REPORT ON ACTIVITIES OF THE SUB-WORKING GROUP 2 “POLAR MOTION AND UT1” OF THE IAU/IAG JOINT WORKING GROUP ON THEORY OF EARTH ROTATION

A. BRZEZIŃSKI[1,2]
[1] Inst. of Geodesy and Geodetic Astronomy, Warsaw University of Technology, Warsaw, Poland
[2] Space Research Centre, Polish Academy of Sciences, Warsaw, Poland
e-mail: alek@cbk.waw.pl

ABSTRACT. This is the mid-term report of the Sub-WG2. The main objectives are (1) to summarize the status of the current theories of Earth rotation focusing on variations with long and diurnal periods, and on modeling of geophysical excitations; (2) to point out some unsolved problems which should be discussed by the Sub-WG2.

1. INTRODUCTION

The purpose of this report is to define the framework for discussion of the S-WG2. We start from description of the definitions and current conventions regarding polar motion and UT1, and end up with proposal of splitting up the scope of considerations between S-WG1 and S-WG2. Section 3 is devoted to the review of the theory of polar motion, giving the list of simplifying assumptions and defining the improvements of the theory which should be done first. We also mention some selected recent publications contributing to the progress in the theory. The last part of report is devoted to the subject of geophysical excitation. Due to the limited space of the paper, we give only a brief review of the current situation and point out some problems which should be considered by the S-WG2.

2. POLAR MOTION AND UT1 VARIATION, DEFINITIONS AND CONVENTIONS

According to the classical definition, a change of direction of the Earth’s rotation axis with respect to the Earth-fixed reference system is called *polar motion* while a change with respect to the space-fixed reference system is called *nutation.* The *universal time UT1* is a parameter used to measure the angular speed of rotation. However, according to the 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). Also UT1 expresses the rotation rate about the CIP axis. 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 celestial system, is the interval $(-0.5\Omega, +0.5\Omega)$, where Ω denotes the mean angular frequency of diurnal sidereal rotation. The frequency domain of polar motion, expressed in the terrestrial system, is $(-\infty, -1.5\Omega) \cup (-0.5\Omega, +\infty)$ therefore polar motion comprises both the low-frequency and the high-frequency components.

To the first order, the time variations of the terrestrial coordinates of the CIP are related to those of the instantaneous rotation pole by a simple differential relationship, therefore the equation of polar motion can be transformed to the form using the reported parameters as variables.

As far as we are interested in the 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 to the WG Chairs and members is to follow the last decomposition in the discussion of the WG, that means

- astronomical components of polar motion, which are associated with the multipole structure of the Earth's inertia tensor (size up to 0.1 mas), should be considered by the S-WG1 "Precession/nutation";
- geophysical effects in nutation, mainly the FCN and S1 signals (size up to 0.5 mas), should be considered by the S-WG2 "Polar motion and UT1"; see the next section.

3. THEORY OF POLAR MOTION AND UT1 VARIATION

Long periods. The investigations of polar motion and UT1 variation are usually based on the linear equations of Earth rotation, developed originally by Munk and MacDonald (1960) who introduced the perturbation scheme into the Liouville equations. Later on, Wahr (1982, 1983, 2005) derived a more general linear equations of motion based on the earlier models of Hough (1895), Dahlen (1976), and Smith and Dahlen (1981). Gross (2007, 2015) 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; and 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.

The linear equations of Earth rotation are expressed by the excitation variables: h_ℓ which are components of the relative angular momentum vector $\vec{h} = [h_1\ h_2\ h_3]^T$ defining the motion term of excitation, and $c_{\ell j}$ – the incremental components of the Earth's inertia tensor defining the mass term of excitation, and by the rotational variables m_ℓ related to the rotation vector $\vec{\omega} = \Omega\,[m_1\ m_2\ 1{+}m_3]^T$. Gross (2015) summarized the simplifying assumptions underlying the linearized theory of Earth rotation as follows

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

With the current accuracy of determination of the Earth orientation parameters, which is at the level of 0.05 mas corresponding to 1.5 mm, some of those simplifications are no more adequate. Gross (2015) proposed the following improvements of the theory of Earth rotation to be considered first

- 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 Earth rotation, which are along those guidelines, have been reported recently. We should mention here the three papers by Wei Chen and his co-workers: 1) 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; 2) 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.

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

Diurnal periods, the free core nutation resonance. 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). 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): $a_p = 9.200 \times 10^{-2}$, $a_w = 2.628 \times 10^{-4}$.

The difference of the two estimates of the pressure term coefficient a_p is small, at the level of 3%, and much larger in case of the wind term coefficient. The new value of a_w is about two times smaller than the old one. Note, however, that the contribution of the wind term has been usually considered small and neglected in the FCN excitation studies.

Geophysical excitation functions. 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 (2007) 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 have been estimated and made available for the users by the International Earth Rotation Service (IERS) and its special bureaus.

The AAM series have been estimated by several meteorological agencies on regular basis since almost 3 decades, and 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 first OAM series were computed in the middle of 1990-ties, but only recently three OAM series have been updated on regular basis. Two of them are produced by the Jet Propulsion Laboratory, USA, with daily sampling, and one by the GeoForschungsZentrum (GFZ) Potsdam, Germany, with 6-hourly sampling.

Several HAM series based on different hydrology models have been published so far. Only one HAM series, estimated by the GFZ, has been regularly updated and made available for users via the IERS website. Note however that in contrast to AAM and OAM, the contribution from HAM is expected to be important only at seasonal and lower frequencies.

Adding OAM improved 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 still far from being conclusive.

The mass redistribution within the surficial geophysical fluids can also be estimated from the time variations of gravity measured by the satellite experiment GRACE. Hence, the GRACE-based "gravimetric" excitation function can be considered as an equivalent of the mass term of AAM+OAM+HAM. That makes it useful for studying excitation of polar motion, where the contribution from the mass term is dominant. However, the low time resolution of GRACE data (1 month) and the limited period of data (from 2002 up to now), impose a frequency limit on its application for the excitation studies. Also various estimates of the GRACE-based excitation series are still not fully consistent with each other and do not close the seasonal excitation balance of polar motion.

4. DISCUSSION

Here we attempt to list some important problems which should be addressed in the discussion of S-WG2:

- Improving excitation balance of the seasonal variations, particularly in polar motion. That includes also improvements of the estimation of geophysical and gravimetric excitation functions.
- Explaining the excitation mechanism of the free signals in Earth rotation, the free core nutation FCN and the Chandler wobble CW; that includes also improvement of the FCN and CW parameters.
- Estimation of the 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.

Additional problems, put forward by Wei Chen and Jim Ray, 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.

We should add here that also equations of motion which are used in practice are all derived under the assumption that the underlying Cartesian system is instantaneously geocentric.

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