ATMOSPHERIC, NON-TIDAL OCEANIC AND HYDROLOGICAL LOADING INVESTIGATED BY VLBI

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ABSTRACT. Today, the small deformations associated with the response of the Earth to atmospheric and hydrological loading are of growing interest. These effects cause site- dependent vertical displacements with ranges up to ± 30mm due to atmospheric pressure variations and due to mass redistribution in surface fluid envelopes, in particular in continental water reservoirs (soil moisture, snow cover, and groundwater). Models of site displacements based on new global and regional databases of soil moisture and snow depths are now available and also models exist for non-tidal ocean loading. The NEOS-A VLBI sessions and also the extremely precise CONT sessions (two continuous weeks in 1994 and in 2002) are used to investigate how the effects influence the results of high precision VLBI measurements. Main emphasis is put on the repeatability of station heights and of baseline lengths. Small improvements are achieved when applying the considered loading models but are still not clearly above the significance level. This yields to the conclusion that the global loading models are not yet precise enough in some regions of the Earth and that other uncorrected influences disturb the VLBI measurements.

1. INTRODUCTION

The temporal redistribution of oceanic, atmospheric, and hydrological masses perpetually loads and deforms the Earth's crust. Surface displacements, due to atmospheric mass circulation, are dominated by the effects of synoptic scale systems (1000-2000 km wavelength) having periods of less than two weeks. Peak-to-peak vertical displacements of 10 to 20mm are common at mid-latitudes (Rabbel and Zschau, 1985; van Dam and Wahr, 1987; Manabe et al., 1991). The effects are larger at higher latitudes due to the larger pressure variability found there.

While surface displacements are largest for atmospheric pressure variations with periods of one to two weeks, annual signals are also existing having amplitudes between 0.5 and 3mm. At annual periods, variations in continental water storage become important, too.

Tidal and non-tidal motions of oceanic mass also contribute to the deformation spectrum at points on the Earth's surface. Variations in bottom pressure driven by uncompensated changes in sea surface heights can induce vertical deformations at coastal sites of up to 12mm with periods of approximately one month.

For all of these loading signals, the vertical deformations are larger than the horizontal ones by factor 3 to 10. Given the amplitude of the loading induced vertical crustal motion, it is necessary to evaluate the effects of loading on when interpreting geodetic data. Loading effects caused by the redistribution of surface masses have been observed in high-precision geodetic data for some time now (see for example, van Dam and Herring, 1994; van Dam et al., 1994; MacMillan and Gipson, 1994; Sun et al., 1995; Haas et al., 1997; Scherneck et al., 2000; and van Dam et al., 2001). As the results of space geodetic measurements are more and more being interpreted in terms of geodynamic processes (plate tectonics, post-glacial rebound, sea level rise, etc.) it is becoming necessary to remove loading effects from the geodetic data.

2. MODELS USED FOR LOADING COMPUTATIONS

A brief description of the various approaches for modeling loading displacements is given by Schuh et al. (2003). All loading models need two ingredients:

- the input data in terms of global mass variations;
- the computation of the corresponding displacements using one of the various approaches and based on different Earth models and geodynamic parameters.

For further details see the paper mentioned above. Here, only one example for loading deformations will be given: hydrological loading due to soil moisture. At annual periods, variations in continental water storage are significant. The modeled vertical displacements have ranges of up to 30mm, with root-mean-square values as large as 8mm.

Several new global models exist for soil moisture that were used for our study. These include

- Huang et al. (1996);
- Global Soil Wetness Project (GSWP), (Douville et al., 1999);
- Milly et al. (2002).

All models provide $1° \times 1°$ gridded data of soil water in the upper layer of the ground (usually the top 2 meters) that were interpolated to the position of the ground stations. The GSWP and Milly models provide also snow depth variability.

The annual displacements of Algonquin Park from each of these models are shown in Fig. 1 covering a total range of 3mm. There is about a 2mm peak-to-peak difference in the annual component determined using the Huang model versus the Milly model. Current geodetic techniques can determine annual crustal motions to at least this accuracy, indicating that we may be able to use these techniques to refine the long-wavelength models of soil moisture variability.

