goals:

(1) **Precession/Nutation** chaired by Juan Getino and Alberto Escapa,

(2) **Polar Motion and UT1** chaired by Aleksander Brzeziński, and

(3) **Numerical Solutions and Validation** chaired by Robert Heinkelmann.

The terms of reference of the JWG are published on the IAU web site and in *The Geodesist's Handbook 2016*.

A directly managed website has been established to facilitate and document the group's activities: http://web.ua.es/en/wgterv. Reports of the JWG meetings, including progress reports and some accompanying material, minutes of sessions and discussions when relevant can be found on-line there. The web site contains also a link to the documents elaborated by the previous IAU/IAG JWG ThER.

Meetings

In this term, the JWG organized open splinter meetings and special sessions or discussions at conferences that were of particular relevance to its activities. These were:

- Open splinter meeting at the EGU General Assembly 2016. Vienna, April 20, 2016 (SMP14, http://meetingorganizer.copernicus.org/EGU2016/session/22333)

- Open splinter meeting at EGU General Assembly 2017. Vienna, April 24, 2017 (SMP85, http://meetingorganizer.copernicus.org/EGU2017/session/26247)

- Session 8 at the Geodesy, Astronomy and Geophysics in Earth Rotation Symposium held in July 2016 in Wuhan, China (GAGER 2016) entitled: "Current situation, progress, and challenges of the theory of Earth rotation from the JWG TERV perspective". Reports of progress of all the SWGs were presented in this session, and afterwards there was a long and fruitful discussion whose minutes are available at: https://web.ua.es/es/wgterv/jwg-terv-meetings/open-meeting-at-gager2016.html

- Open splinter meeting at EGU General Assembly 2018. Vienna, April 12, 2018 (SMP40, https://meetingorganizer.copernicus.org/EGU2018/session/29605)

In addition, the JWG Chairs were involved in the Scientific Organizing Committee (SOC) of the **"Journées 2017, des Systèmes de Référence et de la Rotation Terrestre"**, (https://web.ua.es/journees2017/index.html) held in Alicante, Spain. This meeting resumed the successful series of the *Journées "Systèmes de Référence spatio-temporels"*, also supported by IAU and IAG, whose last edition was held in 2014. The final session included an updated report of the JWG TERV activities, gathering the main points of the mid-term report presented at the 2017 IAG-IASPEI Scientific Assembly that is published in the IAG Travaux 2015–2017 and ended with a discussion of future plans and matters to be treated in the framework of the JWG or the whole Commission. In particular, the need to keep the highest coordination between IAU and IAG regarding the Earth's rotation and the associated resolutions or standards recognized by each organization was widely agreed.

Outline of research progress

Next we outline briefly some of the main facts and ideas underneath the research activity of the JWG members and correspondents and present a short selection of their contributions as well. More details are available in the reports of the JWG and its three SWGs available on-line on the JWG web site.

The space geodetic techniques have improved to the point that the theoretical results are judged less accurate than the observational results and therefore the current theory of the Earth's rotation is no longer sufficient. This theory suffers from various inconsistencies and at least several components of it are seen as outdated and require better modeling.

In precession-nutation theory, the consistency between the official theories IAU2000 and IAU2006 has been revised thoroughly and new corrections have been derived to improve their mutual consistency and complement the corrections to the IAU2000A series that appear in the IERS Conventions (2010). Within this context, SWG1 and other colleagues have discussed the possibility of proposing an IAU supplemental precession-nutation consistency resolution, concluding that further considerations about precession-nutation model enhancements, their nomenclature, and implementation are needed.

The precession model has been re-assessed as well as a set of the minor contributions to the longitude rate of the precession of the equator. The magnitude of the yet unaccounted contributions shows that the value of the Earth's dynamical ellipticity H_d, one of the most important geodetic parameters for the Earth's rotation, is affected at a level that produces non-negligible "indirect" effects on nutations. Other contributions to nutations are under study, either of new physical origin or better approximations to previous solutions. Among them, the Hamiltonian method has recently been applied to re-compute the second order (quadratic in H_d) contributions to precession and nutation for a two-layer earth model. The RotaNut team is advancing in the modeling of the effects of the inner Earth layers, and besides, it is expected to obtain updated values of the MHB2000 basic earth parameters (BEP) in a few years. Although many of those corrections are very small, several terms are above the GGOS accuracy threshold particularized to the Earth rotation parameters (EOP).

