ATMOSPHERIC AND OCEANIC EXCITATION OF EARTH ROTATION

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ABSTRACT. All kinds of mass variations in the Earth's surface fluids accordingly change the tensor of inertia, while moving particles in wind or current flows induce relative angular momentum. Via interaction with the solid Earth, both matter and motion effects cause fluctuations in the direction of the Earth's rotation axis, signified as polar motion, as well as changes in the angular velocity, expressed, e.g. in terms of length of day (LOD). This paper gives an overview of the most important atmospheric and oceanic effects on polar motion and LOD from subdaily to multi-annual time scales and discusses the variable agreement between the observational evidence of excitation effects and their corresponding geophysical models. Special emphasis, including a brief synopsis of recent results, is placed on tidal phenomena and in particular on those caused by short period ocean tides.

1. EARTH ROTATION OBSERVATION AND MODELING

Variations in the magnitude and orientation of the Earth rotation vector are conventionally quantified as Earth orientation parameters (EOP). These EOP comprise the length of day (LOD) or dUT1 (UT1-UTC), representing irregularities in the Earth rotation speed, the pole coordinates x_p and y_p, determining the orientation of the reference axis w.r.t. the terrestrial reference system, and X and Y, which are the coordinates of the CIP (Celestial Intermediate Pole) in the celestial reference system. Strictly speaking, the EOP do not represent the Earth rotation axis, but the observed axis of reference, which is the axis of the CIP by convention. The subset of parameters referring to the terrestrial motion of the CIP, the pole coordinates and LOD or dUT1 is often denoted as Earth rotation parameters (ERP).

The EOP are regularly monitored by means of space geodetic techniques and published by the IERS (International Earth Rotation and Reference Systems Service) as continuous time series, combined from the results of different measurement techniques. The measurements of Earth rotation provide only the purely geometric information about the deviation of the rotation axis from a mean state, without permitting the distinction between different causes of the observed effects.

The most prominent and common formulation to investigate the driving mechanisms of Earth rotation variations is the angular momentum approach. In this approach, the Earth with oceans and atmosphere is considered as one closed system, the total angular momentum of which is conserved. If one of the subsystems, such as the atmosphere, undergoes a change of its associated angular momentum, the solid Earth experiences a coincident variation of its proper angular momentum, leading to a corresponding variation of the Earth rotation vector. Such variations of angular momentum of single subsystems are expressed using so-called angular momentum functions (AMF). The AMF are composed of two parts, a mass term containing changes of the tensor of inertia due to mass redistribution and a motion term representing relative angular momentum caused by relative particle motion where one mass element is immediately replaced by another after its dislocation.

Atmospheric and oceanic excitation of Earth rotation are studied on the basis of numerical models, which provide certain state variables of the respective fluid for distinct points in time on a global grid. The quantities of special interest are vertical density or surface pressure, respectively, and wind velocities in case of the atmosphere and ocean bottom pressure as well as current velocities in case of the oceans. Yet in oceanic excitation there is usually a distinction between non-tidal effects and tidal effects, which are mostly treated separately. The parameters of ocean tide models relevant to Earth rotation are tidal height variations and tidal current velocities. Atmospheric, oceanic and ocean tidal angular momentum functions are derived from the mentioned model outputs by global integration.

2. OBSERVED VS. MODELED EARTH ROTATION VARIATIONS - FORMALISM

Basically there are two ways to compare ERP observed with space geodetic techniques to Earth rotation variations predicted from geophysical modeling. One option is to transform the ERP to so-called geodetic excitation and then compare them to the geophysical excitation given in terms of AMF. The second possibility is to express the AMF in terms of Earth rotation parameters. At least regarding polar motion this is a somewhat more sophisticated procedure because it involves the solution of a convolution integral. The most important formulae describing both methods are provided below. The AMF as they are quoted here are actually called effective angular momentum functions (EAMF), since they consider the non-rigidity of the Earth. The components of polar motion are in the following equations denominated p_x and p_y (equivalent to x_p and y_p). They represent the polar motion of the CIP, while the Earth rotation vector is composed of $\Omega \cdot (m_1, m_2, 1 + m_3)$, with the nominal angular velocity of the Earth Ω. $\hat{\sigma}_{CW}$ is the complex angular frequency of the Chandler Wobble. LOD_0 stands for the nominal length of the solar day of 86400 s. $\hat{\chi}(t) = \chi_1 + \mathrm{i}\chi_2$ represents equatorial excitation.

