Investigation of Hydrological and Atmospheric Loading by Space Geodetic Techniques

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Abstract. Observations of sea level can only be interpreted correctly if land motion in particular in terms of vertical deformation of coastal areas is taken into account. In the last decades space geodetic techniques such as VLBI (Very Long Baseline Interferometry), SLR (Satellite Laser Ranging), the GPS (Global Positioning System), and Doris (Doppler Orbitography and Radio positioning Integrated by Satellite) have proved to be very powerful for determining displacements of points on the solid Earth. These can be modeled by using various geodynamical parameters, e.g. the Love and Shida numbers in the model of the solid Earth tides and site-dependent amplitudes and phases of the ocean loading models. 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, and groundwater). Several new global and regional models of soil moisture and snow depths are now available and can be validated by space geodetic techniques. This paper is intended to give a short overview about state-of-the-art of modeling loading effects. A short introduction to the Special Bureau for Loading within the Global Geophysical Fluid Center (GGFC) of the IERS will be given, too. Finally, it will be shown how the effects influence the results of high precision space geodetic measurements. The paper mainly concentrates on vertical crustal motions on seasonal and interannual time scales observed by VLBI and describes also some results obtained from Doris.

Keywords.VLBI, atmospheric loading, hydrological loading, IERS

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 approximately 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 amplitude pressure systems found there.

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

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 height 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,

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van Dam and Herring, 1994; van Dam et al., 1994; MacMillan and Gipson, 1994; Sun et al., 1995; Haas et al., 1997; Scherneck, 2000; and van Dam et al., 2001). As these data 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. Currently, however, there is no clear consensus on how this should be done. In this paper, we compare various atmospheric and hydrological loading models with VLBI measurements. We compare these results with results from Doris.

2 Modeling Loading Effects of the Earth's Crust

The main elements required in the computation of loading predictions include (1) an Earth model, which determines the geometry, with specific mechanical properties and if necessary, the rheology, and (2) a mathematical model for the surface load including the boundary conditions at the Earth's surface and the extension of the load. Selected parts of continuum mechanics can then be used to solve the boundary value problem to obtain the system's response to a unit load. For the problem of Earth deformation, the system's response is best described by Load Love Numbers (LLN's) which can be used to compute the Green's functions of the boundary problem.

For the actual computation of loading effects, surface load data are required for all relevant loads. These loads are then convolved with the Earth's response (either in the space or the wave number domain) to determine the loading effects (e.g. surface displacements, gravity variations, and geocenter displacements). Loading responses to non-tidal surface loads are normally computed in one of three ways:

(1)Point loading approach in which a gridded surface mass is convolved with Green's functions to determine the load response;

(2)Spherical harmonics approach in which the LLN's are used directly to carry out the convolution with a given surface load in the wave number domain. This approach requires the surface loads to be given as a spherical harmonic expansion.

(3)Using a local regression coefficient determined by fitting local changes in pressure to the vertical component of observed deformation.

We refer to the point loading approach and the spherical harmonic approach as 'geophysical approaches' as they are both based on geophysical models. We refer to the local regression coefficient approach as an 'empirical approach'.

The approach chosen for calculating loading deformation is usually determined by the proposed application. For example, if global loading corrections were desired for several years of high resolution loading data, the spherical harmonics approach would be desired because of its computational speed. However a potential problem arises when this approach is used for computing the effects of atmospheric pressure loading on an Earth model that includes an ocean. For simplicity an inverted barometer ocean model is usually applied. In an inverted barometer ocean, the pressure over the oceans is essentially zero. In this case, there is a discontinuity in the atmospheric pressure anomaly at all continental/ocean boundaries as the pressure goes from ambient over the continents to near zero over the oceans. This discontinuity is problematic when one trys to generate a spherical harmonics representation of the pressure. Large errors in the pressure field are introduced at coastal sites. Differences between the vertical displacement calculated using the point loading and spherical harmonics approach for an inverted barometer ocean can reach 11mm.

In the point loading approach, the deformation at a point is determined by convolving a gridded representation of a global load of dimensions N x M with elastic Green's function of dimensions N x M and is thus computationally intensive.

The geophysical model approach (point loading or spherical harmonics) for computing loading effects is based on a physical understanding of the way the pressure interacts with an elastic Earth model. The major advantage of the geophysical model approach is that loading effects can be computed in a standardized way for any point on the Earth's surface more or less instantaneously. The geophysical model approach currently suffers from a number of problems including the requirement of a global pressure data set, a minimum of 24 hours in time delay in the availability of the global pressure data set, limitations of the pressure data itself (low temporal and spatial resolution), uncertainties in the Green's functions, and uncertainties in the ocean response model.

