RESPONSE OF THE EARTH SYSTEM TO ZONAL TIDAL FORCING EXAMINED BY VLBI BASED dUT1 VARIATIONS

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ABSTRACT. The VLBI group at the Institute of Geodesy and Geophysics of Vienna University of Technology is developing the software VieVS (Vienna VLBI software) for the analysis of geodetic VLBI data. VieVS incorporates the most recent models recommended by the IERS Conventions and in contrast to other VLBI software uses a parameterization with piece-wise linear offsets at integer hours. Thus it provides more flexibility for combination or comparison with time series from other space geodetic techniques or of geophysical origin. We employed this new software to re-process all available geodetic VLBI sessions from 1984 till 2010, suitable for the determination of the Earth rotation parameters (ERP), i.e. dUT1 (UT1–UTC) and the polar motion coordinates x_p and y_p. Zonal tidal signals with periods from 5 to 35 days in the derived dUT1 long-time series were then used to estimate the so-called zonal response coefficient κ defined by Agnew and Farrell (1978). The frequency dependent zonal response coefficient is an extension to the concept of the Love number k_2 which allows for a response of the Earth to tidal forcing, deviating from purely elastic behaviour and thus taking into account effects of ocean tides, a fluid core and mantle anelasticity. A tidally induced change of the rotation rate of the Earth and consequently of dUT1 is proportional to the tide-generating potential through the zonal response coefficient κ. The values estimated for κ for different tidal frequencies from VLBI observations of dUT1 were compared to theory and to the results of previous determinations of κ from observations of space geodetic techniques.

1. dUT1 TIME SERIES FROM VieVS ANALYSIS

A new software for the analysis of geodetic VLBI observation data, called VieVS (shortly for Vienna VLBI Software) is developed at the Institute of Geodesy and Geophysics of the Vienna University of Technology (Boehm et al., 2009). The recent, fully operational release of the software is available free of charge for registered users (refer to VieVS webpage for further information). VieVS is written in Matlab and consists of several main programs (i.e. Matlab-scripts) which are usually executed in a pre-defined sequence but can be processed independently from each other as well, if the necessary input information has already been created in a previous run. The following table provides a sketch of the VieVS structure:

VIE_SETUP	processing setup (choosing the data, storage folders...)
VIE_INIT	data reading (observation data in NGS-format)
VIE_MOD	calculation of observed–computed, partial derivatives
VIE_LSM	least squares adjustment (Gauss-Markov-Model)
VIE_GLOB	module for global solution (multi-year solution)
VIE_SIM	tool for the simulation of VLBI measurements

Table 1: VieVS structure

VieVS differs from other VLBI software packages, which use least squares adjustment, in a slightly different way of parameterization. All estimable parameters (this holds also for station coordinates) can be estimated as piecewise linear offsets at integer hours (like 12:00 or 18:00 UTC) or integer minute fractions of integer hours (like 12:20, 12:40 UTC). Traditionally, i.e. in other VLBI software packages, the parameters are modelled as piecewise linear functions where the first offset is estimated at the epoch

of the first observation, which is usually not taken at an exact full minute time point. The alternative parameterization used in VieVS facilitates the allocation of estimated parameters at the same epochs as they result from other space geodetic techniques and thus provides a good starting basis for the combined estimation of the parameters from observation data of different techniques. The delay model implemented in the software adheres to the latest IERS recommendations including the transformation from celestial to terrestrial reference frame using the concept of the non-rotating origin.
In order to generate a long-time series of dUT1 we re-processed all 24 hours sessions from 1984 to 2010 with an adequate global station distribution. dUT1 was estimated with six hours resolution whereas the other Earth orientation parameters (polar motion, nutation/precession) were set up in daily intervals. Station positions were calculated sessionwise applying no-net-rotation and no-net-translation conditions on the coordinates of the VLBI terrestrial reference frame VTRF2008. The coordinates of the radio sources were fixed to the second realisation of the international celestial reference frame, ICRF2.

2. DETERMINATION OF THE ZONAL RESPONSE COEFFICIENT κ

For a perfectly elastic, spherically symmetric Earth without oceans the zonal tidal potential of degree two would induce a change δLOD in the length of day (LOD) (Moritz and Mueller, 1987):

$$\frac{\delta LOD}{LOD_0} = -k_2 \frac{2}{3} \frac{R^3}{GC} a_{20} \tag{1}$$

where LOD_0 corresponds to the nominal length of day of 86400 seconds, C is the axial moment of inertia, G is the gravitational constant and R stands for the mean Earth radius. k_2 denotes the Love number for degree two which usually is used as a proportionality factor to express a change of the gravitational potential of the Earth due to a perturbing potential such as the tidal potential. The zonal tidal potential can be represented using Legendre polynomials as $V_{20} = a_{20} P_{20}(cos\theta)$, with the tidal potential amplitude a_{20}.
To allow for a more realistic Earth behaviour considering also mantle anelasticity, dynamic oceans and a fluid core, Agnew and Farrell (1978) introduced a kind of extension of the Love number concept which they called the zonal response coefficient of the Earth-ocean system κ. The zonal response coefficient is frequency dependent and complex-valued, thus permitting a retarded response of the Earth system to the acting force. We exchange the Love number k_2 in the above-mentioned equation with κ and express the change of the Earth's rotation speed in terms of universal time instead of LOD (i stands for the complex unit):

$$\delta UT1(\omega) = -\kappa(\omega) \frac{1}{i\omega} \frac{2}{3} \frac{R^3}{GC} a_{20}(\omega) \tag{2}$$

