Report on activities of the IAU/IAG Joint Working Group on Theory of Earth Rotation, Sub-WG 2 “Polar motion and UT1”

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Presented at

Journées 2014 “Systèmes de Référence Spatio-Temporels”

“Recent developments and prospects in ground-based and space astrometry”

22–24 September 2014, Pulkovo Observatory, St. Petersburg, Russia

IAU/IAG Joint Working Group on Theory of Earth Rotation

Sub–Working Group 2 “Polar motion and UT1”

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Objectives of the report

- to summarize the status of the current theories of Earth rotation
  - long periods,
  - diurnal periods,
  - geophysical excitation;
- to give a list of selected recent publications contributing to the progress in the field;
- to point out some unsolved problems which should be discussed by Sub–WG2.

Theory of polar motion and UT1 variation: definitions and current convention

Definition, classical approach

A change of direction of the Earth's rotation axis with respect to the Earth-fixed reference system (TRS) is called *polar motion* while a change with respect to the space-fixed reference system (CRS) is called *nutation*

UT1 – *universal time*, is a parameter used to measure the angular speed of rotation.

Current convention: The reference pole for polar motion and nutation is not the instantaneous rotation pole but the conventional pole called the *Conventional Intermediate Pole* (CIP).

The equatorial component of rotation is split up into polar motion and nutation based on the frequencies of perturbations (IERS Conventions 2010)

- all perturbations with space-referred periods longer than 2 days are treated as nutation and all other as polar motion,
- hence, the frequency domain of nutation, expressed in the CRS, is
  $$(-0.5\Omega, +0.5\Omega),$$
  where Ω denotes the diurnal sidereal frequency,
- the frequency domain of polar motion, expressed in the TRS, is
  $$(-\infty, -1.5\Omega) \cup (-0.5\Omega, +\infty)$$
  therefore PM comprises both the low-frequency and the high-frequency components.

Convention vs. theory

To the first order, the coordinates of the conventional pole are related to those of the instantaneous rotation pole by a simple differential relationship, therefore

$\Longrightarrow$ the equation of motion can be transformed to the form using the reported parameters as variables.

As far as we are interested in scientific aspects of Earth rotation, a more adequate decomposition into polar motion and nutation is based on the excitation mechanism

- astronomical effects (due to the lunisolar and planetary torques upon the rotating Earth) are considered as nutation;
- geophysical effects (due to the mass and angular momentum exchanges between the solid Earth and its liquid envelopes) are considered as polar motion.

Our proposal is to follow the last decomposition in the discussion of the WG ThER, that means

- astronomical components of PM, associated with the multipole structure of the Earth's inertia tensor (size up to 0.1 mas), should be considered by the S-WG 1 "Precession/nutation";
- geophysical effects in nutation, mainly the FCN and S1 signals (size up to 0.5 mas), should be considered by the S-WG 2 "Polar motion and UT1".

Development of the theory, selected contributions

- (Munk and MacDonald, 1960) introduced the perturbation scheme into the Liouville equations and derived the linear equations of Earth rotation;
- Wahr (1982, 1983, 2005) developed a more general linear equations of motion based on the earlier models of Hough (1895), Dahlen (1976), Smith and Dahlen (1981);
- Gross (2007; 2014) recomputed the coefficients of the equations of Wahr using the most up-to-date values of geodetic and geophysical constants. He proposed a hybrid theory in which:
    1. the body tide Love number k_2 has been replaced with a wobble-effective Love number k_w computed from normal mode theory in order to more accurately model the structure of the core and the deformation of the crust and mantle;
    2. the theoretical Chandler wobble frequency has been replaced with its observed value in order to account for the effects of mantle anelasticity since no adequate theory of these effects currently exists.

Gross R. S., 2007, Earth rotation variations - long period. In: *Herring T. A. (ed.) Physical Geodesy: Treatise on Geophysics, Vol. 3*, Elsevier, Oxford, pp. 239–294.

Gross R. S., 2014, Theory of Earth rotation variations, *presented at the VII Hotine-Marussi Symposium in 2009, to be published in: N. Sneeuw (ed.), IAG Symposia Series Vol. 142*, Springer-Verlag, New York, 2014, in press.

Theory of polar motion and UT1 variation, long periods

Gross (2014) summarized the assumptions underlying the linearized theory of Earth rotation:

1. the perturbing excitations are small with $h_\ell(t) \ll \Omega C$ and $I_{\ell j}(t) \ll C$;
2. the rotational response of the Earth is small with $m_\ell(t) \ll 1$;
3. the induced relative angular momentum of the core is linearly related to changes in the rotation of the solid Earth;
4. the induced deformations of the mantle, crust, and oceans are linearly related to the changes in rotation;
5. the rotating terrestrial reference frame is the Tisserand mean-mantle frame;
6. the oceans stay in equilibrium as the rotation changes;
7. the core is uncoupled from the mantle;
8. the crust, mantle, and core are axisymmetric;
9. the rotational variations occur on time scales much longer than a day;
10. the coupling between the components of rotation introduced by a non-uniform ocean are negligibly small and hence can be ignored to first order;
11. the difference in the oceanic Love number for the two components of PM is negligibly small and hence to first order can be replaced by a mean oceanic Love number for the wobble.

Theory of polar motion and UT1 variation, long periods

Gross (2014) considered the following extensions of the theory of the Earth's rotation to be the most important at the moment

- the theory should describe the rotation of a triaxial body with a fluid core;
- the theory should account for the non-equilibrium response of the oceans which is particularly important at the fortnightly period.