3. INVESTIGATION OF LOADING EFFECTS BY VLBI

Considering the accuracies of a few mm that are going to be achieved by high precision global geodetic measurements, it becomes quite clear, that loading displacements have to be taken into account when analyzing space geodetic data.

3.1. VLBI DATA ANALYSIS

In the investigations reported here, all NEOS-A sessions (weekly VLBI measurements, each 24h with 5-7 stations) from January 1996 to December 2001 were analyzed and also the CONT02 session covering a continuous period of 15 days in October 2002. In a first solution following the standard procedure of VLBI analysis no a-priori loading corrections were applied. In the least-squares fit a free network solution was done for each 24h VLBI session to determine baseline lengths; then a second solution was carried out, constraining the horizontal coordinates to

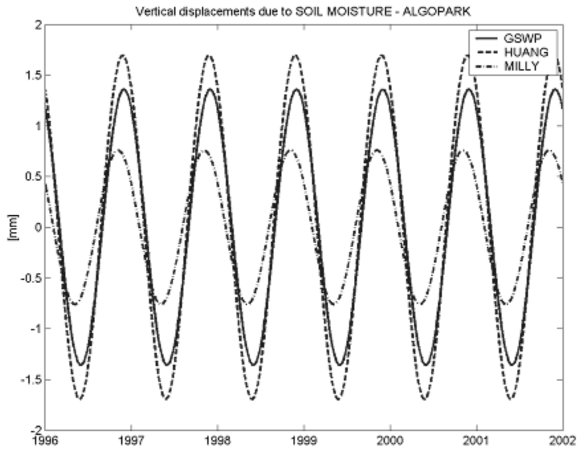

Figure 1: Vertical displacements due to soil moisture

ITRF2000 and estimating the vertical coordinates (i.e. station heights), only. These two solutions will be called 'reference' in the following sections. The VLBI Software package OCCAM (V 5.1) was used for the analysis of the VLBI data. It has been developed by European VLBI groups since 1983 and is applied by six IVS Analysis Centers (three operational Analysis Centers). It can be applied under MS/DOS and Unix or Linux and is a very flexible VLBI program (Titov et al., 2001).

3.1.1. VLBI STATION HEIGHTS AND BASELINE LENGTHS

Now, the VLBI analyses were repeated with a-priori loading corrections applied. Again all NEOS-A sessions from January 1996 to December 2001 were analyzed. The station heights and baseline lengths were determined and compared with the results of the first, uncorrected 'reference' solution by computing the scatter around the mean station heights and around straight-lines fitted to the baseline lengths. Figures 2 and 3 represent the number of VLBI sessions with improved repeatabilities. Improvements of the station heights and baseline lengths when correcting for loading effects were obtained in 64% of all combinations of loading models treated here. The average positive improvement is 3 to 4% never exceeding 13%. If the improvement is negative, i.e. if the results became worse, it is less than 1% on the average.

Considering all of the stations there is not one combination of the loading models that seems to be superior to the others. From this, it can be concluded that the existing mass loading models that were used for this study still have deficiencies on several regions of the globe.

CONT02 was a VLBI sessions observing 15 days continuously in October 2002. The goal of the CONT02 campaign was to acquire the best possible state-of-the-art VLBI data over a two-week period to demonstrate the highest accuracy of which VLBI is capable.

For these sessions only displacements due to atmospheric loading computed by H.-G. Scherneck were available (Scherneck, 2000). As for the NEOS-A sessions, the station heights and baseline lengths were determined. The results of the first 'uncorrected' version were compared with the VLBI results where the atmospheric loading displacements were applied a priori. For these analyses the tropospheric mapping function NMF (Niell, 1996) was used first. Then the computations were repeated with the new tropospheric mapping function IMF (Niell, 2001) in order to test the influence of the chosen mapping function when investigating atmospheric loading.