Depending on the presumed Earth model we can give some possible values for κ. According to Chao et al. (1995), for a spherically symmetric Earth without oceans κ would have the value of the (static) Love number $k_2 = 0.3$. An equilibrium ocean would increase the value by 16%, whereas a completely decoupled fluid core would decrease it by about 11%, leading to a total theoretical value of $\kappa = 0.315$. If the oceans are additionally considered to have a dynamic response and furthermore time dependent core-mantle coupling and mantle anelasticity are assumed then the zonal response coefficient becomes frequency dependent and a phase lag is introduced, making it complex-valued. Equation (2) could be used to introduce values for κ derived from theoretical considerations and deduce modelled variations of universal time. The other option is to calculate the UT1 variations from measurements of space geodetic techniques and estimate the corresponding κ values for each tidal frequency ω. In this study we chose the second option and estimated the zonal response coefficient, within a period range from 5–35 days, from dUT1 variations observed by VLBI.
Since equation (2) merely holds for tidally induced changes in universal time a certain pre-processing has to be applied in order to reduce the observed dUT1, containing all kinds of signal, to $\delta UT1$, which denotes purely tidal variations. The dominating sources of excitation within the investigated frequency bands besides tidal excitation are strong zonal winds and to a moderate extent also atmospheric pressure variations. The atmospheric excitation can be modeled with atmospheric angular momentum functions (AAMF) which are calculated from numerical weather model data. We used so called effective AAMF from NCEP/NCAR reanalyses to account for dUT1 variations induced by the atmosphere. These functions are provided by the Special Bureau for the Atmosphere of the IERS Global Geophysical Fluids Center (Salstein and Rosen, 1997) and were computed from reanalysis data of the National Centers for

Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The axial AAMF χ_3 mass and motion terms were in a first step converted to length of day variations and subsequently integrated to derive variations of universal time. The atmospheric UT1 variations were then subjected to a high-pass filtering to eliminate signal with periods beyond 40 days. The same filtering was applied to the dUT1 time series calculated with VieVS. We derived the final tidal $\delta UT1$ time series by subtracting the filtered atmospheric UT1 variations from the filtered observed dUT1 time series. Equation (3) served as a functional model for the estimation of κ in a least squares adjustment using $\delta UT1(t)$ as pseudo-observations:

$$\delta UT1(t) = \sum_j -\kappa(\omega_j)\frac{1}{i\omega_j}\frac{2}{3}\frac{R^3}{GC}a_{20}(\omega_j t) \tag{3}$$

The amplitudes a_{20} were taken from the HW95 tidal potential catalogue (Hartmann and Wenzel, 1995). We estimated κ for a total of 41 tidal frequencies ω_j. The resulting values including error bars for the nine terms with the largest tidal amplitudes are shown in Figure 1 in terms of κ magnitudes and phases. In addition to the values obtained from the VieVS dUT1 time series the picture shows resulting