In the empirical approach, site-dependent pressure loading effects are empirically computed by determining the fit of local pressure variations to the geodetic observation of the vertical crustal motion. In this case, the loading correction can be applied in quasi real-time and short-time site displacements due to rapidly changing pressure can be modeled. However, with this approach one is uncertain whether other pressure correlated signals in the geodetic observations are not being fit in the regression coefficient determination.

A two-coefficients-approach has also been proposed (Rabbel and Zschau, 1985) which uses local barometric pressure p(t) and pressure variations in a surrounding area p_{2000km}:

$$\Delta U = -0.55(p_{2000km}(t) - p_{Ref}) - 0.35(p(t) - p_{Ref}) \quad (1)$$

A simple model using local barometric pressure p(t) and atmospheric loading coefficients α for each station was proposed by Manabe et al. (1991):

$$\Delta U = \alpha \cdot (p(t) - pRef) \quad (2)$$

with
p_{Ref} = reference pressure, e.g. mean of several years.
The empirical approach is likely to produce better results than the geophysical approach for a given site but like the geophysical approach, has a number of drawbacks as well.

- Geodetic observations have to be available for a certain period of time before a reliable regression coefficient can be determined; this period of time may be as large as several years.
- The regression coefficients cannot be extrapolated to a new site (for which no data exist);
- The regression coefficient has been observed to change with time and with observing technique;
- The regression coefficient can only be used for vertical crustal motions;
- It is uncertain that other pressure correlated geodetic signals are not being 'absorbed' into the regression coefficient determination. So while this approach would lower the scatter on a given geodetic time series the most, one would always be uncertain whether only atmospheric loading effects were being removed with the correlation coefficient.

3 Models Used for Loading Computations

In this section, we discuss the various loading fields and look in detail at the computed loading effects in the vertical.

3.1 Atmospheric Loading

Since 1985 several studies on atmospheric loading have been carried out, e.g. by Rabbel and Zschau (1985), Rabbel and Schuh (1986), van Dam and Wahr (1987), Manabe et al. (1991), van Dam and Herring (1994), MacMillan and Gipson (1994), van Dam et al. (1994), Sun et al. (1995), Haas et al. (1997), Scherneck (2000).

Three basic methods for computing atmospheric loading corrections to geodetic data have been applied in the various references given above:
(1)using
(2)geophysical models or simple approximations derived from these models (following schemes 1 or 2 described in section 2);
(3)using empirical models based on site-dependent data (following scheme 3 described in section 2);
(4)a hybrid method combining the two previous methods.

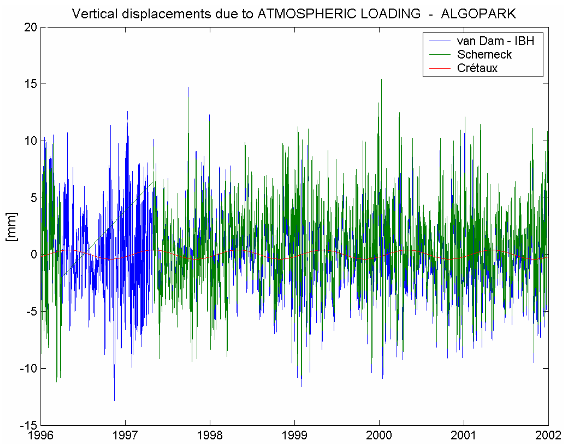

Fig. 1 Vertical displacements due to atmospheric loading at Algonquin Park

In a hybrid method (3.), regression coefficients determined from a geophysical model instead of geodetic observations could be used to operationally correct observed vertical position determination from local air pressure alone. The vertical deformation caused by the change in pressure, in this case, can then be given in terms of a local pressure anomaly. The regression coefficients can be determined by fitting local pressure to the vertical deformation predicted by the geophysical model. Regression coefficients determined in the manner would still suffer from both the uncertainty in the Green's functions and the quality of the air pressure data.

