Report of the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation

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Abstract

This report focuses on some selected scientific outcomes of the activities developed by the IAU/IAG Joint Working Group on Theory of Earth rotation and validation along the term 2015–2019. It is based on its end-of-term report to the IAG Commission 3 published in the Travaux de l'IAG 2015–2019, which in its turn updates previous reports to the IAG and IAU, particularly the triennial report 2015–2018 to the IAU Commission A2, and the medium term report to the IAG Commission 3 (2015–2017). The content of the report has served as a basis for the IAG General Assembly to adopt Resolution 5 on Improvement of Earth rotation theories and models.

Keywords

Earth rotation theory · Earth rotation models · Earth orientation parameters · Precession–nutation · Polar motion · UT1

1 Introduction

In 2015 the IAG, jointly with the International Astronomical Union (IAU), established the IAU/IAG Joint Working Group on Theory of Earth rotation and validation (IAU/IAG JWG TERV, or only JWG for short) that continued the former IAU/IAG JWG on Theory of Earth rotation (ThER), which operated in 2013–2015. This JWG had the purpose of promoting the development of theories of Earth rotation fully consistent and in agreement with observations, useful for providing predictions of the Earth orientation parameters (EOP) with the accuracy required to meet the needs of the near future as recommended by GGOS, the IAG Global Geodetic Observing System. The accuracy and stability goals are very stringent, since the benchmarks set by the JWG are 30 µas and 3 µa/y in terms of geocentric angles; those figures arise from the requirements to the Terrestrial Reference Frames (TRF) accuracy and stability that are necessary for monitoring the sea level rise properly and adopting the policies suitable to act against global change and minimize its prejudicial effects.

The JWG addressed the whole set of five Earth orientation parameters (EOP), since there are interrelations among them and consistency was a main goal besides of accuracy. Because of that the JWG had a complex structure, with a Vice-chair (Richard Gross) and three partially overlapped sub-working groups (SWG) that operated independently but in coordination:

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(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 complete terms of reference appear in The Geodesist's Handbook 2016 (Drewes et al. 2016), and a website with further information is hosted by the University of Alicante (UA) (https://web.ua.es/en/wgterv).

Coordination among the SWGs and with other IAG components (in particular GGOS and IERS) was facilitated by the existence of common members (including correspondents) affiliated to the JWG and e.g. to the IERS Earth Orientation Centre, Rapid Service/Prediction Centre, Conventions Centre, and Central Bureau, the IERS Analysis Coordinator and the GGOS Scientific Panel, Bureau of Products and Standards, and Committee on Essential Geodetic Variables. Coordination with the IAU was also guaranteed by a majority of JWG members in the Organizing Committee of IAU Commission A2, Rotation of the Earth, the IAU body to which the JWG reported. More details on that can be found on the Travaux 2015–2019 Commission 3 report (Drewes and Kuglitsch 2019), which also details the organization of splinter meetings or sessions at large conferences. Additional information appears in the precedent JWG reports, like those to the IAU in 2018 and to the IAG in 2017 (Drewes and Kuglitsch 2017)

The scientific outcomes and findings can be cast according to their level of maturity in

– Advances or findings on topics that can be considered scientifically solved, and
– Advances showing remarkable improvement of knowledge but still on progress

Next section emphasizes on outcomes of the first kind. Many of them are related to precession and nutation, since those parameters are a main object of theoretical developments due to its origin, astronomical forcing in the main, and subsequent better predictability.

