Atmospheric pressure loading corrections applied to GPS data at the observation level

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[1] Space-geodetic techniques can detect elastic deformation of the Earth caused by atmospheric pressure loading (ATML). However, it has not yet been demonstrated whether these surface displacements should be accounted for at the time of reduction of the observations or by applying time-averaged values to the coordinates after the analysis of the observations. An analysis of the power spectral density of the ATML predicted vertical deformation shows that, aside from the diurnal and semi-diurnal periods, there is very little power in the sub-daily frequencies. The present tidal ATML models improve the analysis at sites near the equator but seem to degrade the height estimates elsewhere. The majority of the non-tidal deformation can be modelled by applying a daily-averaged correction to daily estimates of coordinates but a greater improvement in height RMS is found if non-tidal ATML is applied at the observation level. **Citation:** Tregoning, P., and T. van Dam (2005), Atmospheric pressure loading corrections applied to GPS data at the observation level, *Geophys. Res. Lett.*, *32*, L22310, doi:10.1029/2005GL024104.

1. Introduction

[2] It has long been acknowledged that atmospheric pressure loading (ATML) causes deformation of the surface of the Earth [e.g., *Darwin*, 1882]. Such deformations have been detected in time series of Global Positioning System (GPS) [e.g., *van Dam et al.*, 1994; *Dong et al.*, 2002] and Very Long Baseline Interferometry analyses [e.g., *van Dam and Herring.*, 1994; *MacMillan and Gipson*, 1994; *Petrov and Boy*, 2004]. Daily site coordinates have been corrected for ATML, averaged over a 24 hour period, once the observations have been processed [e.g. *Zerbini et al.*, 2004; *Scherneck et al.*, 2003]. This approach is sufficient if the deformation across the time interval of the solution is linear (and the number of satellites observed per epoch remains constant throughout the solution interval). On the other hand, higher frequency components of the ATML signal can propagate into annual and semi-annual periods [*Penna and Stewart*, 2003; *Stewart et al.*, 2005], time-averaged values may not adequately represent the actual site motion and, as a result, the daily averaged approximation could be inferior to applying corrections at the observation level.

[3] Are 24-hour averages of ATML sufficient for correcting for the signal in GPS height time series or should one correct for the deformation at the observation level? Could one apply a model for the ATML tidal deformations at the observation level and then just add a daily-averaged correction for the non-tidal component of the deformation? The maximum vertical variation in a 24 hour period can be as large as 18 mm (Figure 1), while the power spectral densities of estimated ATML vertical displacements show significant power at the diurnal and semi-diurnal frequencies [*Petrov and Boy*, 2004] (Figure 2).

[4] We compared the RMS of daily height estimates for 2004 from an analysis of global GPS data. The GPS data were processed using the GAMIT software [*King and Bock*, 2005; *Herring*, 2005] (modified to apply ATML at the observation level) to produce daily, fiducial-free global polyhedra of over 130 sites in the CM frame. We show below the effects on station height estimates of applying combinations of tidal and non-tidal ATML deformation corrections.

2. Atmospheric Pressure Loading Model

[5] We used crustal displacements predicted by convolving the National Center for Environmental Prediction (NCEP) Reanalysis surface pressure estimates for the years 2000–2004 with elastic Green's functions [*Farrell*, 1972]. The study of the application of any model will be affected by limitations of the model itself. There are two critical factors of the ATML model to consider: firstly, the NCEP global pressure data (with 6-hourly global temporal sampling on a 2.5° × 2.5° regular grid) have a Nyquist frequency of 12 hours, which corresponds to the frequency of the semi-diurnal atmospheric tide [*van den Dool et al.*, 1997]. Therefore, any signals with frequencies of 2 cycles/day or higher will not be properly sampled in this pressure data set.

[6] Secondly, in modelling the surface displacement due to ATML, we must include a model for the response of the oceans to pressure loading. An inverted barometer (IB) response of the sea surface is expected in the deep ocean for all frequencies and wavenumbers [*Wunsch and Stammer*, 1997]. However, *Ponte* [1993, 1994] showed that the ocean response deviates from inverted barometric at periods shorter than two days in high latitudes, shallow water and in the tropics.

