An Empirical Atmospheric Tidal Loading Solution for Particular VLBI Stations

A. Girdiuk, M. Schindelegger, J. Böhm

Abstract Tidal atmospheric loading causes small but periodic reference point displacements that are conventionally treated in the space geodetic analysis reductions. On the one hand, numerical model estimates of these displacement signals are provided, e.g., by TU Wien, Goddard Space Flight Center (GSFC) or the Global Geophysical Fluid Center (GGFC). On the other hand, with the large data base of modern Very Long Baseline Interferometry (VLBI) observations and the high precision of other reduction models, the small effects of the tidal atmospheric loading variations can be determined directly in the analysis. Here, by utilizing the Vienna VLBI and Satellite Software (VieVS), hourly station coordinates are obtained and particular measures are taken to mitigate the obvious correlations with tropospheric parameters. Specifically, the hourly intervals of zenith wet delay estimates are replaced by six-hourly intervals, similar to the estimation interval of tropospheric gradients. Retrieved time series (06/2011–02/2016) of positions for station Katherine, Australia, reveal amplitudes of the diurnal atmospheric signal in the range (0.5 – 1.5) mm with a confidence interval of 1.5 mm (threefold formal error) as provided by single session solutions for different analysis setups. Generally, these amplitudes exhibit fair agreement with estimates from the applied loading models, that is cosine and sine amplitudes: (−0.6 mm; 0.7 mm) for the TU Wien solution, (−0.4 mm; 0.5 mm) for GSFC and (−0.8 mm; 1.0 mm) for GGFC.

Keywords Atmospheric tides, harmonic variations of station positions, single session solution

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1 Introduction

Atmospheric tides are regular variations induced by solar insolation and appear with Sun-locked periods of 24 and 12 hours. These geophysical phenomena are visible in geodetic parameters, i.a., Earth Rotation and variations of station positions. This paper focuses on the less studied harmonic variations in Very Long Baseline Interferometry (VLBI) station positions. Currently, various numerical models — TU Wien (Wijaya et al., 2013), Goddard Space Flight Center (GSFC) (Petrov and Boy, 2004) or the Global Geophysical Fluid Center (GGFC) (van Dam, 2010) — provide station position corrections associated with atmospheric loading. Routine VLBI analysis takes into account atmospheric loading reductions, along with other distortions due to solid Earth tides and ocean tides as recommended by the IERS Conventions (Petit and Luzum, 2010). Atmospheric tidal loading induces one of the smallest displacements of the reference points on the crust with amplitudes mostly at or below the 1 millimetre level. These obvious systematic influences are required to be considered in the analysis. The proper determination of these small variations is one of the challenges imposed on the modern geodetic VLBI observations. To achieve this goal in the present paper, loading results from numerical weather models are reviewed to pinpoint VLBI stations with large-magnitude atmospheric tidal variations. Because the modern geodetic VLBI technique approaches the millimetre accuracy level, the tidal loading maxima are probed, and station Katherine in Australia is found to be a suitable example. In detail, hourly station positions at Katherine estimated in single sessions solutions are favored over the standard parametrization, in which station coordinates have only one estimate per session. This modification requires to adjust the tropospheric parameter evaluation interval because of correlations with station positions. A compromise is found in changing the zenith wet delay interval from 1 hour to 6 hour. Additionally, the impact of other reductions and parametrization is studied to test the hourly station

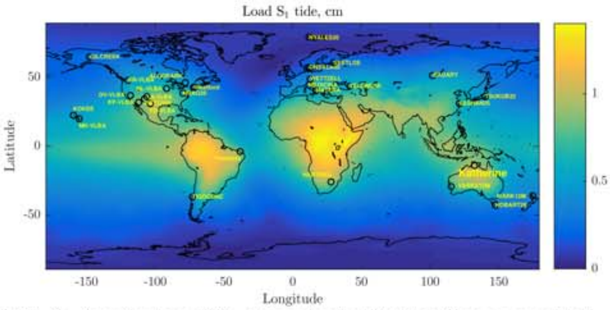

Fig. 1: Amplitudes of S_1 atmospheric tidal loading as provided by the TU Wien model.