2 Selected Outcomes

Several papers published in recent years by JWG members in the main unveil that a noticeable part of the unexplained variance of the determined EOP series can be attributed mainly to:

– Systematic errors, e.g. in conventional or background models,
– Inconsistencies, either internal to theories or among components of them, and
– Need of updating some specific components after 20 years of their derivation

That happens particularly for the Celestial pole offsets (CPO) that provide the deviations of the precession-nutation parameters with respect to the conventional models adopted by the IAU and IAG/IUGG. Some of the main outcomes related to the CPO are:

1. The amplitudes of the main nutation terms have to be updated after almost 20 years of use. This is particularly important for the 21 frequencies used to fit the nutation theory IAU2000, at a time in which the amplitude formal errors were not better than 5 μas (Herring et al. 2002) and may exceed some tens. Currently the number of separable frequencies has increased drastically up to several tens, and the uncertainties of the fitted amplitudes are reduced to about 2–3 μas. The existence of amplitude inaccuracies that can reach several tens μas has been confirmed by many different independent results, e.g. Malkin (2014), Gattano et al. (2016), Belda et al. (2017a), Schuh et al. (2017), Zhu et al. (2017). Methodologies are varied; for instance, Malkin (2014) fitted a reduced set of amplitudes to various single and combined CPO time series, in different time intervals. Gattano et al. (2016) also used different single and combined series, whereas Belda et al. (2017a) used a global VLBI solution derived from 2990 sessions ranging from 1990 to 2010 (the last year used for the ICRF2 realization) to fit the widest set of amplitudes, 179. To give an idea of the magnitude of the potential improvement, the decrease of the WRMS of the CPO residuals is roughly around 15 μas when the 14 major amplitudes and precession offsets and trends are corrected according to that fit.
2. Also for nutation theory, it has been found that the two independent blocks that compose the IAU2000 series, namely lunisolar and planetary, are inconsistent with each other (Ferrándiz et al. 2018). In fact, the MHB2000 transfer function was not applied to the amplitudes of the 687 planetary terms, either direct or indirect; instead, those terms were taken without change from an early version of the rigid-Earth theory REN2000. Besides, the planetary terms are nutations of the angular momentum vector, whereas the 678 lunisolar terms are nutations of the figure axis of a non-rigid three-layer Earth. That surprising fact was clearly reported by Herring et al. (2002), and a likely cause might be that the effect of the transfer function application on individual amplitudes was assumed to be negligible and less than 5 μas, the threshold for truncation that IAU recommended at that time for the renewal of the nutation theory. It is not really the case, since the magnitude of this effect has been proved to reach near 20 μas in single amplitudes, a value much larger than the joint contribution

Table 1 Largest Oppolzer terms of planetary origin for the Earth's figure axis

L_{Ve}	L_E	L_{Ma}	L_J	p_A	Period (days)	dX_{in} (sin)	dX_{out} (cos)	dY_{in} (cos)	dY_{out} (sin)	Origin code
0	1	0	−1	0	398.884	0.2	0	0.2	0	0
2	−4	0	0	2	−487.638	−1.8	−0.1	1.7	−0.1	1
0	1	0	−2	0	439.332	1.1	−14	1.3	14.3	1
0	3	−4	0	0	418.266	−3.2	0.5	−3.1	−0.4	1
3	−4	0	0	0	416.688	−2.9	8.2	−2.9	−7.9	1
0	1	0	−1	0	**398.884**	**−18.8**	−3	**−17.2**	3	1
0	2	−2	0	0	389.968	−4.3	−0.4	−3.8	0.4	1
2	−4	0	0	2	−487.638	−5.6	−0.5	5.6	−0.5	2
0	1	0	−1	0	398.884	1.6	0.2	1.5	−0.2	5

Units: amplitudes in µas, periods in mean solar days
Effect origin code: 0 indirect Moon; 1 indirect Sun; 2 direct Venus; 5 direct Jupiter

