The 5^{th} IVS General Meeting Proceedings, 2008, p. 314–318

Re-assessment of Ocean Tidal Terms in High-Frequency Earth Rotation Variations Observed by VLBI

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Abstract. Periodic changes in the ocean heights and currents, driven by the tidal acceleration due to the Moon and Sun, are the main cause for diurnal and semidiurnal variations in polar motion (PM) and Universal Time (UT1). It has been shown, e.g. by Gipson [1], that VLBI observations can be used for the derivation of high-frequency Earth rotation variations and hence for the determination of ocean tidal terms. In this study we present a re-processing of 23 years of VLBI observational data with the purpose of obtaining high-resolution Earth Rotation Parameters (ERP). The time series allows for the separation of tidal terms, which differ by only one cycle in 18.6 years. We solved for 77 tidal terms, to gather a VLBI-based estimation of ERP variations occuring in the diurnal and subdiurnal frequency band. The rms differences of the estimated tidal coefficients w.r.t. the conventional model [12] are on the level of 5 μas for PM and 0.5 μs for UT1 variations, respectively.

1. Introduction

The effects of diurnal and semidiurnal ocean tides on the Earth rotation parameters have been subject to many different studies in the past. First predictions of the effects were based on theoretical ocean tide models, derived from Laplace's tidal equations [2]. In [3] derived the effect of the oceanic M2 tide on UT1, using a hydrodynamical model. Brosche et al. published a follow-up study, incorporating effects of more partial tides [4]. Ocean tidal variations were then detected in UT1 data from VLBI observations [5]. They were followed amongst others by Gipson [1] and more recently by Haas and Wünsch [6]. Ultra-short period ERP variations were also seen in measurements of Satellite Laser Ranging (SLR) [7] and Global Positioning System (GPS) e.g. [8, 9]. Ray et al. [10] predicted variations in the Earth's rotation rate induced by ocean tides on the basis of empirical tide models deduced from TOPEX/Poseidon altimetry measurements. A complete compilation of publications on the topic is provided in [11].

The model for diurnal and subdiurnal variations in UT1 and PM, that is recommended in the current IERS (International Earth Rotation and Reference Systems Service) Conventions [12] contains the amplitudes of 71 tidal constituents and was provided by Eanes. This model is an extension of the IERS Conventions model from 1996 calculated by Ray, which consisted of the eight major tidal terms: Q1, O1, P1, K1 in the diurnal band and N2, M2, S2, K2 in the semidiurnal band. The aim of our work was to re-assess the amplitudes and phases of the tidal constituents included in the model, from high-frequency PM and UT1 observed by VLBI. A number of the considered terms are very close in frequency and differ by only one or two cycles in 18.6 years (period of the lunar ascending node). In previous studies it was therefore necessary to introduce constraints on the amplitudes in order to separate these adjacent terms, because the observations only covered shorter time spans. At present we have more than 23 years of VLBI observation data available, permitting us to estimate major tidal terms and sideband terms in an unconstrained solution.

2. ERP Solutions

We generated two VLBI solutions with the VLBI software OCCAM applying the Gauss-Markov model with two different Terrestrial Reference Frames (TRF). In solution "IGG07" the coordinates of the stations were fixed to a recent IGG VLBI-TRF solution. For the second solution called "ITRF05" the current ITRF2005 was employed. The used observations cover the period 1984.0-2007.5. For reasons of consistency we processed the same sessions for the derivation of the ERP as were carefully selected for the IGG TRF solution. PM and UT1 parameters were estimated with hourly resolution without any constraints. Nutation was fixed to the IAU2000 model [12].

3. Analysis of High-Frequency ERP Variations

All low-frequency signals inherent in the ERP series (excited by atmosphere, oceans, solid Earth tides, Chandler Wobble) were removed by subtracting interpolated values of the IERS C04 05 ERP series. The remaining diurnal and semidiurnal variations in PM and UT1 were introduced in a least squares adjustment as pseudo-observations. The formal errors of the observations were introduced as weights for the ERP variations. We estimated the same set of tidal terms that are present in the IERS2003 model, except one sideband of the S1 tide, since the two terms differ by only 2 cycles in 20942 years (period of the solar perigee). Additionally we implemented six "zero" terms at periods where actually no significant tidal signal is expected. The magnitude of this zero terms should give an estimate of the noise level of the observed variations and serve as a kind of validation for the formal errors of the adjustment. Furthermore the terdiurnal term M3 was also included in the estimation. The same series expansion as in the IERS Conventions was used as observation equation (1) for the observed variations in the pole coordinates (ΔX, ΔY) and UT1 ($\Delta UT1$). We use ΔERP representative for each of the parameters:

$$\Delta ERP(t) = \sum_{i=1}^{n} [A_i sin\xi_i(t) + B_i cos\xi_i(t)] \quad with \quad \xi_i(t) = \sum_{j=1}^{5} N_{ij} F_j(t). \quad (1)$$

