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Mass Loading Effects on Crustal Displacements Measured by VLBI

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Abstract

The geodetic precision of VLBI (very long baseline interferometry) has improved to the level that baseline lengths can be measured with a wrms precision of 1 ppb and site positions with precision of 8-14 mm in the vertical and 2-3 mm in the horizontal components. Observed VLBI site position variations contain significant contributions at seasonal (annual and semiannual) frequencies. Here, we will concentrate on the site vertical annual amplitudes that mostly range from 2-6 mm. We determine the extent to which annual site variations can be explained by mass loading signals. Specifically, we examine the contributions from atmosphere pressure loading, hydrologic loading, and nontidal ocean loading. We have also examined the effect of two modeling errors specific to the VLBI measurements: tropospheric delay mismodeling (hydrostatic mapping function) and antenna thermal deformation.

1. Loading Models

We have computed the site displacements due to each contribution to mass loading using the Green's function approach [Farrell, 1972]. For atmospheric pressure loading, the NCEP Reanalysis numerical weather model gridded data was used. A complete description of the procedure used and the validation of the model using VLBI observations is given in Petrov and Boy [2003]. Hydrologic loading was computed using a model of large-scale continental water and energy balances developed by Milly and Shmakin [2002]. The sum of model storage outputs of soil water, groundwater, and snow yields the monthly continental water storage. Nontidal ocean loading was computed using ocean bottom pressure fields from the ECCO (Estimating the Circulation and Climate of the Ocean ocean) model. The annual amplitude and phase for hydrology loading is shown in Figure 1. The maximum amplitude over the continents is 4 mm, but the average amplitude for VLBI sites is about 2 mm. The phase (where the signal is maximum) over most of the northern hemisphere is around 180 days (summer months).

2. Solution Description

Group delay data were analyzed from more than 3500 experiment sessions carried out from 1984 through 2003 amounting to over 4 million observations. For this work, we have concentrated on observations from 36 VLBI stations that have observed the most frequently. In our standard terrestrial reference frame (TRF) solutions, we estimate the site positions, velocities, and radio source positions as global parameters. The VLBI program SOLVE and most of the theoretical models that are generally applied are described in Ma et al. [1990]. The VLBI delay observable is invariant to several transformations of the estimated variables. To remove the corresponding

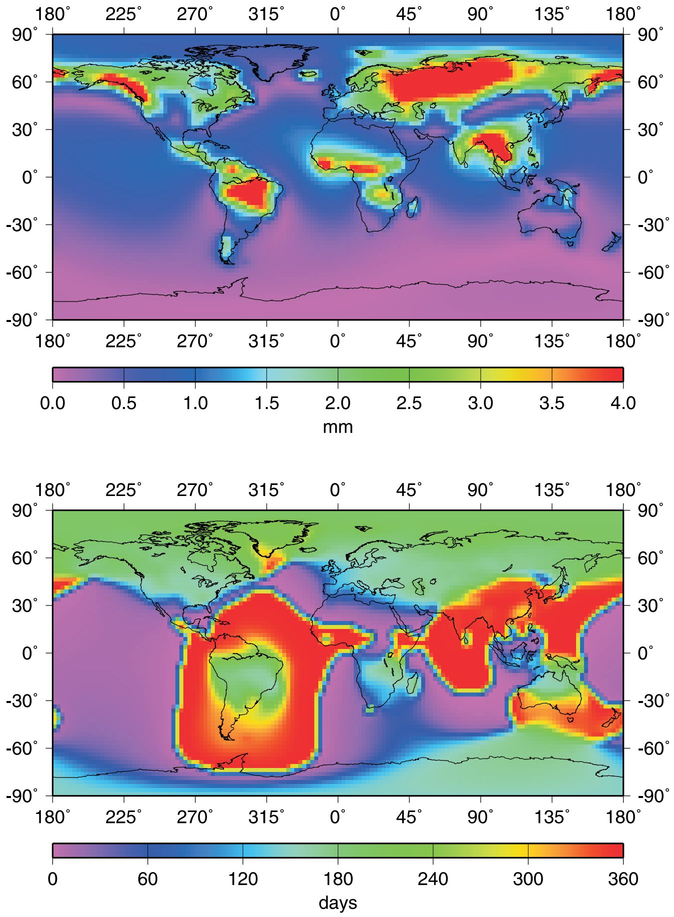

Figure 1. Annual amplitude (top) and phase (bottom) of the vertical displacement due to loading computed using the hydrology model of Milly and Shmakin [2003].

degeneracies, no net translation (NNT) and no net rotation (NNR) conditions are applied to align the TRF with the ITRF2000 and celestial reference frame with the ICRF positions. For the analysis of seasonal variation, we estimated the cosine and sine components of site displacement at annual and semiannual frequencies as additional global parameters for the 36 sites. To remove translational and rotational degeneracies, additional NNR and NNT constraints were applied. The phase of the variations of the expected seasonal vertical signals (mass loading, antenna thermal deformation) for Northern Hemisphere sites will generally be opposite the phases for Southern Hemisphere sites. In order not to constrain the estimated vertical seasonal variation and avoid biasing results due to predominance of Northern Hemisphere sites, the NNT condition constrained the sum of only the horizontal components of site amplitude adjustments to zero.