Polar motion of the CIP:

$$\hat{p}(t) = p_x(t) - \mathrm{i}p_y(t) \tag{1}$$

Polar motion of the rotation pole:

$$\hat{m}(t) = \hat{p}(t) - \frac{\mathrm{i}}{\Omega}\frac{\mathrm{d}\hat{p}(t)}{\mathrm{d}t} \tag{2}$$

Excess length of day:

$$\frac{\delta\mathrm{LOD}(t)}{\mathrm{LOD}_0} = -\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{dUT1}(t) = -m_3 \tag{3}$$

Geodetic excitation:

$$\hat{\chi}(t) = \hat{p}(t) + \frac{\mathrm{i}}{\hat{\sigma}_{CW}}\frac{\mathrm{d}\hat{p}(t)}{\mathrm{d}t} \tag{4}$$

$$\chi_3(t) = \frac{\delta\mathrm{LOD}(t)}{\mathrm{LOD}_0} \tag{5}$$

The variable components of the tensor of inertia are $\hat{c} = c_{13} + \mathrm{i}c_{23}$ and c_{33}. The vector of relative angular momentum is called h with the elements $\hat{h} = h_1 + \mathrm{i}h_2$ and h_3. C signifies the polar moment of inertia and A' the average of the equatorial moments of inertia. C_m is the polar moment of inertia of the mantle only. The numerical factors in the EAMF are taken from Gross (2007).

Equatorial EAMF:

$$\hat{\chi}(t) = \frac{1.100 \cdot \hat{c}(t)}{(C - A')} + \frac{1.608 \cdot \hat{h}(t)}{\Omega \cdot (C - A')} = \hat{\chi}^{mass} + \hat{\chi}^{motion} \tag{6}$$

Axial EAMF:

$$\chi_3(t) = 0.748\frac{c_{33}(t)}{C_m} + 0.998\frac{h_3(t)}{C_m\Omega} = \chi_3^{mass} + \chi_3^{motion} \tag{7}$$

Geophysical excitation in terms of ERP:

$$\hat{p}(t) = e^{\mathrm{i}\hat{\sigma}_{CW}t}\left(\hat{p}(0) - \mathrm{i}\hat{\sigma}_{CW}\int_0^t \hat{\chi}(\tau)e^{-\mathrm{i}\hat{\sigma}_{CW}t}d\tau\right) \tag{8}$$

$$\delta\mathrm{LOD}(t) = \chi_3(t) \cdot \mathrm{LOD}_0 \tag{9}$$

The prevailing procedure of comparison is to express atmospheric and oceanic effects as well as ERP observations in terms of excitation, i.e. using Equations (4)–(7).

3. NON-TIDAL EFFECTS OF ATMOSPHERE AND OCEANS

The following paragraph provides a chiefly graphical overview of the most important non-tidal atmospheric and oceanic effects in polar motion and LOD on seasonal and intraseasonal time scales. The numbers shown in the figures were extracted from Gross et al. (2003, 2004). The geophysical excitation investigated therein is derived from atmospheric angular momentum based on data from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis project and from oceanic angular momentum calculated from the ECCO (Estimating the Circulation and Climate of the Ocean) consortium's simulation of the general circulation of the oceans. The observed ERP variations are the COMB2000 series, which stem from a combination of Earth rotation measurements taken by the techniques of optical astrometry, Lunar and Satellite Laser Ranging, Very Long Baseline Interferometry and Global Navigation Satellite Systems.

Seasonal variations are subdivided into annual, semiannual and terannual periods. The term intraseasonal covers all periodic and irregular phenomena from four days to one year, except seasonal fluctuations. Seasonal effects are plotted in terms of excitation amplitudes, whereas intraseasonal effects are given in percent of variance explained (10).

$$\text{variance explained} = 100\% \times \frac{var(obs) - var(obs - model)}{var(obs)} \tag{10}$$