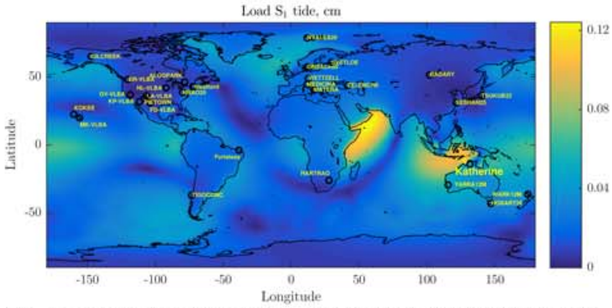

Fig. 2: Amplitudes of S_1 ocean tidal loading as provided by the FES2014b model.

position time series reliability. To meet this challenge, the method of the least squares adjustment (LSA) at the frequencies of atmospheric tides is applied to obtain an empirical tidal solution for station Katherine.

2 Numerical loading solutions

Using pressure data from numerical circulation models, station position corrections induced by the atmospheric tides S_1 and S_2 can be deduced for a set of components in Radial, East and North directions (REN system) for each station. For S_1 (the diurnal atmospheric oscillation), the maximal displacement is concentrated in the radial direction illustrated in Fig. 1, because it receives the most of the tidal loading power. The model calculated at TU Wien exemplifies the distribution of the atmospheric impact on the Earth's crust including maximum and minimal values. Other available models (GSFC and GGFC) possess rather similar scattering and amplitude patterns.

In Fig. 1 the VLBI station Hartrao can be found close to the equatorial area where the atmospheric tidal loading attains largest values over the South African continent. Yet, the load tide amplitude at this station is smaller than the corrections at the station Katherine in Australia provided by numerical models. The numerical corrections (cosine and sine amplitudes) to the Katherine position are (−0.6 mm; 0.7 mm) for the TU Wien solution, (−0.4 mm; 0.5 mm) for the GSFC model and (−0.8 mm; 1.0 mm) for GGFC. These small magnitudes cause certain difficulties in terms of the detection in VLBI analysis; yet, being systematic influences on daily and sub-daily time scales, their estimation should be feasible.

Larger loading effects in the diurnal and semi-diurnal bands belong to the effect of the ocean tides. As a rule, ocean tide loading is introduced in VLBI reductions for 8 major tides (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2) and 3 long term tides (Mf, Mm, Ssa), where S_2 denotes the frequency corresponding to a period of 12 hour, thus matching the frequency band of the atmospheric S_2 tide. The oceanic S_2 tide induces maximal loading values at VLBI station Fortaleza (South America, 1.1 cm) and at the same time the atmospheric tide S_2 is less then 1 mm. This coincidence of atmospheric and oceanic contributions is unavoidable and required to be considered properly for both studied frequencies, i.e. S_1 and S_2. In the VLBI reductions, following the IERS Conventions example, ocean tides are taken into account commonly by means of the FES2004 ocean model. Girdiuk et al. (2016a,b) compared tidal loadings from different providers, and rather similar solutions in terms of VLBI baseline length repeatabilities are found when the underlying ocean model is changed. Here, the last available version of the FES numerical ocean model series (Letellier et al., 2004) FES2014b (Aviso, 2014) is chosen for reductions because this model includes the ocean response to the atmospheric forcing at the S_1 frequency (Fig. 2). Older models, for instance FES2004, do not consider S_1. At the station of interest in this paper, Katherine, the corrections due to the S_1 load tide based on FES2014b (shown in Fig. 2) are found to be approximately 0.4 mm.