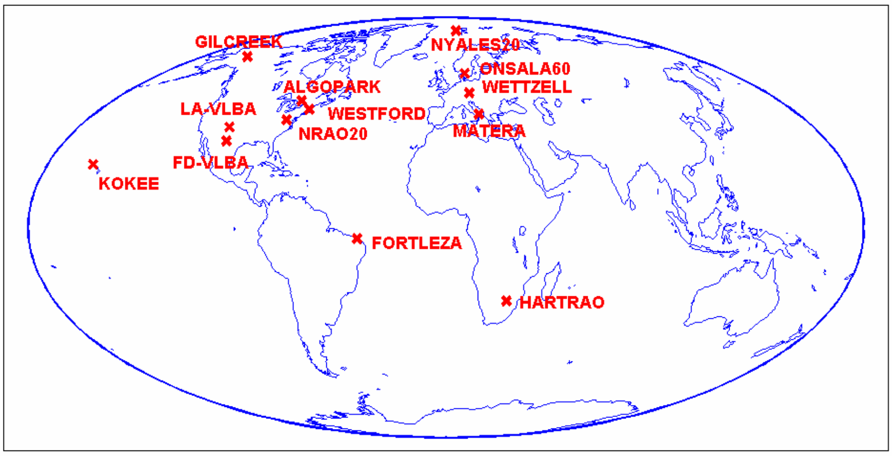

Fig. 2 Global distribution of VLBI sites

The data used for the atmospheric loading computations by van Dam and Crétaux were taken from the National Center for Environmental Prediction (NCEP) reanalysis data set. This global data set is provided on a 2.5°x2.5° global grid at 6 hour periods. Scherneck used the data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).The vertical displacements of VLBI station Algonquin Park located in eastern Canada as modelled by the various authors for an inverted barometer ocean model are plotted in Fig. 1.

At this site, we observe that peak-to-peak surface motions of 20mm are common. As hardly can be seen in the black/white figure the differences between van Dam's and Scherneck's results are at ±3mm. Crétaux determined the annual variations only for which he obtained a rather small amplitude. Displacements for the same period would be smaller for low altitude sites due to the smaller pressure variations found in the low to equatorial latitudes. Algonquin Park is located approximately 500km inland from the Atlantic ocean and is thus classified as a continental site (see Fig. 2). Coastal sites at the same latitude would experience smaller atmospheric loading displacements due to the inverted barometer effect.

3.2 Hydrological Loading

At annual periods, variations in continental water storage are significant. The modeled vertical displacements have root-mean-square values as large as 8mm, with ranges of up to 30mm.

3.2.1 Soil Moisture

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

- Huang et al. (1996) which provide monthly results for 1979-1993;
- Global Soil Wetness Project (GSWP), (Douville et al., 1999);
- Milly et al. (2002) which provide groundwater, soil moisture and snow for the period 1978-1998.

These models solve for a water balance equation of the form dw/dt = P-E-R (where w is soil water, t is time, P is precipitation, E is evapotranspiration, and R is runoff). In this approach, the forcing terms (precipitation, and atmosphere and landmass energy fluxes) are derived from observations. The GSWP and Milly models provide also snow depth variability. All models provide 1°x1° gridded data of soil water in the upper layer of the ground (usually the top 2 meters) that we have interpolated to the position of the ground stations where geodetic instruments are installed.

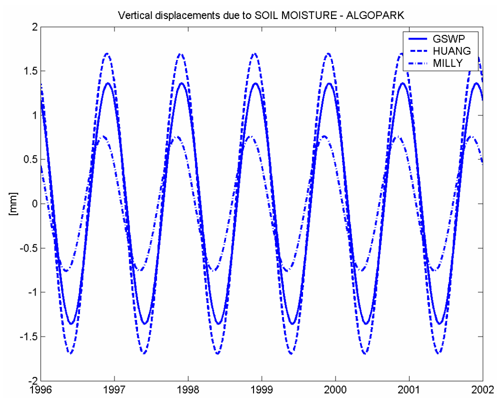

Fig. 3 Vertical displacements due to soil moisture at Algonquin Park

The annual displacements of Algonquin Park from each of these models are shown in Fig.3 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.

3.2.2 Snow Cover

We compared vertical crustal motions predicted from the following models of snow cover:
- International Satellite Land Surface Climatology Project (ISLSCP, Meeson et al., 1995);
- Global Soil Wetness Project (GSWP, Douville et al., 1999);
- Milly et al. (2002).

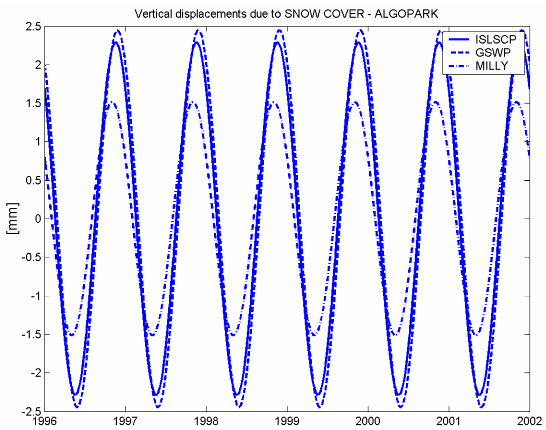

Fig. 4 Vertical displacements due to snow cover at Algonquin Park

The displacements were again modeled in terms of annual variations (see Fig. **4**) with a total range of 6mm. There is about a 2mm peak-to-peak difference in the annual component determined using the GSWP model versus the Milly model. Again, current geodetic techniques should be able to resolve this signal to such an extent that we might be able to improve the long-wavelength models of snow cover.