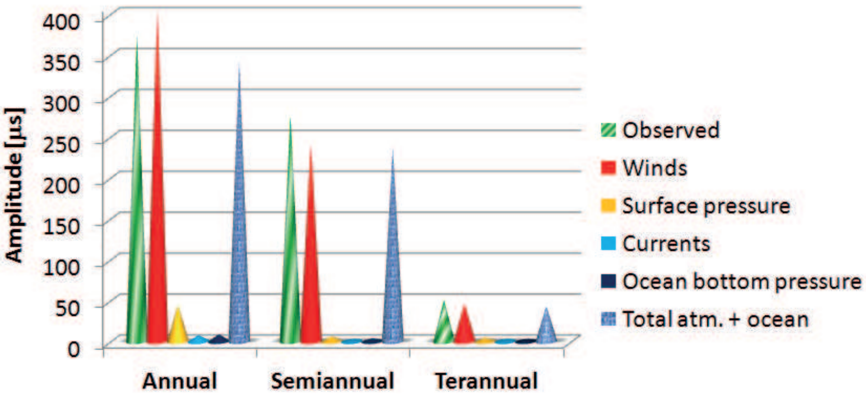


Figure 1: Seasonal excitation of LOD

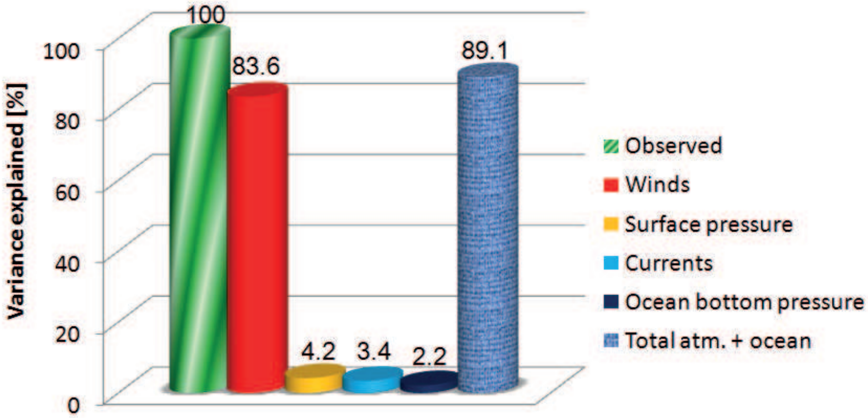


Figure 2: Intraseasonal excitation of LOD

Figures 1 and 2 display diagrams of seasonal and intraseasonal excitation in the axial component or in LOD, respectively. The plots show the magnitude and variance explained of the geodetic excitation (observed) and of atmospheric excitation, split into a wind and surface pressure portion, and oceanic excitation, divided into a current and ocean bottom pressure term. Figures 3 and 4 contain the same effects for the equatorial components or polar motion excitation, respectively.