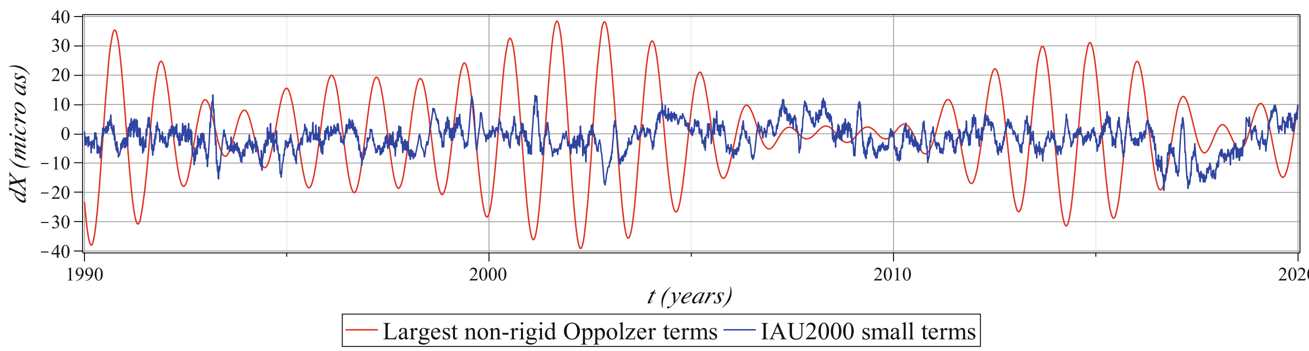

Fig. 1 dX: Comparison of the accumulated effects of the six leading non-rigid planetary Oppolzer terms (in red) and the 533 planetary terms of IAU2000 with amplitude <1 µas (in blue). Period 1990–2020

of several hundreds of small planetary terms included in the IAU2000 model. The joint effect of the neglected terms can be above the GGOS threshold. Those facts are illustrated in Table 1 (an abridged version of Table 1 in Ferrándiz et al. 2018) and Fig. 1. The largest amplitudes and its associated period are marked in bold in Table 1.

3. The background geophysical models of IAU2000, particularly those corresponding to the ocean mass and currents effects, were among the best ones available before 2000, but since then those models have become obsolete. For instance, the computation of oceanic effects is reported as based on the GOT94 model (Chao et al. 1996). Outdating of background models poses a new source of inconsistency, since they are different from the corresponding models currently used to process the observation data for determining the EOP, either separately or jointly with a terrestrial reference frame (TRF). The impact of this fact on the accuracy of those IAU2000 components has not been assessed in most cases. Besides, the update needed to improve consistency and assessing accuracy is not straightforward, since the final MHB2000 nutation series were computed numerically from the dynamical equations and not from the simpler resonance formulae, as described in 6.1 of Mathews et al. (2002); besides, the full set of either oceanic or anelastic contributions was never published separately and only a few sample terms were displayed on the cited paper.
4. Regarding the mutual consistency of the conventional precession and nutation models, it has been proved that the precession theory IAU2006 is not fully dynamically consistent with the nutation theory IAU2000 (MHB2000 by Mathews et al. 2002), though dynamical consistency was required by the 2006 IAU Resolution B1 endorsing P03 (Capitaine et al. 2003). Inconsistencies arise from the fact that IAU2006 considers J_2 as a linear function instead of a constant like IAU2000, and besides uses different values, at J2000.0, for the obliquity and the rate of longitude (*precession constant*) than those of IAU2000. Making the two theories consistent requires applying certain corrections to the nutation part, as already noticed by Capitaine et al. (2005) although no correction was recommended by the IAU WG in charge (Hilton et al. 2006) nor included in the text of the Resolution. The set of corrections already recommended in the IERS Conventions (2010) (Petit and Luzum 2010) has been found to be incomplete, but full consistency can be achieved by applying to the IAU2000 series a recently determined set of small corrections that

include a few so-called Poisson or secular-mixed terms, whose amplitudes are factorized by the time and thus increase as it departs from J2000.0 in either sense (Escapa et al. 2017a,b; Escapa and Capitaine 2018). Using µas and Julian centuries as units, the complete set is given by

$$\begin{aligned}(-d\,\Delta\psi) = & -15.6\sin\Omega - 1.4\cos\Omega - 0.5\cos l_s \\ & +39.8t\sin\Omega - 0.6t\sin 2\Omega, \\ (-d\,\Delta\epsilon) = & +0.8\cos\Omega - 0.8\sin\Omega - 25.1t\cos\Omega \\ & -1.7t\cos(2F - 2D + 2\Omega).\end{aligned} \quad (1)$$

While these effects are small, they are systematic, not random, and should therefore be included in an improved theory according to the discussions inside the JWG, but preferably along with other major updating of the models for the final users' convenience.