3. Results

We have run several solutions in which different combinations of models have been appplied. In Figures 2 and 3, the annual vertical amplitudes are shown for the most frequently observing VLBI

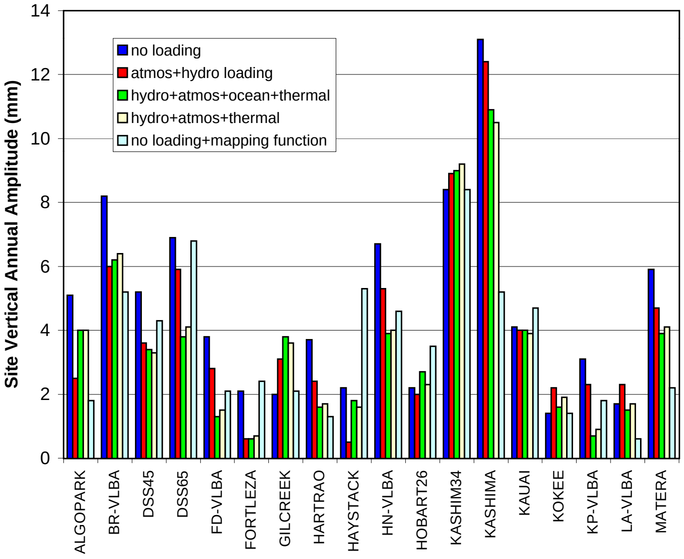

Figure 2. Observed site annual vertical amplitudes and effect of applying different models.

sites. The observed amplitudes are mostly in the range 2-8 mm. After applying hydrology loading, 70% of the amplitudes are reduced by up to 3 mm. Since the nontidal ocean loading amplitude is at most 1 mm (coastal sites), its contribution to the observed amplitudes is very small.

Phasor plots of the observed site amplitudes and the different model contributions are shown in Figure 4 for Medicina and Fairbanks. The sum of the model contributions lies within the 2-sigma error ellipse of the observed annual variation at Medicina. For Fairbanks, we do not see this agreement, but it can be seen that if the contribution from snow loading is not included, that the agreement is better. Snow modeling is known to be poor at higher latitudes mainly due to lack of sufficient data.

We have made comparisons of site vertical amplitudes from colocated VLBI and GPS antennas using GPS amplitudes from Dong et al. [2002]. Figure 5 shows that there is good agreement for a few sites, but the overall agreement is not very good. The amplitudes are within 1 mm for only 4 sites and within 2 mm for 13 sites.

4. Other Seasonal Errors

The reference points on VLBI antennas range from 5-25 meters above the ground. An antenna structure will expand and contract in response to temperature variations. For an expansion coefficient of 1.2 x 10^{-5} K^{-1} for steel, an annual variation of 40 C (Fairbanks, Alaska) and a reference height of 15 meters, the annual variation in height will be about 4 mm. To model this variation in our analysis, we applied a simple expansion model for each antenna using the height of the reference point and the expansion coefficient (either for steel, aluminum, or concrete depending on the antenna). For each 24-hour session, the average measured temperature was used since we were only interested in seasonal variations and were not trying to model the diurnal variation of antenna height. For many sites, the estimated annual vertical amplitude is reduced when this model is applied. See Figures 2 and 3 and the example of Medicina in Figure 4. This can be seen

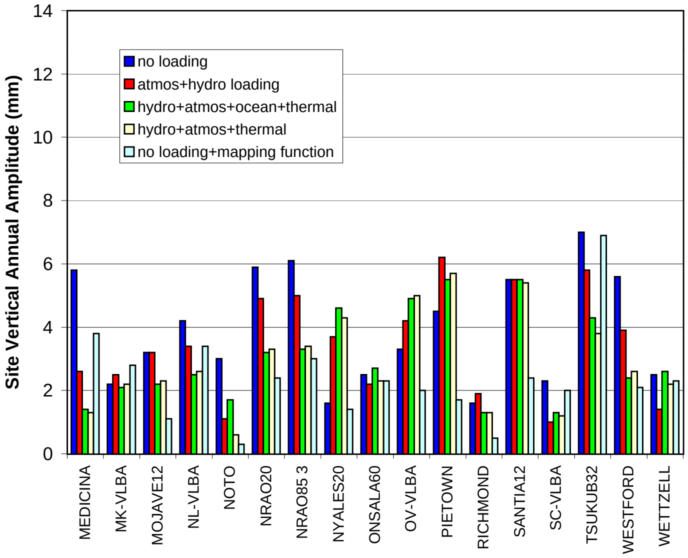

Figure 3. Observed site annual vertical amplitudes and effect of applying different models.