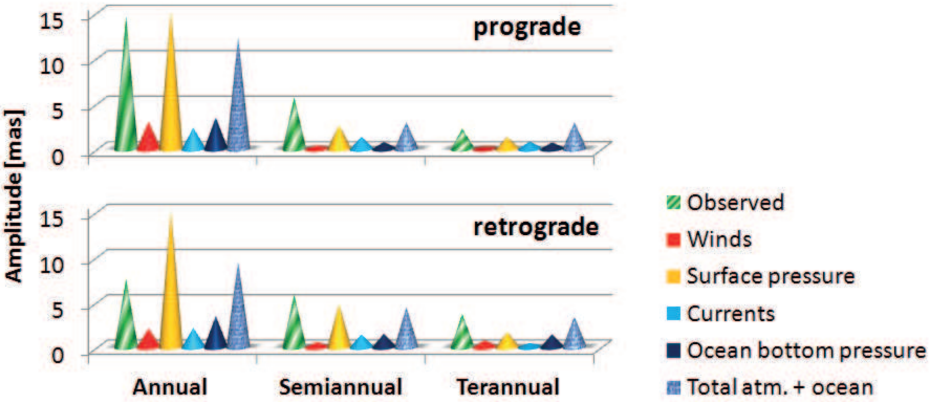


Figure 3: Seasonal polar motion excitation

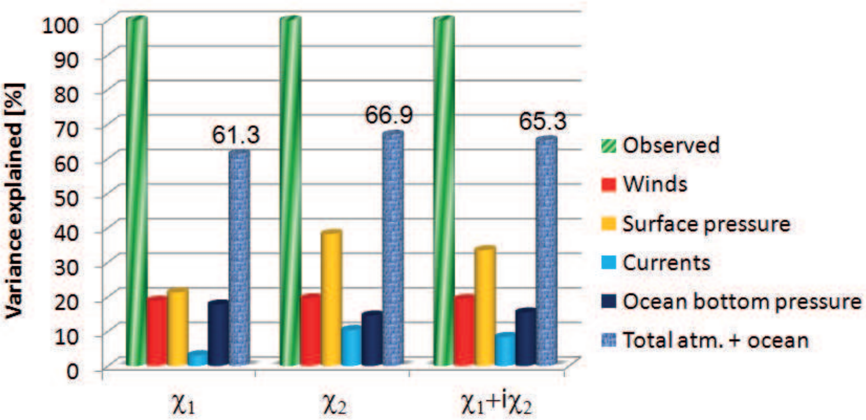


Figure 4: Intraseasonal polar motion excitation

4. TIDAL EFFECTS OF ATMOSPHERE AND OCEANS

As a completion to Section 3, where only non-tidal atmospheric and oceanic effects were treated, this section deals with the influence of tides of the atmosphere and the oceans on Earth rotation. Generally, the term "tidal" implies phenomena which are caused by the tidal forces exerted on solid Earth, oceans and atmosphere by the Moon and the Sun. More specifically, these effects are called gravitational tides in contrast to so-called radiational tides. The latter are caused by the diurnal and annual solar heating cycle of the atmosphere and oceans. In the case of Earth rotation excitation the impact of the radiational atmospheric tides is much more dominant than the effect of gravitational tides in the atmosphere. Concerning the oceans the size of the radiational tides is almost negligible compared to the gravitational ocean tides.

The following Figures 5 and 6 provide a compilation of tidal effects in universal time and polar motion broken down into period groups. Tides of the atmosphere occur at diurnal and semidiurnal periods with the smallest amplitudes. Ocean tides are present in the high as well as in the low-frequency range with periods up to 18.6 years. Solid Earth tides affect LOD or dUT1, respectively, at the same periods as the long-period ocean tides. The body tides also cause retrograde diurnal polar motion, which however is considered as nutation according to the definition of the CIP, just as well as the retrograde diurnal part of the ocean tidal polar motion.

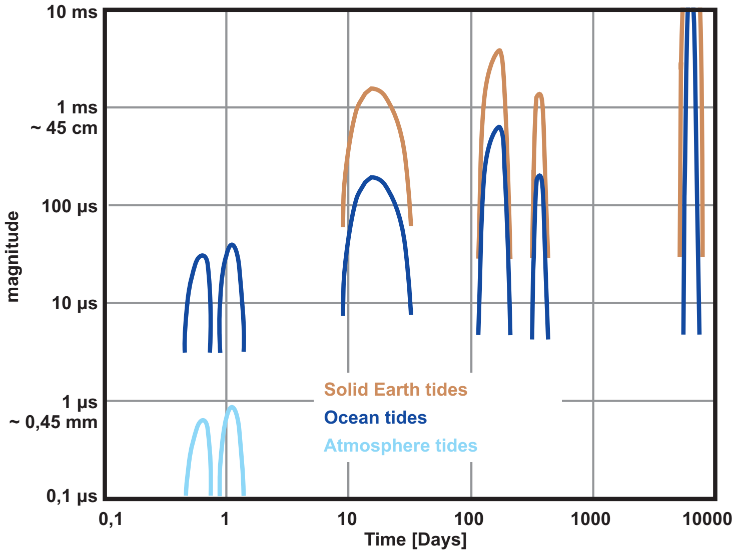


Figure 5: Tidal effects in UT

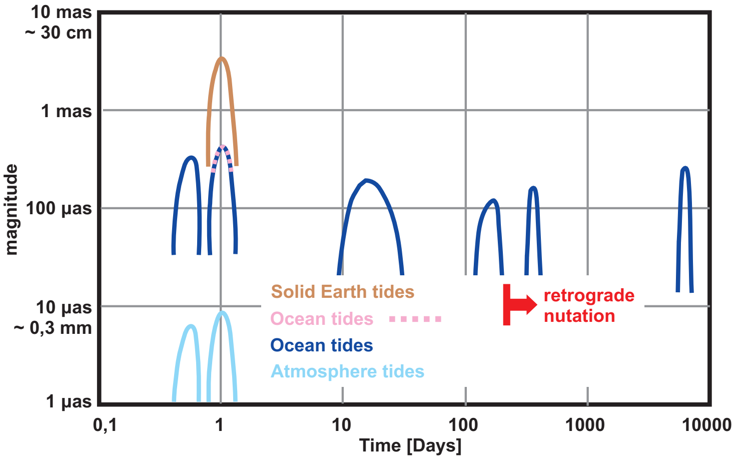
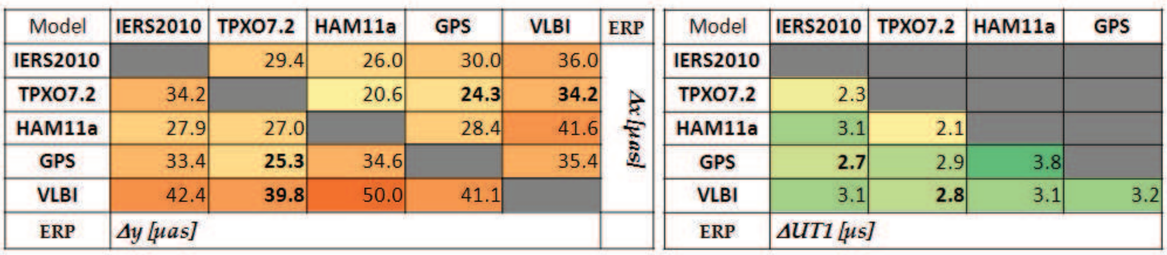