The free core nutation (FCN), which is of particular relevance for improving the prediction of the celestial intermediate pole offsets (CPO), has been addressed from different perspectives, ranging from new theoretical approaches, relying on convolution or numerical integration, to the development of new empirical models. Also, new determinations of a set of nutation amplitudes from existing or newly developed VLBI session-wise and global solutions have been carried out recently. These amplitudes are classically used to fit theories, but for the sake of consistency and accuracy it has to be considered that the reference frames used in data analysis are not identical to the reference systems or frames used for theory; this topic is being investigated.

Polar motion theory has been extended to a triaxial Earth with a fluid core and the appearance of non-negligible associated corrections to the BEP for this extended model have been shown. While these effects are small they are systematic, not random, and should therefore be included in an updated theory according to the discussions inside the JWG. Other improvements to the Earth's interior modeling and the evaluation of ellipticity of the inner components have been made or are in progress. Due to all these advances, the theoretical estimates of the free periods, particularly Chandler's, have been brought closer to their observed values.

The knowledge of the geophysical excitation of polar motion and UT1 at different frequency bands has also advanced inside the JWG, although more insight is needed, e.g. at high frequencies or regarding the excitation balance of the annual wobble. The quality and consistency of the implied geophysical models seem to be an unavoidable limiting factor.

Among the validation issues we note the research performed on the consistency and actual accuracy of the EOP estimates and their relationship to the celestial and terrestrial frames and processing strategies used for their determination.

Members

We acknowledge the dedication of the JWG members and correspondents.

IAU members: Barkin, Yuri (deceased 2016); Bizouard, Christian; Brzeziński, Aleksander; Capitaine, Nicole; Chao, Benjamin; Dehant, Véronique; Dickman, Steven; Escapa, Alberto; Ferrándiz, José; Folgueira, Marta; Gambis, Daniel; Getino, Juan; Gross, Richard; Gusev, Alexander; Huang, Cheng-Li; Jin, Shuanggen; Kosek, Wiesław; Luzum, Brian; Malkin, Zinovy; Müller, Jürgen; Nastula, Jolanta; Ray, James; Rogister, Yves; Ron, Cyril; Salstein, David; Sansaturio, Maria; Schuh, Harald; Seitz, Florian; Souchay, Jean; Thaller, Daniela; Thomas, Maik; Vondrák, Jan; Zharov, Vladimir; Zhou, Yonghong

IAU Associates: Belda-Palazón, Santiago; Chen, Wei; Dobslaw, Henryk; Gerlach, Enrico; Heinkelmann, Robert; Herring, Thomas; Navarro, Juan; Ponte, Rui; Schindelegger, Michael; Shen, WenBin; Zotov, Leonid

Correspondents: Baenas, Tomás; Kaplan, George; Urban, Sean

5. Organization reports

5.1. *Report of the International Association of Geodesy*

by Zinovy Malkin and Harald Schuh

A highlight of the International Association of Geodesy (IAG) activities in the last period was its Scientific Assembly held from July 30 to August 4, 2017 in Kobe, Japan together with the International Association of Seismology and Physics of the Earth's Interior (IASPEI). IAG and IASPEI are two of the eight semiautonomous Associations of the International Union of Geodesy and Geophysics (IUGG). Altogether, 1,107 participants from 63 countries registered for the Kobe meeting. The IAG Scientific 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 Scientific Program of the General Assembly consisted of 27 IAG symposia and 9 Joint symposia; in total 254 presentations were given in IAG symposia and 301 presentations in Joint symposia. Among those, there were 18 invited talks in the Joint symposia and 17 invited talks in the IAG symposia. The IAG Council approved two Resolutions, which might have some relevance for IAU:

1. IAG Resolution for the definition and realization of an International Height Reference System (IHRS);
2. IAG Resolution for the establishment of a global absolute gravity reference system.

In Kobe, new joint entities of three Associations were established as sub-components of IAG Commissions: the commissions on volcano-geodesy (IAG and IAVCEI), on seismo-geodesy (IAG and IASPEI), and on cryospheric deformations (IAG and IACS). The next IAG General Assembly will be held during the 27th IUGG General Assembly in Montreal, Canada, from 9 to 18 July, 2019.

Many research topics are common to IAG and IAU CA2. Those are mostly conducted in the IAG Commission 1 "Reference Frames" and IAG Commission 3 "Earth Rotation and Geodynamics". IAG Commission 1 coordinates activities in several directions related to the IAU CA2 interests. The sub-commissions participating in these activities are:

SC 1.1 "Coordination of Space Techniques",

SC 1.2 "Global Reference Frames", and

SC 1.4 "Interaction of Celestial and Terrestrial Reference Frames".