3.3 Oceanic Loading

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 height can induce vertical deformations at coastal sites of up to 20mm with periods of approximately one month (van Dam et al., 1997).

3.3.1 Ocean Tide Loading

The calculation of ocean tidal loading effects is analogous to methods described in section 2 as the geophysical model approach. Computation of ocean tidal loading requires two ingredients, namely ocean tidal models describing the load and Earth models, on which the load acts. For ocean tide loading the parameters provided by Scherneck et al. (2000), from his Web-based ocean loading service (http://www.oso.chalmers.se/~loading) were used. The Green's functions are from Farrell (1972) and the Gutenberg-Bullen A Earth model was used; 11 tides were considered. It should be mentioned that the coastline is treated very well by Scherneck.

3.3.2 Non-Tidal Oceanic Loading

For non-tidal oceanic loading data were taken from TOPEX/Poseidon (T/P) and from the Parallel Ocean Climate Model (POCM, Johnson et al., 1999). From Fig. 5 it can be seen that the agreement between the two models is rather poor but fortunately the effect itself is very small.

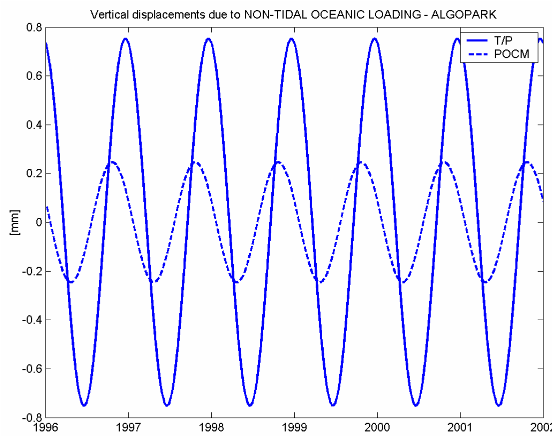

Fig. 5 Vertical displacements due to non-tidal oceanic loading at Algonquin Park

4 The Special Bureau for Loading within the Global Geophysical Fluid Center (GGFC) of the IERS

On 1 January 1998, the International Earth Rotation Service IERS established the Global Geophysical Fluids Center (GGFC) in an effort to expand the

IERS services to the scientific community. Under the GGFC, seven Special Bureaus (SB) were established (see http://bowie.gsfc.nasa.gov/ggfc/). Each of these is responsible for research activities relating to a specific Earth component or aspect of the geophysical fluids of the Earth system. However, until recently, there was no specific focus on the interaction of the different components through gravitational and surface forces on the boundaries. In particular, consistent models of the deformation of the solid Earth due to loading of the atmosphere, ocean and terrestrial hydrosphere are presently not available. This fact is reflected in the IERS Conventions 2000 (2003), where standard models for solid Earth tides and ocean loading are discussed while no standard procedure is recommended for the case of other surface loading effects.

In order to foster the development of consistent models for predicting loading effects, the IERS on 31 October 2001 issued a Call for Proposals for a Special Bureau for Loading (SBL). In this call it was stated that the IERS Conventions currently do not give comprehensive recommendations for treating the loading signals due to the full range of possible effects and that it therefore was timely to set up the tools that provide a basis for a future conventional treatment of loading effects in all IERS analyses. Furthermore, it was pointed out that meeting future requirements calls for considerable theoretical work, algorithm development, model compilations and studies of relevant observations.

Eventually, the SBL is expected to provide in near real-time a consistent global solution data set describing at least the surface deformation, gravity signal and geocentre variations due to the various surface loading processes, in reference frames relevant for direct comparison with existing geodetic observing techniques.

On 1 February 2002, the SBL (see http://www.gdiv.statkart.no/sbl/) was formally established with a team of ten members. Their expertise covers all areas relevant for accurately modeling surface deformations, namely:

(1) the theory of Earth deformation and Earth models,
(2) observations of surface loads,
(3) computation of tidal and non-tidal loading effects,
(4) and space geodetic and gravimetric observations.