Several promising advances in modeling theory of Earth rotation have been reported recently. We can mention here the following 3 papers by Wei Chen and his co-workers:

- Chen and Shen (2010) have developed a theory of the Earth's rotation that accounts for the triaxiality of the mantle and core, the anelasticity of the mantle, and dissipation in the oceans;
- Chen et al. (2013a) attempted to improve the polar motion theory by developing refined frequency-dependent transfer functions with the most recent models for ocean tides, the Earth's rheology, and core-mantle coupling;
- in the associated paper, Chen et al. (2013b) applied the frequency-dependent transfer function to compare the geophysical excitations derived from various global atmospheric, oceanic, and hydrological models.

Chen W., Shen W., 2010, New estimates of the inertia tensor and rotation of the triaxial nonrigid Earth, *J. Geophys. Res. 115:B12419, doi:10.1029/2009JB007094*.

Chen, W., J. Ray, J. Li, C. Huang, and S. Shen, 2013a, Polar motion excitations for an Earth model with frequency-dependent responses: 1. A refined theory with insight into the Earths rheology and core-mantle coupling, *J. Geophys. Res. Solid Earth, doi:10.1002/jgrb.50314*.

Chen, W., J. Ray, S. Shen, and C. Huang, 2013b, Polar motion excitations for an Earth model with frequency-dependent responses: 2. Numerical tests of the meteorological excitations, *J. Geophys. Res. Solid Earth, doi:10.1002/jgrb.50313*.

Other interesting recent contribution is by Bizouard and Zotov (2013):

- they have developed a theory of the Earth's rotation that accounts for the triaxiality of the Earth and includes the effect of asymmetric, but still equilibrium, oceans.

Bizouard C., Zotov L., 2013, Asymmetric effects on polar motion, *Cel. Mech. Dyn. Astron., Vol. 116, Issue 2, pp. 195–212*.

The following problems, put forward by Wei Chen and Jim Ray (e-mail message), concern the differences between the terrestrial system (ITRS) and its realization (ITRF):

- the ITRF is geocentric in a long-term average sense (CF frame) whereas the ITRS is instantaneously geocentric, following the resolutions of the IAU and IUGG;
- the ITRS is also geocentric in the general relativistic sense and the appropriate timescale (TCG) and SI units are recommended by the Unions. However, for very practical reasons, times related to terrestrial time TT (e.g., UTC) are used by all geodetic analysts.

Theory of polar motion and UT1 variation, diurnal periods

Development of the theory

- Sasao and Wahr (1981) showed that diurnal atmospheric and oceanic loading of the Earth's surface provide an efficient excitation mechanism of the free core nutation (FCN) signal. They developed dynamical model of diurnal excitation including both the FCN and the Chandler wobble (CW) resonances.
- A new dynamical model of the excitation of nutation by geophysical fluids has been recently published by Koot and de Viron (2011).

Koot L., de Viron O., 2011, Atmospheric contributions to nutations and implications for the estimation of deep Earth's properties from nutation observations, *Geophys. J. Int. 185:1255–1265*.

The corresponding dimensionless response coefficients a_p, a_w appearing in the broad-band Liouville equation of polar motion (Brzeziński, 1994), expressing how sensitive is the FCN mode relative the CW mode to the excitation by the mass and motion terms of the atmospheric and oceanic angular momenta, are the following:

Sasao and Wahr (1981): $a_p = 9.509 \times 10^{-2}$, $a_w = 5.489 \times 10^{-4}$;

Koot and de Viron (2011): $a_p = 9.200 \times 10^{-2}$, $a_w = 2.628 \times 10^{-4}$.

Theory of polar motion and UT1 variation, geophysical excitation

The influence of geophysical fluids, the atmosphere, the oceans and the land hydrosphere, is a dominant source of the excitation of polar motion and plays an important role in driving variations in UT1; see (Gross, 2009) for review. Hence modeling the dynamics of geophysical fluids and comparison with the observed polar motion and UT1 is of crucial importance for understanding variability of Earth rotation at time scales from subdaily to decadal.

The global atmospheric, oceanic and hydrological angular momentum (AAM, OAM, and HAM, respectively) data are estimated and made available for research purposes by the IERS and its special bureaus. Let us mention some important developments in this field:

- the AAM series are estimated by several meteorological agencies on regular basis since almost 3 decades
  - some of the series begin around 1950,
  - particularly important are the multidecadal reanalysis series offering several advantages over the routine operational series,
  - as a rule, the sampling interval of AAM is 6 hours that enables studies of excitation at periods from daily to decadal;
- the mass redistribution within the surficial geophysical fluids can also be estimated from the time variations of gravity measured by the satellite experiment GRACE.

Geophysical excitation of Earth rotation, important problems to be addressed in the discussion:

- Excitation of seasonal variations
  - the wind term of AAM is a dominant seasonal contribution to UT1, while the pressure term of AAM is the most important factor in driving the seasonal polar motion;
  - adding OAM improves in most cases the agreement with the observed (geodetic) excitation of polar motion;
  - unfortunately, there are still large differences between the HAM models, therefore combining HAM with AAM and OAM at seasonal frequencies is not conclusive;
  - also the GRACE-based gravimetric excitation series are different and do not close the seasonal excitation balance of polar motion.
- Excitation balance of the free signals in polar motion, the free core nutation FCN and the Chandler wobble CW; that includes also improvement of the FCN and CW parameters.
- Contribution of diurnal and subdiurnal atmospheric tides to polar motion, UT1 and nutation, particularly modeling of the S_1 tide.
- Improvement of the model of the ocean tide contributions to all 3 components of Earth rotation, polar motion, UT1 and precession/nutation.