The latter has been working, in particular, on development of the methods of consistent realizations of terrestrial and celestial reference frames, and EOP. These studies are coordinated by the IAG WG 1.4.1 "Consistent Realization of ITRF, ICRF, and EOP". IAG Commission 1 holds its general meetings, called REFAG, every four years. The next meeting, REFAG-2018 will be held in July 2018 in Pasadena, CA, USA. IAG Commission 3 includes Sub-commission 3.3 "Earth Rotation and Geophysical Fluids", which coordinates research and data analysis in areas related to variations in Earth rotation, gravitational field and geocenter. This Sub-commission also supports IAU/IAG Joint Working Group on "Theory of Earth Rotation and Validation".

5.2. *Report of the International Earth Rotation and Reference Systems Service*

by Wolfgang R. Dick, Brian Luzum, and Daniela Thaller

The International Earth Rotation and Reference Systems Service continued to provide Earth orientation data, terrestrial and celestial references frames, as well as geophysical fluids data to the scientific and other communities. The Earth Orientation Centre upgraded the C04 software and data base procedures and introduced a direct combination of the celestial pole offsets with respect to IAU 2000 precession-nutation model. The Rapid Service / Prediction Centre implemented a new system in Bulletin A. Since February 2017, the IERS EOP series are aligned to ITRF2014 and 08 C04 was replaced by 14 C04. The three ITRS Combination Centres (DGFI, IGN, JPL) finalised the combination of the long-term data provided by Technique Centres. In January 2016 the ITRF2014, including 1499 stations located at 975 sites, was published by the ITRS Centre. The ITRS Combination Centres at DGFI-TUM and at JPL realized DTRF2014 and JTRF2014. Studies of the ITRF2014 extended model presentation of post-seismic deformation after large earthquakes as well as on the scale differences between the ITRF2014 and DTRF2014 systems for the VLBI and SLR stations were undertaken by the IERS Analysis Coordinator. The Conventions Centre established a study group to review compatibility of models for VLBI and SLR in an effort to reduce the discrepancy in scale observed by the two techniques. Work on the next ITRF was started. The ITRS Centre participated also in surveys of co-located sites and published recommendations for these. Together with the IAU Division A Working Group on ICRF3, the ICRS Centre continued to prepare the next ICRF. Comparisons were made between the ICRF and the Gaia Data Release 1 optical reference frame. ICRF3 which is expected for 2018 will be competitive in precision with Gaia. Work on technical updates to the IERS Conventions (2010) was continued, with updates of existing content, expansion of models, and introducing new topics; e.g., the Analysis Coordinator compared several different up-todate sub-daily EOP models with the IERS standard model. In February 2018, the Conventions Centre issued a Call for Participation in the next IERS Conventions. The Global Geophysical Fluids Centre (GGFC) evaluated new GGFC products for latency and reliability, before these were made official products. The Central Bureau started work on major updates for the data management component of the IERS Data and Information System. Several 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 has been developed further. The WG on Combination at the Observation Level finished its work with the presentation of a concluding report and ceased operation in 2016. The WG has shown the possibility of a combination at the Normal Equation level to determine simultaneously quasar coordinates, Earth orientation parameters and station coordinates. The WG on SINEX Format, together with other IERS components, worked on modifications and revisions of the format, particularly for the representation of non-linear station motions due to post-seismic movements and for providing more information on radio source positions. A web-based tool has been developed where the content descriptions of the individual SINEX blocks can be added and changed more conveniently. The WG on Site Coordinate Time Series Format continued to work on the definition of a common exchange format for coordinate time series for all geodetic techniques. Based on a list of existing formats at IAG services and GPS time series providers, metadata and data have been examined.

The following IERS publications and newsletters appeared between 2015 and 2018: Z. Altamimi et al.: Analysis and results of ITRF2014 (IERS Technical Note No. 38, 2017); Jean-Claude Poyard et al.: IGN best practice for surveying instrument reference points at ITRF co-location sites (IERS Technical Note No. 39, 2017); IERS Annual Reports 2014, 2015, and 2016; IERS Bulletins A, B, C, and D (weekly to half-yearly); ca. 70 IERS Messages. The central IERS web site www.iers.org and about 10 individual web sites of IERS components have been updated, improved and enlarged continually.

The IERS co-organized the joint IAU/IAG/IERS Symposium on Earth Rotation, July 18–23, 2016 in Wuhan, China, and the IAG/GGOS/IERS Unified Analysis Workshop (UAW), July 10–12, 2017 in Paris.