5. The precession model has been re-assessed as well. On the theoretical side, a set of minor contributions to the longitude rate has been revised and their values improved, particularly two contributions gathering respectively the mathematical second order solution component for a non-rigid Earth (Baenas et al. 2017a) and the anelasticity effects on a rotating Earth (Baenas et al. 2017b), the latter effect named as *non-linear* in the Mathews et al. (2002) terminology. Besides, those findings imply that the value of the Earth's dynamical ellipticity, H_d, must be adjusted since the observed precession rate is of course unchanged. The H_d variation is of some ppm and the resulting corrections to nutations, or *indirect* effects, are non-negligible since they approach near 100 µas for certain terms (Baenas et al. 2019).
6. From a more practical perspective, the accuracy of the precession polynomial has been checked by several authors, e.g. Malkin (2014), Liu and Capitaine (2017), Gattano et al. (2016), Belda et al. (2017a). The most recent results show that the offsets and trends of dX and dY deviate from 0 slightly, but significantly, and reach the µas and µas/y levels—i.e. the current precession model may be not 100% accurate although not at a worrying extent. In general, the offsets of dX and dY are >30 µas, the target accuracy recommended by the IAG Global Geodetic Observing System (GGOS). In contrast, the uncertainties of rates are rather compliant with the GGOS goals.
7. The free core nutation (FCN) is a major source of unexplained variance of the CPO. FCN models have never been included in the IAU and IAG/IUGG theories of Earth rotation, since their excitation mechanism is closer to that of polar motion than to the astronomically forced nutations. Its modeling has been addressed by different approaches; some of them are new, like convolution (Chao and Hsieh 2015) and numerical integration with excitation functions that may include geomagnetic jerks (GMJ) (Vondrák and Ron 2015, 2019). Besides, new accurate empirical models have been derived by Belda et al. (2016) using a sliding window approach with high temporal resolution, therefore closer to Malkin's methods (2013, 2014, 2016) than to Lambert's (2007). Furthermore, FCN models are dependent on the EOP solutions used in their derivation at the current accuracy level (Malkin 2017). Summarizing, the WRMS of the CPO residuals can be reduced near the vicinity of 100 µas by using suitable correction models.

As for polar motion (PM) and UT1, the advances have been also quite impressive.

1. The general theory that is the backbone of IAU2000 has been extended from symmetric to triaxial two- and three-layer Earth models in a series of papers that starts with Chen and Shen (2010). The most recent is by Guo and Shen (2020), who consider the elasticity of the solid inner core (SIC) as well as viscoelectromagnetic couplings between the fluid outer core and elastic inner core and mantle, and the pressure and gravitational coupling acting on inner the SIC. Frequency-dependent responses of PM to excitations have been further investigated by Chen et al. (2013a,b).
2. The S1 signal, considered anomalous for long, has been further explained. Schindelegger et al. (2016, 2017) showed that the S1 LOD estimate (6 µs) determined from VLBI is in agreement with atmosphere-ocean excitation estimates.
3. The analyses of PM and UT1 benefit to a remarkable extent from the improvement of their excitation function models. For instance, we can cite the continuous archive of the NCEP-CAR reanalyses for excitations of PM and UT1 at the IERS Special Bureau (SB) for the Atmosphere, applying the methodology introduced by Salstein et al. (1993) and Zhou et al. (2006) to the new input data; the new release of the oceanic ECCO model by Quinn et al. (2019), available from the IERS SB for Oceans; the time series of operational effective angular momentum (AM) functions provided by the ESM (Advanced Earth system modelling capacity) at GFZ in Potsdam (e.g. Dill and Dobslaw 2019; Dill et al. 2019), which include 3h atmospheric (AAM), 3h oceanic (OAM), 24h hydrologic (HAM) and 24h sea-level (SLAM) contributions, etc.
4. The numerical integration of Brzeziński's broad-band Liouville equations (Brzeziński 1994) with geophysical excitations like OAM, AAM from several sources has shown that all the EOP are sensitive to those excitations. The agreement with observations is improved when GMJ are considered (Vondrák and Ron 2016). The method has

been applied to derive new estimates of the periods and Q of the Chandler Wobble (CW) and FCN (Vondrák et al. 2017, 2019).