Improved repeatabilities of the station heights and baseline lengths when correcting for loading effects were obtained in about 75% of all combinations of loading models treated here. The repeatabilities improve at an average of 11% when applying the atmospheric loading displace-

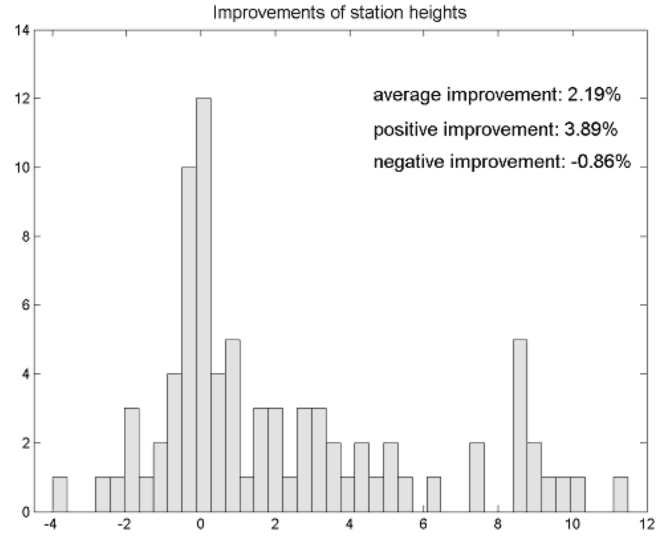

Figure 2: NEOS-A Sessions: Improvements of repeatabilities of station heights

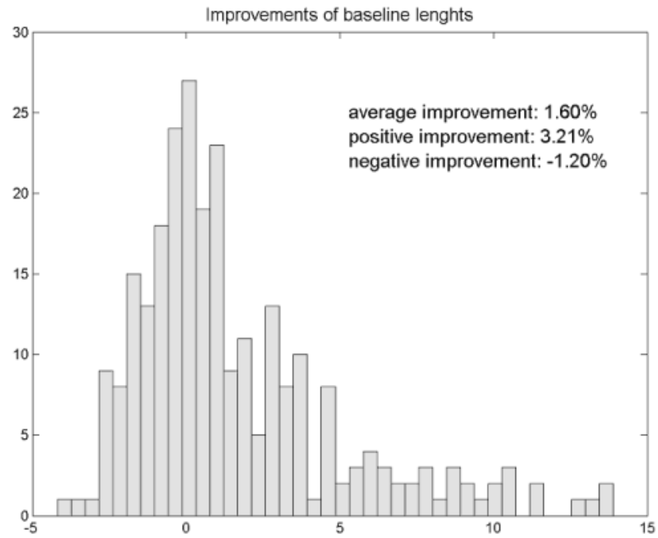

Figure 3: NEOS-A Sessions: Improvements of repeatabilities of baseline lengths

ments and using the NMF. When using the IMF the repeatabilities improve even by 17% on the average.

The results of this investigations are summarized in Tab. 1, which includes the statistics of the continuous session in January 1994 CONT94. It is evident that in particular for the very precise CONT- sessions it is worth applying loading corrections to improve the quality of the geodetic results.

4. CONCLUSIONS

Non-tidal loading effects are in the range of +10 to 30mm and should be corrected when analyzing space geodetic data which are intended to reach an accuracy of a few mm. So far, only weak correlation between VLBI station heights and modeled radial loading displacements (<0.3) can be observed (see Schuh et al., 2003). When applying a-priori corrections due to loading the scatter around the mean station heights and the baseline lengths decreases for most of the

	NEOS-A		CONT 94		CONT 02	
	%	∅	%	∅	% NMF/IMF	∅ NMF/IMF
Baseline lengths	64	3,3	71	12	71/75	3,7/5,2
Station heights	64	3,9	43	25	75/75	10,7/16,8

Table 1: Percentage [%] of improved baseline lengths and station heights and average positive improvements [∅].

stations. The improvements is the bigger the more precise the VLBI observables are and the better the tropospheric refraction is modeled. However, it is obvious, that further improvements of loading models are needed, in particular by using better global models for snow and soil moisture.

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