6. National and institutional reports

6.1. *Report of activities during 2015–2018 in Austria*

by Johannes Böhm and Robert Weber

Research related to Earth rotation is carried out at Technische Universität Wien (TU Wien) where the research area Higher Geodesy is analyzing VLBI and GNSS observations for the determination and investigation of Earth orientation parameters (EOP). For VLBI analysis, the in-house Vienna VLBI and Satellite Software (VieVS; Böhm et al. 2018) has been applied, e.g., to assess the impact of non-linear VLBI station variations (Krásná et al. 2015) or source structure effects (Shabala et al. 2015) on EOP. A lot of effort is also put into the further development of VieVS, e.g., for improving the scheduling capabilities. Emphasis has also been put on the combination of VLBI and ring laser observations for the determination of Earth rotation parameters. GNSS observations have been applied to derive high-resolution Earth rotation parameters from global GNSS networks. In particular, the additional benefit from Galileo satellites for nutation rates and length of day estimates has been investigated (Weber et al. 2017).

In terms of geophysical modeling of the excitation of Earth rotation, TU Wien has carried out several studies. Girdiuk et al. (2016) and Schindelegger et al. (2016) have assessed the influence of the atmospheric S1 tide and related effects in the oceans on EOP. Madzak et al. (2016) derived a model for Earth rotation variations from hydrodynamic ocean tidal models and find good agreement with VLBI observations.

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6.2. *Report of activities during 2015–2018 in Belgium*

by Véronique Dehant

The main objective of the project RotaNut is to significantly improve the model for the orientation of the spin axis to the sub-centimeter level, which has never previously been achieved and which is the aim of all existing decadal surveys in geodesy. This will be extremely helpful to European and international satellite missions and GNSS (Global Navigation Satellite System, such as GPS or its European equivalent Galileo) positioning. At the same time, it will allow scientists to learn much more about the interior of the Earth such as the predominant coupling mechanisms at the core boundaries (inner core boundary and core-mantle boundary) at nutation timescale and the amplitude of the magnetic field at these boundaries, which are not directly observable from the Earth surface (as only a part of the field is observable above the insulating mantle).

For this period, we have addressed the following tasks:

1. Computation of nutation and comparison between theory and observations; determination of basic Earth parameters – P. Zhu

2. Mixing of rotational modes with gravito-inertial and hydromagnetic modes – J. Rekier, S. A. Triana, and A. Trinh

3. Automate the writing of tensor equations in celestial bodies – A. Trinh

4. Inner core differential rotation – inertial wave instability observed in experiments using the same geometrical configuration as the Earth's core (spherical-Couette) – S.A. Triana

5. Influence of core dynamics on the magnetic field – R. Laguerre

6. Effect of topographic features of the core-mantle boundary – R. Laguerre, J. Rekier, A. Trinh and S.A. Triana

6.3. *Report of activities during 2015–2018 in China*

by Chengli Huang

A Joint IAU/IAG/IERS Symposium "Geodesy, Astronomy and Geophysics in Earth Rotation" (GAGER2016) and GAGER 2016 Lectures were held during 18–24 July 2016 in Wuhan, Hubei, China. International Symposium of Asia-Pacific Space Geodynamics (APSG) Program with theme "From Space Geodesy to Astro-Geodynamics" was held in Shanghai, China, during 15–18 August, 2017. Both of them published or will publish proceedings in the journal *Geodesy and Geodynamics.*

The first Chinese VGOS station with a 13 meter antenna in VLBI2010 standard by Shanghai Astronomical Observatory (SHAO), collocated with a 65 meter radio telescope in Sheshan station, Shanghai, is almost finished its construction and will join the international VGOS network before 2019 for 1mm-precision ITRF and EOP measurements. With many-year efforts of LLR experiments, the SLR station of Yunnan Observatory at Kunming, China, received her first laser echoes from lunar retroreflector (A15) on 22 January 2018.

IAU2006 precession model was refined based on the best available solar system ephemerides and geophysical observations (Liu & Capitaine 2017). Basic Earth parameters were updated to be consistent with the CODATA2014 and the latest IAU/IAG numerical standards (Chen et al. 2015, 2017a). A new method to improve the tidal polar motion models according to the tidal alias signals in the polar motion observations was proposed and some basic results were presented (Chen et al. 2017b). A sliding-window complex least-squares fit method (SCLF) is proposed (Zhou et al. 2016) to estimate the free core nutation (FCN) period. The secular decaying phenomenon of a 6 year oscillation signal in length of day (LOD) was detected by NMWT method (Duan et al. 2015, Duan et al. 2017).The mathematical expression between the quality factor value based on the observations and electromagnetic coupling at the CMB was further developed (Duan et al. 2018). The Earth's principal moments of inertia were calculated with a new generalized theory of the figure of the Earth and PREM + CURST 1.0 Earth model (Liu et al. 2017). The IVS 40-year data have been analyzed and find that most of geodetic sources are resolved to some extent, and approximately 1/2 of the residual group delay variance in CONT14 is attributed to source structure (Xu et al. 2016, 2017). A Fourier basis pursuit (FBP) spectrum is proposed to estimate the variable PM during 1900–2015 (Wang et al. 2016). The atmospheric friction torque uncertainties on solid Earth caused by the uncertainty in the different wind stress products is studied (Yan & Huang 2016). Studies of methods to improve EOP prediction are still on-going (Xu & Zhou 2015, Guo et al.).