A_i and B_i denote the cosine and sine coefficients belonging to the tidal wave i, while n specifies the number of tides considered. The time-dependent angle argument $\xi_i(t)$ is built as a linear combination of the five fundamental arguments $F_j(t)$. Each period is specified by a sequence of integer multipliers N_{ij}, with i labeling again the tide [12]. In our study the number of tidal waves n was 77 (70 ocean tidal waves, 6 zero periods and the M3 tide). For better physical understanding the resulting sine and cosine coefficients for ΔX and ΔY were then represented as prograde and retrograde ΔPM amplitudes. This sums up to 111 (43 diurnal prograde, 34 semidiurnal prograde, 34 semidiurnal retrograde) ΔPM terms and 77 (43 diurnal, 34 semidiurnal) $\Delta UT1$ terms. We derived two empirical models from the two ERP solutions, a model called "IGG07" and a second called "ITRF05". Additionally we obtained a third model in order to test the impact of the previously mentioned amplitude constraining, which is in fact not necessary from the mathematical point of view. For this model we used the approach of Gipson [1], where the amplitudes of the terms with very close periods are constrained with the ratio of the corresponding amplitudes in the tidal potential. The constrained adjustment was applied on the IGG07 ERP series only, the resulting empirical model is therefore referred to as "IGG07c".

4. Results and Comparison to IERS2003 Model

The rms difference of coefficients is taken as a measure for the difference between two models. The formalism for the rms difference can be found, e.g., in [8]. Tabl. 1 gives the resulting values for the three empirical models w.r.t. the conventional model IERS2003.

Table 1. Mean rms differences w.r.t. IERS2003

IERS2003	ITRF05	IGG07	IGG07c
ΔPM, μas	5.04	5.06	4.49
$\Delta UT1$, μs	0.52	0.50	0.43

Fig. 1 shows "phasor plots" of the differences w.r.t. IERS2003 for the eight major terms and for S1. The three-fold uncertainty of the adjustment is indicated by the circles. The previously mentioned zero terms were also included in the plot in order to give a visual validation of the formal errors (ΔPM: 2.1 μas, $\Delta UT1$: 0.2 μs). The amplitude of the largest zero term in the diurnal band is 11 μas for ΔPM and 0.8 μs for $\Delta UT1$, in the semidiurnal band the values are 4 μas and 0.3 μs. The estimated amplitudes for the M3 tide are even smaller than the formal errors and cannot be considered as significant. Although S1 is not one of the major ocean tidal terms, the difference for S1 is displayed here, because we expect significant signal in the observations coming from the diurnal atmospheric tide also labeled S1, which is not part of the IERS model.

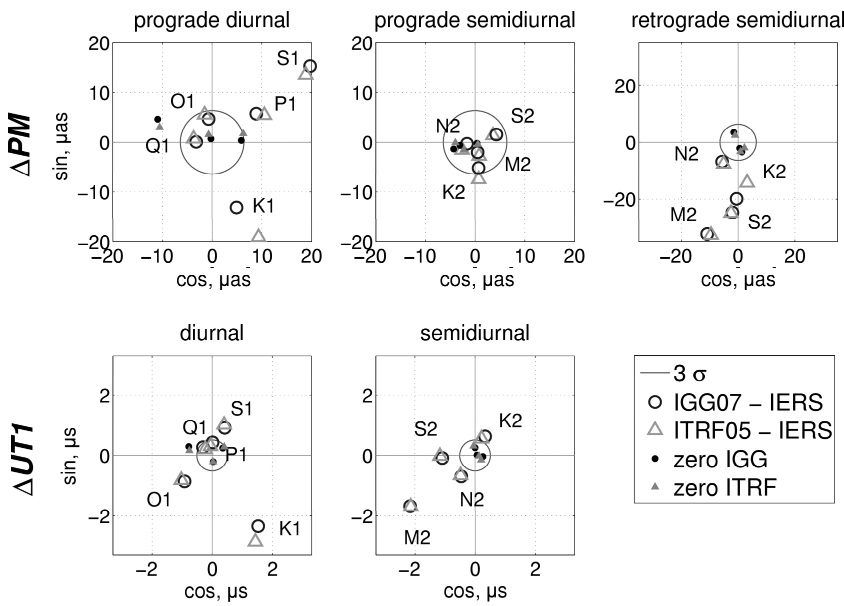

Figure 1. "Phasor plots" of amplitude differences of the eight major tidal terms and S1 to IERS2003 and absolute amplitudes of the zero terms

5. Discussion and Conclusions

The rms differences of the empirical model w.r.t. IERS2003 show differences < 0.03 μas/μs when comparing the solutions, for which different reference frames were used. In terms of unconstrained estimation versus constrained estimation a clear reduction of the rms difference and hence a better alignment to the IERS model is noted for the constrained approach. This reduction of the amplitude differences mainly occurs for the sideband terms. The separation of the sideband terms from the main band terms is possible without any additional information, but the constraints obviously force the preservation of the tidal signature of the variations and restrain other (non-tidal) signals. For each solution notable deviations occur w.r.t. the model in most of the major tidal terms. The largest differences, in terms of ΔPM as well as $\Delta UT1$ arise for the K1 term in the diurnal band and for the M2 term in the (retrograde) semidiurnal band and are in the range of 20–34 μas and 2–3 μs, respectively. In case of prograde semidiurnal ΔPM almost all estimated differences are within the three-fold formal errors. The amplitudes of the zero terms agree with the magnitude of the 3σ uncertainty, except for one diurnal term with a period of 26.56 h, where significant signal seems to be present in both ERP variations. In summary we conclude that important future tasks are further comparisons and also combined estimates with observations from other space geodetic techniques. In addition thorough investigations of the contribution of the atmospheric tides S1 and S2 and of the effect of the triaxial shape of the Earth on the ERP, as well as corresponding updates of the conventional model are needed.

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