[7] Lacking a better alternative, in this paper we have assumed an IB response for the oceans when modelling the non-tidal component. This may affect the accuracy of the modelling of the higher frequency signals but will only

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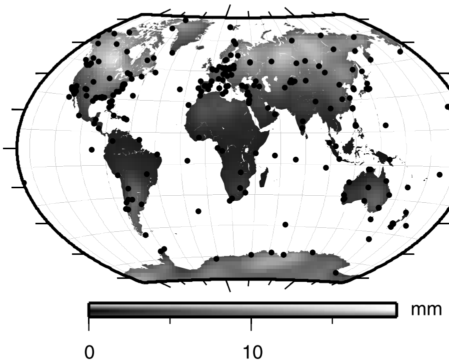

Figure 1. Peak-to-peak sub-daily vertical surface displacement from atmospheric pressure loading. GPS sites used in the analysis are plotted as black dots. See color version of this figure in the HTML.

affect coastal sites because the further away from the oceans a station is located the less the influence of the ocean response to the local deformation. We assume a non-IB response when modelling the tidal component of the deformation.

[8] The maximum peak-to-peak sub-daily vertical surface displacements expected from ATML over the Earth during 2004 (Figure 1) shows mid- to high-latitude displacements reaching up to 18 mm (independent of time of year). Near the equator, the sub-daily surface displacements are smaller due to smaller variability of the surface pressure [*van Dam and Wahr*, 1987]; however, the predicted maximum radial displacements are still of the order of 4–6 mm peak-to-peak. As expected, the ATML effect on islands is generally small due to the assumed IB response of the oceans. The predicted ATML sub-daily vertical surface displacements is greater in amplitude than many of the periodic vertical surface displacements caused by ocean tide loading - crustal displacements that are routinely modelled at the observation level in geodetic software packages.

3. Power Spectral Density

[9] We calculated the power spectral density (PSD) of the vertical component of ATML at 160 GPS sites scattered across the globe. Figure 2 shows the PSD for one typical site, Wettzell (Germany), derived from four different ATML pressure models: the raw NCEP data (known to contain partial information of the atmospheric tides [e.g., *van den Dool et al.*, 1997]) (Figure 2a), the 'non-tidal' model of *Petrov and Boy* [2004] (Figure 2b, available at http://gemini.gsfc.nasa.gov/aplo/aplo.html), and two models generated here following *Ponte and Ray* [2002]. There is some seasonal variation in the amplitude of the atmospheric tides [*Ponte and Ray*, 2002, and references therein]. In our first model, we removed only annually meaned tides (Figure 2c) while in the second we removed monthly meaned tides (as per equation (1) of *Ponte and Ray* [2002]) (Figure 2d).

[10] That there are peaks at the S_1 and S_2 frequencies in the raw NCEP data is no surprise. However, while the magnitude of the peaks may have been reduced, none of the so-called 'non-tidal' models are truly without power at the S_1 and S_2 frequencies. This probably results from the averaging processes described by *van den Dool et al* [1997] and *Ponte and Ray* [2002]. Whilst clearly not 'non-tidal', we will use this term below to distinguish this component from the tidal component of the deformation. We apply below the 'non-tidal' model computed by subtracting annual mean tides.

[11] Other than tidal, there is little power present at sub-daily frequencies. In fact, the integrated power between 1 cycle/day and 2 cycles/day at most sites is often less than 10% of the total power. The only exceptions to this are low-latitude sites where there is only a very small loading signal in the first place and where the S_1 and S_2 tidal loading signals can contribute up to 20% of the total power. The power contained in frequencies between one day and one week can reach as much as 35% of the total power.

4. Application of ATML to GPS Analyses

[12] The ATML model applied at the observation level in the GPS analysis was computed in the CM frame (solid Earth plus fluid loads [e.g., *Farrell*, 1972; *Dong et al.*, 2003; *Blewitt*, 2003]) with 6-houly values interpolated linearly to the time of the observations. Daily-averaged ATML was applied in the CM frame and only the non-tidal component was applied in the averaged loading values (the periodic signals average to zero over 24 hours).