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6.4. *Report of activities during 2015–2018 in the Czech Republic*

by Jan Vondrák

Studies of geophysical effects in Earth's orientation continued at Astronomical Institute, Czech Academy of Sciences. We showed that not only the motions of the atmosphere and oceans, but also the influence of geomagnetic jerks (GMJ – rapid changes of intensity of geomagnetic field) is most probably responsible for these changes. All Earth orientation parameters are affected (Ron et al. 2015, Vondrák & Ron 2015, Ron & Vondrák 2015, Vondrák & Ron 2017a). To this end, we used the numerical integration of Brzeziński's broad-band Liouville equations, the initial conditions for the integration being estimated to yield the best fit to observations. The comparison with the observed values proved that the fit was always significantly better when the influence of GMJ (modeled as sporadic quasi-impulse function) was considered. We also compared the effect of atmospheric and oceanic excitations from different data sources on Earth's orientation (Vondrák & Ron 2016) and found that while the European model ERA + OMCT yields the best results in case of polar motion, American model NCEP/NCAR with inverted barometer correction is the best in describing celestial pole offsets. For length-of-day changes it is MERRA + ECCO model that gives the best agreement. The inclusion of GMJ effect always improved the solution significantly.

Brzeziński's equations were also used for estimating the period T_c and Q_c-factor of Chandler wobble – their numerical integration was used repeatedly for different combinations of T_c, Q_c and we looked for the best fit with observed pole position (Vondrák et al. 2017, Ron & Vondrák 2018). Our preferred values, based on the data in interval 1974.0–2014.0 and ERA/OMCT excitations plus GMJ effects, are $T_c = 432.86 \pm 0.04$ mean solar days and $Q_c = 35.0 \pm 0.3$. A similar method, but more complicated, was applied to estimate free core nutation (FCN) parameters – its period T_f and Q_f-factor (Vondrák & Ron 2017b, Ron & Vondrák 2018). Since the amplitudes and phases of individual nutation terms depend on these parameters, the observed celestial pole offsets had to be recalculated to correspond to each individual combination of T_f, Q_f, before they were used to calculate the rms fit with integrated data. Several models of excitation were used, and the best fit to observations was achieved for Sun-synchronous correction, combined with GMJ effect. The obtained values of FCN parameters, based on the data in interval 1986.0–2016.0, are $T_f = 430.28 \pm 0.04$ mean solar days and $Q_f = 19500 \pm 200$. A review paper on history of monitoring Earth orientation and re-analyses of historical astrometric data was also published (Vondrák 2018).

In close collaboration with our Bulgarian colleague Yavor Chapanov, we studied the problem of interaction between Earth's orbital variations and mean sea level (Chapanov et al. 2015), detection of jumps in time series (Chapanov et al. 2017a), or correlations among Earth rotation, mean sea level, solar activity and climate (Chapanov et al. 2017b, Chapanov et al. 2018).

The first successful and unique experiment with length-of-day estimation from pure DORIS observations was performed at the Geodetical Observatory Pecný, based on the data in 2006.0–2015.0 (Štěpánek 2016, Štěpánek et al. 2018). The results agree with IERS C04 solution on the level of ±0.12 ms for the last years of the campaign 2012.0–2015.0. Differences show the domination of the annual signal together with several draconitic periods and a high frequency signal with period 14.2 days. LOD series estimated from single-satellite DORIS solutions were also analyzed to identify satellite-specific issues.

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6.5. *Report of activities during 2015–2018 in France*

by Christian Bizouard

The general scientific theme of Paris Observatory/SYRTE department is Space-time Reference system (https://syrte.obspm.fr).

One team is "Earth rotation and Space rotation". Over the period 2017–2018 it was composed of 6 permanent scientists (Christian Bizouard - director, Sébastien Lambert, Pascal Bonnefond, Olivier Becker, Jean-Yves Richard, Teddy Carluccy), one emeritus (Nicole Capitaine), two post-doc (Yann Ziegler, Cesar Gattano) and one Ph.D. thesis student (Ibnu Nurul Huda). This team hosts two services of the IERS: the Earth Orientation center directed by C. Bizouard since 2015 and since 2016 the IERS Convention Center co-chaired with USNO. These services are mainly operated by C. Bizouard, O. Becker, S. Lambert and T. Carlucci.