3 Single session solution modifications

Almost 390 24 h VLBI sessions were assembled for the period of June, 2011 – Feb, 2016, in which the station Katherine participates. This relatively short but dense time series of 5 years were processed by solving each session with the LSA using the Vienna VLBI and Satellite Software (VieVS) (Böhm et al., 2012). An additional criterion for the selection of a session is that it contains observations at more than 5 stations. This requirement for the network is necessary because station Katherine has to be excluded from the datum, so that the rest of the stations (4 antennas) is enough for its realization. The datum can be realized by a part of the antennas per session. The main reason for excluding Katherine from the datum is that in our analysis the station positions for Katherine are evaluated at hourly intervals to resolve daily and sub-daily variations. This scheme is in contrast to the standard approach where the station coordinates are estimated once per session or fixed to a priori values.

In the standard approach (Schuh and Böhm, 2013) of solving VLBI observations in single session solutions, the design matrix is set up for:

1. Clocks:piecewise linear offsets at hourly intervals plus a linear and quadratic terms per session;
2. Tropospheric parameters: Zenith Wet Delay (ZWD) at hourly intervals and tropospheric gradients in North and East directions (NGR and EGR) at 6-hour intervals.
3. Earth Orientation Parameters daily constant value;
4. Station coordinates once per session;
5. Source coordinates once per session.

Given the elevation angle dependence for both the station heights and the ZWD (Sovers et al., 1998), and the associated correlations in the inversion, the estimation interval of one of them has to be modified. The hourly station coordinates are the subject of this paper, thus the ZWD is evaluated at 6-hour intervals for all solutions presented below in this paper. Yet, some undesired dependencies are retained in the solutions. In order to reduce some of them, ray-traced delays were applied to the NGR and EGR as well as to the ZWD because this approach might be more accurate in application to the VLBI observations (Hofmeister, 2016), so a statistical formal error level improvement was expected. Hence, solutions with gradients fixed to their a priori values were used in addition to the standard strategy. Therefore, for the one atmospheric loading variant (Sect. 2) four solutions were obtained.

Concerning the rest of reductions and constraints applied in the processing, we follow the common approach widely used at TU Wien and given by Krásná et al. (2014). The only difference in the reductions is that the atmospheric tidal loading is excluded from the station position corrections, but the corrections due to ocean loading are introduced using FES2014b, so that the oceanic contribution at the S_1 frequency is included. In this way, oceanic and atmospheric contributions are considered separately, and explicit emphasis can be given to the atmospheric part.

4 An empirical assessment

Hourly station position variations for the station Katherine are obtained in the geocentric rectangular coordinate frame as provided in VieVS single session solutions. In order to facilitate numerical model comparisons, these time series can be transformed to the REN system in a straight-forward manner by a rotation matrix at the angle of latitude and longitude of the location. These hourly estimates are supplied with formal errors of the stochastic model in VieVS. However, the time series is contaminated for various reasons, among them insufficient network geometry as the most prominent factor (Girdiuk et al., 2016c). Influences from these sporadic outliers can not be mitigated through the formal error analysis. To remove these outliers, a better approach is to limit the hourly station position time series by 10 cm condition in X and Y directions, and 7 cm in Z.

Finally, the LSA is undertaken to retrieve atmospheric tidal contributions from the hourly time series of station positions. A similar approach was implemented by Girdiuk et al. (2016c) for the high-frequency Earth Rotation Parameter analysis, but in this paper we introduce the pre-defined frequencies S_1 and S_2 only. The results of this assessment for four VLBI solutions described above are demonstrated in Fig. 3 for the primary S_1 radial component. The circles indicate formal errors, i.e. $3\,\sigma$ (1.5 mm), $2\,\sigma$ (1.0 mm) and $1\,\sigma$ (0.5 mm). These levels are almost the same for all shown solutions, so the width of the circles on the plot should underline this fact. Fig. 3 illustrates the substantial empirical estimates of the S_1 load tide in radial direction. Unfortunately, modeled values are found under the $3\,\sigma$ reliability level, but the atmospheric tides estimates obtained for Katherine have a good agreement with these models except for some separation in phase (see Fig. 3). Also, due to noise in the time series, improved results using ray-tracing instead of VMF1 (Böhm et al., 2006) to better account for the troposphere is not evident. And, the significant difference of about 1 mm between the strategy of fixing gradients and estimating them does not allow to validate the ray-tracing or VMF1 approach. In future, a larger number of observations for station Katherine will increase the reliability of such assessments based on lower formal error statistics.