[13] Below we consider some specific possible analysis strategies for applying combinations of the tidal and non-tidal components of ATML in GPS analyses. Making the

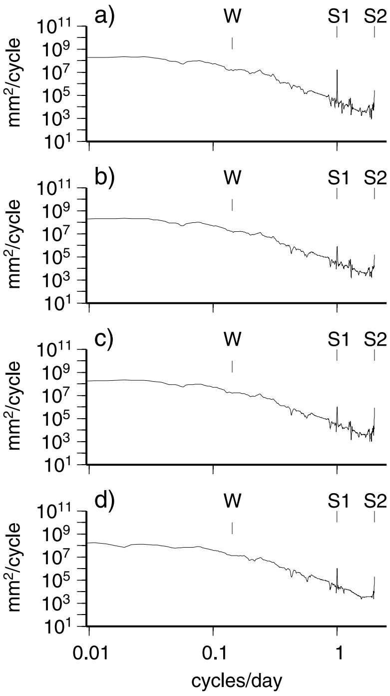

Figure 2. Power spectral densities (using a sine multitaper adaptive process) of ATML for the vertical component at Wettzell, Germany, using ATML from (a) raw NCEP pressure data, (b) 'non-tidal' ATML of *Petrov and Boy* [2004], (c) our 'non-tidal' model with mean atmospheric tides removed and (d) our 'non-tidal' model with monthly atmospheric tides removed. W: Weekly; S_1, S_2: diurnal and semi-diurnal ATML tides. See color version of this figure in the HTML.

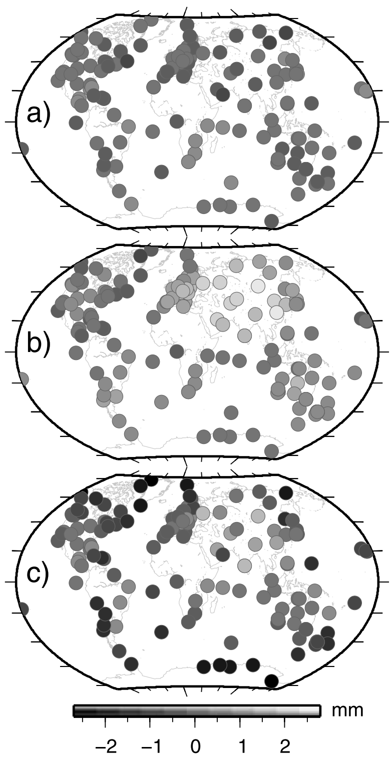

Figure 3. Reduction in WRMS of station heights relative to a solution with no ATML corrections. (a) Tidal ATML applied at the observation level, (b) daily-averaged non-tidal correction and (c) both tidal ATML and a daily-averaged non-tidal correction applied. See color version of this figure in the HTML.

assumption that the 'perfect' height time series will be linear, the most accurate model will produce the smallest height WRMS at the global sites. In Figures 3 and 4, a positive value for the reduction in WRMS indicates that the first-mentioned solution produced a smaller WRMS than the second; that is, it produced more accurate estimates.

4.1. Applying the S_1 and S_2 Tidal Models

[14] Corrections for the S_1 and S_2 tides should be applied at the observation level in a manner similar to ocean tide loading displacements in order to mitigate the aliasing of these periodic effects into longer period signals [*Penna and Stewart*, 2003; *Stewart et al.*, 2005]. Applying only the ATML tidal model improves the height WRMS at many sites near the equator where the ATML tidal effects are largest (Figure 3a). However, at higher latitude sites there is a general increase in WRMS, suggesting that the periodic signals are adding noise rather than removing signal. A better solution is obtained by applying just a daily-averaged non-tidal correction (Figure 3b) than both the tidal model and daily-averaged non-tidal correction (Figure 3c).

4.2. Non-tidal ATML at the Observation Level?

[15] It is more complicated to apply the non-tidal ATML at the observation level than as a daily-averaged value after the reduction of the geodetic observations. Is it worth the effort? In the majority of cases, the 'observation level' approach yields smaller height WRMS values (Figure 4a), in particular in the southern hemisphere and throughout Asia. 77% of sites have an improved height WRMS when applying non-tidal ATML at the observation level. This provides clear evidence that the non-tidal component of ATML should be applied at the observation level. We do not consider further any solutions involving daily-averaged corrections.