The scientific activity is devoted to the determination of Earth rotation irregularities and their modeling in light of geophysical and astronomical causes.

Determination of Earth rotation is reflected by routine Earth Orientation Parameter (EOP) solutions done in the framework of the IERS: daily C04 since 1962, 0.05 year C01 since 1846, and 100 day C02 (LOD, UT1) since 1830. Updated C04/C01 solution, consistent with ITRF2014, are disseminated since February 2017 (Bizouard et al. 2018, to be published in J. Geodesy). This production is completed by the development of multi-technique combination by J. Y. Richard in close partnership with the teams belonging to the French group of space geodesy (Groupe de

Recherche en Géodésie Spatiale, GRGS) (Richard et al. 2018, to be submitted to J. Geodesy). In December 2016 César Gattano defended his Ph.D. thesis, part of which was devoted to the influence of celestial reference frame instability on nutation estimates (Gattano et al. 2017).

Having in mind that the knowledge of air and water mass redistribution is of primary importance for understanding Earth rotation changes, we actively develop the reconstruction of hydro-atmospheric angular momentum through two collaborations: (1) with the French Private Company MERCATOR OCEAN operating the French Ocean Global Circulation Model NEMO, and (2) with Leonid Petrov in the framework of a project founded by NASA. In December 2017 we organized the workshop "Océans et Rotation de la Terre" in Paris Observatory, aimed at making the state of the art with French experts of ocean circulation and tide models, and undertaking concrete actions (support of the talks can be downloaded from ftp://syrte.obspm.fr/bizouard/ATELIER_OAM_17).

On the other hand we continued the analysis of Earth rotation excitation. In 2015 we discovered in the polar motion excitation an elliptic polarization towards 80° East whatever the frequency, and mostly associated with the atmospheric excitation (Bizouard 2015). The length of day change caused by the last El-Nino in 2015–2016 and its causes have been thoroughly investigated by Lambert et al. (2017). In the framework of a cooperation with Moscow University (started in 2010) we found possible interrelation between Earth rotation and climatic variability at decadal time-scale (Zotov et al. 2016).

Since 2017 our interest is partly reoriented on the Earth interior. Following the approach of Rosat et al. (2017) mixing gravimetric and VLBI data, Yann Ziegler has refined the estimation of Free Core Nutation parameters through a Bayesian approach. He also looked for the possible influence of the Free Inner Core Nutation (Journées 2017 Proceedings). The Ph.D. thesis of Ibnu Nurul Huda, begun in December 2016, is devoted to the study of Earth interior parameters associated with quasi-diurnal Earth rotation changes in an Earth system (nutation in the celestial frame, diurnal polar motion and libration) by processing VLBI delays. First step was to set up the determination of nutation as global parameters (Nurul Huda, Journées 2017 Proceedings).

In September 2017 we had the task to co-chair the conference "Journées 2017 Rotation de la Terre" with Prof. José Ferrándiz in Allicante University (Spain). The proceedings will be published electronically on internet in 2018.

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6.6. *Report of activities during 2015–2018 in Germany*

by Florian Seitz

Comprehensive research activities related to Earth rotation and Reference Systems in Germany were performed in the frame of the coordinated Research Unit (RU) 1503 of the German Research Foundation (DFG) with the title "Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space". This RU started its work in 2012 and continued in a second phase during 2015–2018. It consists of eight inter-related sub-projects comprising 13 inter-disciplinary positions for young scientists from nine universities and research institutions. The RU aims at developing integrative methods and procedures for a consistent definition and realization of geodetic reference systems on Earth and in space as well as to accomplish computations for their establishment and maintenance (www.referenzsysteme.de).

Topics cover new approaches to planetary ephemerides, a new celestial reference frame through rigorous combination, lunar and planetary reference frame studies, observations of satellites with radio telescopes, impacts of geophysical models on results, consistent estimates of celestial and terrestrial reference frames, as well as datum definitions based on physical background models. The final outcome of the research will be published in a special issue of Journal of Geodesy. Some of the projects have already come to an end with online versions of their results available under https://link.springer.com/journal/190/onlineFirst.

One outcome of the RU is the first simultaneous and consistent realization of the global Terrestrial Reference Frame (TRF), the Celestial Reference Frame (CRF) and the Earth orientation parameters (EOP) from the space-geodetic observing techniques VLBI, SLR, GNSS, DORIS (Seitz et al. 2014, Kwak et al. 2018) following the requirement of IUGG Resolution R3 (2011). This resolution urges that the highest consistency between the ITRF, ICRF and EOP should be a primary goal in all future realizations. Furthermore, within the RU, the estimation of EOPs from LLR observations was studied. The improved data situation allows an estimation of nutation coefficients down to a period of 13.6 days and a possible validation of VLBI-derived dUT within nights with more than 14 normal points (Müller et al. 2014, Hofmann et al. 2018).