Some distortions of the final results (Fig. 3) can arise from the applied method of the LSA at two pre-defined frequencies because of possible leakage from side lobes. In fact, the large-amplitude ocean tides P_1 and K_1 (see Table 8.2a of the IERS Conventions) are the closest to the frequency S_1 and, by this reason, might corrupt loading estimates at this frequency. Note that the gravitationally induced S_1 constituent is a product of the P_1 and K_1 side lobes as derived from the tide generating potential. This oceanic variation is of a small amplitude and its impact is neglected in the station position variations. But, the atmospheric impact at the frequency S_1 has a completely different source, that is, diurnal atmospheric pressure variations induce regular motions of

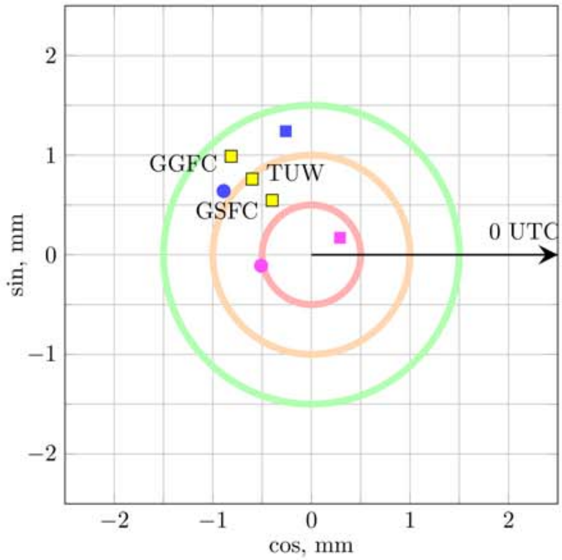

Fig. 3: Atmospheric tides retrieved in harmonic variations of station positions of radial component for Katherine. The 1 σ level of standard deviations is depicted on both planes as circle of pink color, 2 σ as orange color, and 3 σ as green color; squares mark ray-tracing, circles denote VMF1, pink color represents solutions where gradients are fixed, blue where gradients are estimated. The phase reference is Greenwich midnight (0 UTC).

the crust at the order of 1 mm as provided by the numerical models (TU Wien, GSFC, GGFC). Also, the atmosphere forces the ocean to vary at the same frequency as atmospheric tides. As we have seen, FES2014b provides this hydrodynamic response at the S_1 line (Fig. 2); see also Ray and Egbert (2004). At the frequency of S_2, the atmospheric forcing is difficult to distinguish from the oceanic S_2 influence because the semi-diurnal ocean tide S_2 is one of the main lobes in the tide generating potential and possesses amplitudes which are approximately 10 times bigger than the response to the meteorological S_2 signal (Arbic, 2005). Evidently, an improper account of ocean tidal loading can lead to uncertainties in the evaluation of the amplitude and phase of the atmospheric tidal loading contribution.

5 Conclusions

On the one hand, atmospheric tidal loading estimates are available from various numerical models, where three of them were investigated and this study revealed the maximum contribution at the VLBI station Katherine. On the other hand, using modern VLBI observations we retrieved atmospheric tidal signals in hourly station position variations for station Katherine. This empirical result was cleansed from the ocean response to the atmospheric forcing at the S_1 frequency using a load tide solution from the most recent ocean model FES2014b. We presented here results for the atmospheric-induced S_1 load tide in the radial component mainly to exemplify the involved magnitude of signals. It became clear that the time series need to be extended to achieve lower formal errors and a more robust empirical assessment. Although the reliability level of the obtained atmospheric tidal loading estimates at the S_1 frequency may be critical we find that the agreement between numerical loading models and VLBI-based results is encouraging.

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