5. More insight into the hydrological effects on PM, taking into account time-varying gravity, has been provided by the research performed at the Polish Space Research Centre (e.g. Wińska and Śliwińska 2019; Śliwińska and Nastula 2019).

Regarding the EOP determination, the advances have been also illuminating. A few of them are:

1. In VLBI data analysis, the usual session-wise solutions can be complemented with global solutions (Belda et al. 2017a) and with the simultaneous determination of "quasi instantaneous" terrestrial reference frames (TRFs) and EOP by Kalman filter and more sophisticated methods (Abbondanza et al. 2017; Soja et al. 2016a,b, 2018a).
2. In the search for potential sources of discrepancies between theory and observations, several experiments have assessed the impacts of the variations of reference frames or processing strategies. It has been shown that different realizations of TRFs or data processing strategies can give rise to not negligible differences in the EOP determination at the GGOS level of accuracy (see e.g. Wielgosz et al. 2016; Heinkelmann et al. 2017, Belda et al. 2017b; Soja et al. 2018b). This is not irrelevant from the theoretical perspective since theory must explain observations and help predictions, but it does not accommodate to the actual observational environment as tightly as desirable in some aspects. For instance, the reference systems used in the derivation different sets of fundamental equations that the EOP must satisfy, with IAU2000 among them, have been never realized (Chen and Shen 2010; Ferrándiz et al. 2015) although the analysis of observations is carried out for specific realizations of reference frames—e.g. the current conventional EOP 14C04 series (Bizouard et al. 2019) links the ITRF14 (Altamimi et al. 2016) and the ICRF2-ext2 (Fey et al. 2015), to be superseded by the ICRF3 recently approved by IAU and IAG/IUGG.
3. There is also a wide agreement on the need of improving the consistency between the terrestrial and celestial (CRF) reference frames and the rotation relating them given by the EOP. This is a major challenge since TRFs and CRFs and realized independently and using data that cover different time spans. Better consistency can be expected from simultaneous realization of those three elements (Heinkelmann et al. 2017), but that is not easy and a deeper insight into the meaning of the realizations resulting from each procedure is required; it is well-known by theory that the definitions of EOP and TRFs are intrinsically related, but can be done in infinitely many ways (Munk and McDonald 1960). In the term 2019–2023 a dedicated IAG/IAU/IERS JWG on Consistent realization of TRF, CRF, and EOP will tackle the problem.

Besides those findings, there are many valuable research works still in progress; a non-comprehensive list was included in the said JWG final report. Because of their theoretical interest, let us comment only some work related to the improvement of the Earth's interior modeling. For instance, the evaluation of the ellipticity of the inner layers, and the theoretical estimates of the free periods, particularly Chandler's, have been brought closer to their observed values (Huang et al. 2019; Liu et al. 2019); more insight has been got into effects related to the inner gravitational interactions among the Earth's components (Chao 2017; Rochester et al. 2018).

3 Conclusion and Outlook

From all those findings and research in progress, it is possible to conclude that at least a partial update of the Earth rotation theory is needed and feasible within a reasonable time span. Not only accuracy but also consistency among EOP, ICRF, and ITRF has to be improved. The extent of the renewal is to be determined in the forthcoming years, since neither any complete new theory nor any integrated set of corrections aimed at improving the theories in force have been published or proposed so far. Future potential candidates should be thoroughly validated with observations and compared to the current theories regarding accuracy and consistency before taking decisions on the update.

Those conclusions were the basis of the Resolution 5, on *Improvement of the Earth's Rotation Theories and Models*, approved by the 2019 IAG General Assembly. The IAG resolved:

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

Finally, a new working group was created by the IAG to help in the implementation of these recommendations.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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