In 2016, the "First International Workshop on VLBI Observations of Near-field Targets" (http://www3.mpifr-bonn.mpg.de/div/meetings/vonft/index.html) has been organized with the aim of discussing steps towards the connection of the TRF to the dynamical reference frames of satellite orbits through VLBI observations of satellites together with those of compact extragalactic radio sources.

Research activities related to TRF and EOP determination in Germany involved the computation of DTRF2014 (Seitz et al. 2016) as one of the three latest realizations of the ITRS in 2014. In the context of the activities related to the ITRS realization, the IVS Analysis Centers in Germany and the IVS Combination Center performed a full re-analysis of all VLBI sessions. The VLBI contribution to the ITRF contains station coordinates and the full set of all five EOPs (Bachmann et al. 2016a, b). After the release of the three ITRS realizations ITRF2014, DTRF2014 and JTRF2014 the impact of different station parameterizations on the VLBI-derived EOPs was investigated (Bachmann et al. 2018). Latest activities of the IVS Combination Center aimed at extending the combination procedures with the radio source positions as additional parameters (Bachmann et al. 2017).

Concerning EOP analysis and interpretation, a new version of Effective Angular Momentum Functions (EAM) describing the effects of atmosphere, terrestrial hydrosphere, ocean circulation and sea-level changes has been made available (https://isdc.gfz-potsdam.de/esmdata/eam/). The time-series has a high temporal resolution of up to 3 hours, extends back to 1976, and is updated once a day with all time-steps of the previous day. In addition, 6 day-long EAM forecasts are routinely provided that improve predictions of both polar motion and dUT1 by more than 40% over widely used Bulletin-A forecasts of the IERS (Dobslaw & Dill 2018).

At the GFZ, Potsdam, we contributed to the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation (see section 4.1.), in particular to the SWG 3 chaired by Robert Heinkelmann. The consistency of reference frames and EOP, where we assessed reference frame-induced errors of EOP with the VLBI technique (Heinkelmann et al. 2015a, 2015b, Belda et al. 2017a) was in the focus of our scientific investigations. Based on VLBI-determined celestial pole offsets (CPO), we computed a state-of-the-art model of the free core nutation (Belda et al. 2016). Considering this model in the VLBI analysis, we reassessed the main nutation terms and found a new interesting signal very close to the expected period of the free inner core nutation (Belda et al. 2017b). In our latest work, we established significant improvements for the prediction of CPO. Besides, we extensively exploited the potential of Kalman Filtering of VLBI observations (Nilsson et al. 2015, Soja et al. 2016, 2018) and particularly for EOP determination (Karbon et al. 2017) and had a look into UT1 estimation by combining VLBI with GNSS (Nilsson et al. 2016).

In the framework of the Global Geodetic Observing System (GGOS), a global terrestrial reference frame (TRF) with highest accuracy, consistency and stability has become increasingly important to correctly interpret geodetic parameters that describe geometry, gravity field and rotation of the Earth. Simulated observations from all space geodetic techniques (DORIS, GNSS, SLR, and VLBI) along with rigorous combination strategies allow to understand the error sources that are limiting the TRF accuracy. Within project GGOS-SIM at GFZ, Potsdam (Schuh et al. 2016), firstly the current ground network of VLBI was simulated, applying state of the art models for VLBI data processing (Glaser et al. 2017a). Secondly, SLR observations were simulated, applying also state of the art models and identical standards where applicable (Glaser et al. 2017b). To ensure reliable solutions both simulated observations were compared to real ones (Schuh et al. 2017).

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6.7. *Report of activities during 2015–2018 in Russia*