4.3. Combined Tidal/Non-tidal Versus Raw NCEP?

[16] Given that the so-called 'non-tidal' models of ATML actually contain tidal signals, is it better to apply at the observation level separate models for the tidal and non-tidal components, or simply apply a model that contains the non-tidal deformation as well as partial information about the tidal components - that is, the deformation convolved directly from the raw 6-hourly NCEP pressure values, acknowledging that these pressure values contain partial tidal information (see Figure 2a). In fact, the tidal plus non-tidal approach yields higher height WRMS values (Figure 4b), probably because the tidal components have effectively been included twice: once with the full periodic tidal model and again with whatever tidal signals remain in the 'non-tidal' deformation model.

[17] In addition, if the tidal ATML model is dominated by noise at mid to high latitudes then applying (at least part of) the tidal model twice will add even more noise. This is borne out by the fact that the 'raw NCEP' approach yields smaller height WRMS values, almost exclusively, at latitudes greater than 30°, whereas the tidal/non-tidal approach is superior in the majority of cases along the equatorial band where the tidal model is probably removing deformation signal rather than adding noise.

5. Conclusions

[18] ATML effects predicted from global surface pressure data sets such as those produced by NCEP show that sub-daily vertical crustal deformations greater than 10 mm are

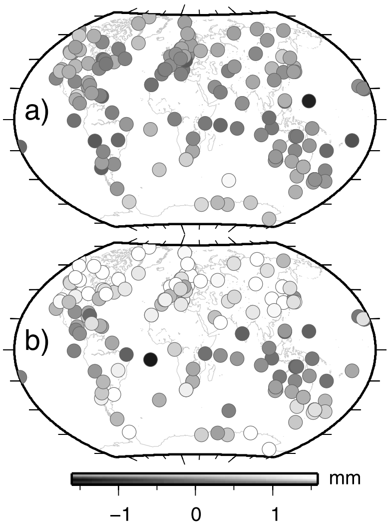

Figure 4. Reductions in WRMS of station heights. (a) Non-tidal at the observation level relative to daily-averaged non-tidal and(b) raw NCEP ATML (containing stronger partial tides) at the observation level relative to tidal and non-tidal component (both at the observation level). See color version of this figure in the HTML.

common at mid- to high-latitude GPS sites, with displacements on the order of 4 mm being common at low-latitude sites. To a first-order, it suffices to correct the GPS height time series for the loading effect by applying a daily-averaged correction for non-tidal ATML in the CM frame. However, over 70% of sites show a greater reduction in variance of heights when non-tidal ATML is applied at the observation level. Thus, considerable improvements in height estimates can be gained by adopting the more rigorous approach for accounting for atmospheric pressure loading deformation.

[19] There is significant power seen in the ATML models at the diurnal and semi-diurnal periods. Applying tidal ATML models reduces the height WRMS at most equatorial sites but tends to have a negative effect at higher latitudes where the tidal loading is smaller. This suggests that, in the latter case, applying the model introduces noise into the geodetic analysis rather than removing deformation signal.

[20] The available methods [e.g., *van den Dool et al.*, 1997; *Ponte and Ray*, 2002] for removing the tidal components from the 6-hourly NCEP data do not actually yield truly 'non-tidal' ATML deformation. The application at the observation level of a tidal ATML model and the 'quasi-non-tidal' component is actually inferior to simply applying the ATML deformation computed from the raw NCEP pressure data directly. This is probably because of the duplication of the tidal corrections in the quasi-non-tidal corrections.

[21] Finally, the limitation of these conclusions are the quality of the NCEP data that were used in this analysis and the assumption that the oceans behave as inverted barometers. Any of the global gridded atmospheric files represents a filtered version in space and time of randomly spaced observations. If in fact there are significant crustal displacements induced by atmospheric pressure that are not captured by the NCEP data then they will not be included in the modelled deformations. Neither applying ATML at the observation level nor as daily-averaged corrections will model such deformation.

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