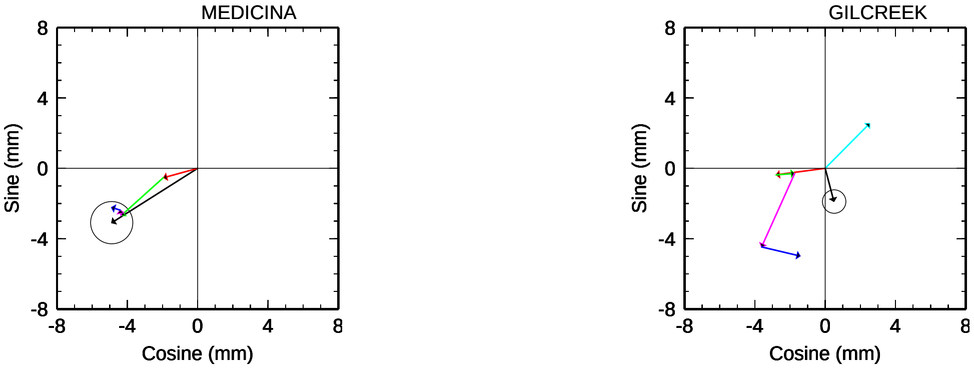

Figure 4. Annual site vertical amplitudes observed at Medicina and Gilcreek (black with 2-sigma error ellipse). For comparison the model contributions to the observed amplitude are summed head to tail starting at the origin: antenna thermal deformation, soil moisture loading, snow loading,and pressure loading.

by comparing the second and fourth bars for each site in Figures 2 and 3.

Our current modeling of tropospheric delay uses the NMF [Niell, 1996] hydrostatic and wet mapping functions. The NMF hydrostatic mapping function has annual amplitudes that depend on latitude. The NMF annual variation reproduces the radiosonde raytrace annual variation reasonably well, but there are errors in amplitude and phase at some sites. To investigate this, we estimated site dependent mapping function parameters (offsets and annual amplitudes of the mapping function coefficients) from the VLBI data. Figures 2 and 3 show that the annual site vertical amplitudes are significantly reduced when these estimated mapping function parameters are applied as a model. This is indicated by the difference between the first and last bars for each site in these figures. More work is required to verify that the estimated mapping functions are reasonable; specifically they will be compared with mapping functions derived from numerical weather model

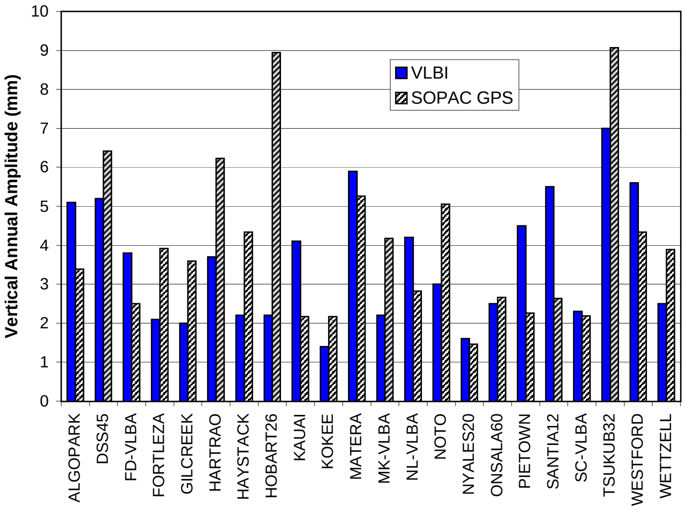

Figure 5. Comparison of annual vertical amplitudes from colocated VLBI and GPS sites.

data (for example, the IMF mapping function derived by A. Niell).

5. Discussion

We find that the annual amplitudes of VLBI vertical displacement are mostly 2-8 mm. The phase of southern hemisphere site variation is generally opposite that for northern hemisphere sites. When hydrology loading models are applied, annual amplitudes are reduced for 70% of the most frequently observing VLBI sites. For most baselines, length repeatabilities are improved. The sum of the annual contributions from mass loading and antenna thermal deformation account for a significant portion of the observed VLBI annual signal at many sites.

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