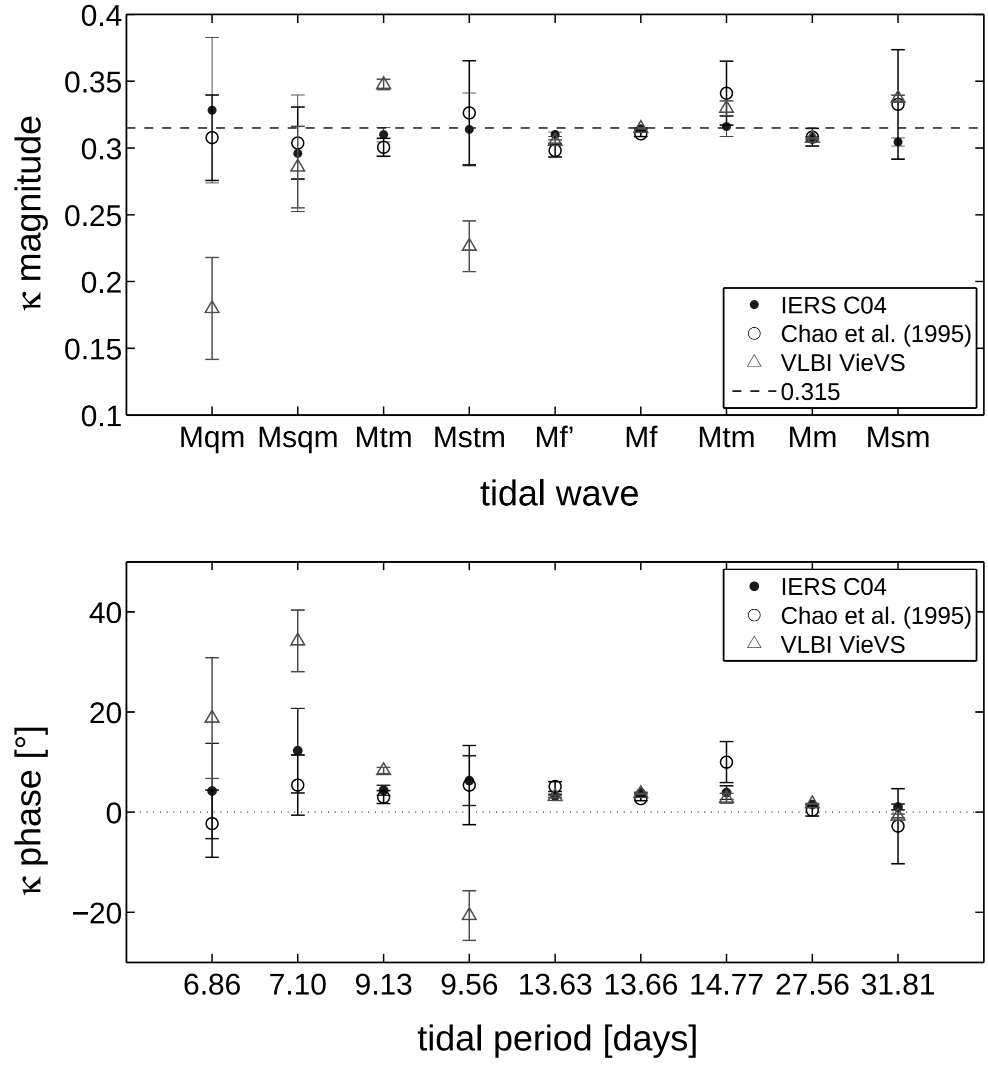

Figure 1: Amplitudes (top) and phases (bottom) of the zonal response coefficient κ

κ for the IERS C04 dUT1 series (IERS webpage) and the estimates given in Chao et al. (1995) for comparison. The IERS C04 κ values were obtained by applying the same estimation procedure as for the VieVS dUT1 times series to the C04 dUT1 time series from 1984-2010, which are provided by the IERS with daily resolution. Chao et al. (1995) used 13 years (1980–1992) of LOD data for their study. The LOD series was derived from a universal time series (with daily sampling) stemming from a Kalman filter combination of different space geodetic measurements of Earth rotation.

3. DISCUSSION OF THE RESULTS

We used the new VLBI analysis software VieVS for the determination of dUT1 time series with six hours resolution from selected 24 hours sessions of the years 1984 to 2010. The time series was cleaned from UT1 variations stemming from atmospheric excitation and filtered for periods longer than 40 days. The remaining zonal tidal signals were introduced to a least squares adjustment as pseudo-observations in order to estimate the complex zonal response coefficient κ for 41 tidal periods from 5–35 days.
The results for the nine main tidal periods are represented as magnitudes and phases in Figure 1. For comparison the figure also contains the κ values calculated from the IERS C04 dUT1 series and the numerical estimates from a study by Chao et al. (1995). We would actually expect a more precise estimation of κ from the VieVS dUT1 time series because of the much longer time interval and higher resolution. This assumption turns out to be true for the periods longer than ten days, where the VieVS results also agree well with the IERS C04 results and have continuously smaller error bars than the estimates from Chao et al. (1995). In the higher frequency bands around seven and nine days we can see partially large deviations of the VieVS based κ values w.r.t. the two reference results, accompanied also by comparably large error bars. It is somewhat surprising that the VieVS estimates also do not agree with the IERS C04 estimates, although they were calculated from the same time interval and the C04 dUT1 series are primarily based on VLBI observations. The main differences between the VieVS dUT1 and C04 dUT1 series are the temporal resolution, which is six hours in the first and 24 hours in the second case, and the continuity. The C04 series is continuous, while the VieVS series has gaps at days where there was no observing session. To which extend these differences are able to influence the estimation of the zonal response coefficient needs to be further investigated. Concerning the larger error bars in the higher frequency bands we should note that they are coherent with smaller amplitudes of these terms in the tidal potential and thus are most probably a consequence of the worse signal-to-noise ratio.

4. CONCLUDING REMARKS

The κ results of this study have to be regarded as preliminary and will not be consulted for further geophysical interpretation before the unexplained discrepancies in the higher frequencies have been clarified. However, the very distinct and precise results for the longer periods show that it is definitely promising and worthwhile to investigate the zonal response of the Earth by means of now accessible long-time series of dUT1 or LOD.

5. REFERENCES

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