Figure 6: Tidal effects in polar motion

4.1 Diurnal and subdiurnal ocean tidal effects

A still ongoing and somewhat open issue is the budget of diurnal and subdiurnal ERP variations, which are predominantly of tidal origin. High-frequency Earth rotation variations are mainly composed of ocean tidal effects, atmospheric effects and libration. Libration which stands for the effect of the lunisolar torque on the triaxial figure of the Earth, is conventionally accounted for within the processing of space geodetic techniques. The IERS Conventions (2010) also provide a model for ocean tidal ERP variations. However, different studies have shown that there are small but, due to their harmonic nature, detectable and significant discrepancies between the predictions of the IERS model and the observations of the space geodetic techniques. In fact, the IERS model is based on a rather old ocean tide model, wherein data from only a few years of satellite altimetry was assimilated. Since then the accuracy of ocean tide models has increased notably, not least because a much longer time span of altimetry measurements has become available. In the last part of this paper we present the results of a study the aim of which was to probe the performance of new ocean tide models in the prediction of high-frequency ERP. The performance was tested by comparing the root mean square differences of time series calculated from different sources according to the following list: (1) IERS2010: conventions model; (2) TPXO7.2: calculated from TPXO7.2 ocean tide model (Egbert and Erofeeva, 2002); (3) HAM11a: calculated from HAMTIDE11a ocean tide model (Taguchi et al., 2011); (4) VLBI: time series (26 years) derived with Vienna VLBI Software VieVS (Böhm et al., 2011); (5) GPS: time series (13 years) derived with Bernese GPS Software (by courtesy of N. Panafidina, ETH Zürich). The resulting values are assembled in Figure 7.



Model	IERS2010	TPXO7.2	HAM11a	GPS	VLBI	ERP
IERS2010		29.4	26.0	30.0	36.0	*Δx [μas]*
TPXO7.2	34.2		20.6	**24.3**	**34.2**	
HAM11a	27.9	27.0		28.4	41.6	
GPS	33.4	**25.3**	34.6		35.4	
VLBI	42.4	**39.8**	50.0	41.1		
ERP	*Δy [μas]*					

Model	IERS2010	TPXO7.2	HAM11a	GPS
IERS2010				
TPXO7.2	2.3			
HAM11a	3.1	2.1		
GPS	**2.7**	2.9	3.8	
VLBI	3.1	**2.8**	3.1	3.2
ERP	*ΔUT1 [μs]*			

Figure 7: RMS differences in terms of polar motion (left) and dUT1 (right) time series

By purely looking at the numbers we can state that the ERP variations based on TPXO7.2 fit best to the GPS and VLBI values, except for GPS dUT1. Nevertheless, the improvement w.r.t. the IERS2010 model is not really significant.

5. CONCLUDING REMARKS

As to Section 4.1, we conclude that taking most recent ocean tide models alone is not sufficient to close the gap between observed and modeled high-frequency ERP variations. Additionally a careful reassessment of the whole model development procedure will be necessary.

In the area of non-tidal atmospheric and oceanic effects, the excitation budget is closed neither for LOD nor for polar motion as can be deduced from the respective figures. Yet, the observed LOD variations can be explained considerably better with present geophysical models than polar motion. At least in case of seasonal and also intraseasonal LOD variations the pictures reveal clearly that the atmospheric winds are the most important driving agents. For polar motion the surface pressure can be explicitly identified as the major excitation mechanism only w.r.t. seasonal time scales.

6. REFERENCES

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