by Zinovy Malkin

Several institutes in Russia have been working on the topics of the IAU Commission A2. VNIIFTRI maintains the Russian State EOP Service and produces combined EOP solutions using individual EOP series provided by several Russian institutes. It is also responsible for keeping and disseminating the Russian national time scale. The Institute of Applied Astronomy (IAA) supports the 3-station VLBI network QUASAR. All three stations – Svetloe, Zelenchukskaya, and Badary – are equipped with the 32-m radio antennas RT32 that participate in the domestic and global observing programs on determination of EOP. Domestic EOP RT32 programs consist of weekly 24h sessions on a 3-station network providing the full set of EOP and daily 1h sessions on a 2-station network for rapid UT1 determination. In November 2015, new fast 13-m antennas RT13 at Zelenchukskaya and Badary started regular operations. They provide ultra-rapid UT1 determination with resolution of a few hours. All three QUASAR stations are also equipped with GNSS receivers and SLR units, and contribute to the IGS and ILRS networks, respectively. IAA is also working on processing the observations collected on global IVS, IGS, and ILRS networks and delivering the obtained EOP, TRF, and CRF products to the IERS and IVS. Pulkovo Observatory supports regular VLBI Intensive data processing and delivers computed UT1 series to the IERS. IVS and IERS combined series are also regularly processed with the goal of computating refined CPO and FCN series that are publicly available. Series of EOP predictions were provided for the IERS EOPCPPP project. GNSS station PULK is an EPN station. The Astronomical department of St. Petersburg State University is working on processing the IVS VLBI data and delivering the results to IERS. 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. 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 products and ITRF densification.

Several groups in Russia have been working on theoretical investigations of the Earth rotation and EOP variations at different time scales from intra-day to decadal. Several authors studied the interconnection between Earth rotation variations and other geophysical and cosmophysical processes, such as crustal movements, solar activity, atmospheric and climate change, and geomagnetic jerks. Russian groups actively participated in ICRF improvement, mostly in the framework of the activity of the IAU Division A Working Group "Third Realization of the International Celestial Reference Frame". A new combined catalog of radio source positions was computed at Pulkovo Observatory.

6.8. *Report of activities during 2015–2018 in Spain*

by Alberto Escapa and José Manuel Ferrándiz

In this term, Earth rotation studies in the Universities of Alicante, León, and Valladolid have focused mainly on consistency issues and on the extension of the theory to the second order, particularly in the sense of perturbation methods.

From the point of view of the construction of precession and nutation theories, consistency problems have been approached in two ways. The first is related to the process followed for adopting both theories, IAU 2000 nutation first and then IAU 2006 precession, which forces the incorporation of some additional terms into the nutation series in order to get a dynamically consistent precession-nutation pair at the micro-arcsecond level. In contrast to previous studies, a specific Earth nutation model has been developed to obtain those adjustments (Escapa et al. 2017). This framework has allowed new sources of the required corrections to be found that were not considered previously and that have the same order of magnitude as the existing ones.

The second line of work arises when considering the nutation-nutation coupling of non-rigid Earth models at full (Escapa et al. 2016). This effect, not taken into account in the current IAU 2000 nutation, causes non-negligible changes in the value of the Earth's dynamical ellipticity H_d. In turn those changes modify the values of the nutation series through a kind of *indirect* effect. It is a manifestation of using slightly different values for H_d in the official precession and nutation models.

With respect to the extension of the theory to the second order, the contributions to the precession of a two-layer Earth model have been determined (Baenas et al. 2017). Specifically, the effects of the elasticity have been incorporated into the Hamiltonian construction by applying Hori's canonical perturbation method up to the second order of perturbation. From this, a revised value has been found of certain second order components of the precession that reaches −55.29 mas/cy. It entails a variation even larger than that due to other contributions included in IAU 2006 precession.

A new, systematic procedure for applying Hori's method to dissipative systems has also been developed (Baenas et al. 2017). It is based on a suitable modification of the Hori kernel in the double dimensional embedding phase space. With the help of a convenient auxiliary system, the path-integrals of the method can be performed in a domain of the phase space with the same dimensionality as the original problem. Hence, the number of variables needed to perform the analytical integration of the system is reduced by half.

Consistency has not been addressed only from a theoretical perspective, but also from that of actual data analysis, in close cooperation with VLBI colleagues from the German Geo-ForschungsZentrum (GFZ). Consistency problems involving reference frames and EOP series were discussed in Belda et al. (2017). Besides, different studies on the empirical modeling of the nutations have resulted in: (1) development of a new Free Core Nutation (FCN) empirical model (Belda et al. 2016); and (2) derivation of updated empirical corrections to the Celestial Intermediate Pole Offsets (CPO) from fitting to VLBI data (Belda et al. 2017).

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6.9. *Report of activities during 2015–2018 at the Jet Propulsion Laboratory, USA*

by Richard Gross

During 2015–2018, 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. In addition, a Kalman filter and smoother was developed to smooth and predict celestial pole offsets (CPOs) for use by the spacecraft navigation teams at JPL.

During the past triennium, JPL also investigated the effect of global-scale continental mass transport on polar motion (Adhikari & Ivins 2016), finding that changes in terrestrial water storage and in glacial and ice sheet mass can explain the change in the drift of the pole that occurred about 2000. Furthermore, they found that changes in terrestrial water storage can explain the lower frequency changes in polar motion observed during 2003–2015.

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president of the Commission