The team also includes the seven chairs of the existing SB. These chairs are ex-officio members of the SBL and participate in the SBL to insure close cooperation between their SB and the SBL.

The accuracy of the products provided through the SBL should, as much as model limitations allow,match the precision of the space geodetic and gravimetric observing techniques. Achieving this ambitious goal requires major scientific advances with respect to the Earth model, the theory and algorithms used to model deformations of the Earth and the surface loading data. Consequently, a scientific agenda has been established to perform the research necessary for the improvement of the models and algorithms, in parallel with an operational agenda which is directed towards establishing a service which provides validated loading products to IERS community.

5 Investigation of Loading Effects by Space Geodetic Technique

Loading displacements have to be taken into account when analyzing space geodetic data.

5.1 Application of Atmospheric Loading Corrections to VLBI Data

First, results will be briefly summarized, that were obtained by Haas et al. (1997) using a site-dependent loading model following eq. (2) with α = -0.4. The local pressure p(t) was taken from records of atmospheric data during the VLBI sessions and the reference pressure p_{Ref} was computed as mean of several years.

In a first step this simple model was applied to subsets of the global VLBI data set. The VLBI results (e.g. baseline lengths) change by a few mm when the atmospheric loading corrections are applied but the post-fit residuals and the baseline length repeatability improve only marginally. Possible reasons for that might be the very simple model which was used, the question of IBH or non-IBH, and possible local effects at some VLBI stations.

In a second step the atmospheric loading coefficients α were determined from VLBI data for 18 stations. The global VLBI data set contained about 800.000 delay observations covering 18 years. When solving for atmospheric loading coefficients the $\chi 2$ decreases slightly by 0.2% and most of the results are numerically significant and are reasonable with respect to the theoretical models. However for some stations the empirical results obviously disagree with the theoretical coefficients. The model parameters and VLBI estimates of atmospheric loading coefficients α are given by Haas et al. (1997).

5.2 VLBI Data Analysis Using the OCCAM Software

In the investigations reported here, all NEOS-A sessions (weekly VLBI measurements, each 24h with 5-7 stations) from Jan. 1996 to Dec. 2001 were analyzed. In a first solution following the standard procedure of VLBI analysis no a-priori loading corrections were applied. In the least-squares fit relative station coordinates were estimated for each 24h VLBI session and used to determine station heights and baseline lengths. This solution 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 6 IVS Analysis Centers (3 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).

5.2.1 Correlation Coefficients

Various sums of the loading effects were computed for the same time epochs as the VLBI estimates considering several combinations of the different models described in section 3 (see Table 1). As an example the geodetic results for Algonquin Park are plotted in Fig. 6. During some time intervals the agreement between the model and the observed station heights is quite good but there are also time intervals when the correspondence is very poor probably because the VLBI estimates are biased by other effects such as unmodelled tropospheric bending. Now, the correlation coefficient between the 'reference' and the modeled loading displacements in terms of various sums of the loading effects were calculated for all VLBI stations. For most of the stations the correlation is very weak with correlation coefficients of less than 0.3.

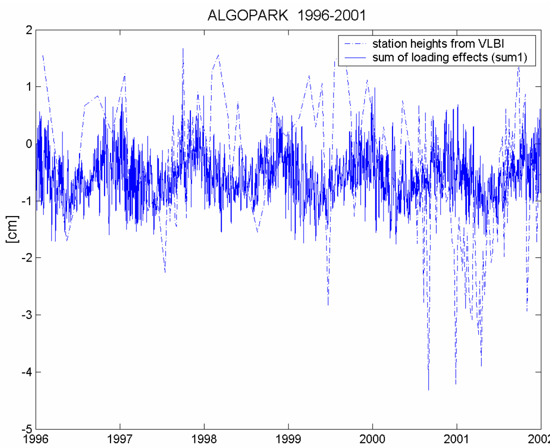

Fig. 6 Station heights and sum of loading effects (sum1) at Algonquin Park

5.2.2 VLBI Station Heights and Baseline Lengths

Now, the VLBI analyses were repeated with a-priori loading corrections applied. Again all NEOS-A sessions from Jan. 1996 to Dec. 2001 were analyzed. Relative station coordinates were estimated and the station heights and baseline lengths were determined and compared with the results of the first, uncorrected 'reference' solution. Finally, the scatter of the station heights and of the baseline lengths was computed. The two tables (Table 2 and Table 3) give standard deviations in [cm] representing the repeatability around a mean station height, and around a straight-line fitted to the baseline lengths. Each first column gives the repeatabilities of the reference solution where no loading corrections were applied. Improved repeatabilities of the station heights when correcting for loading effects, indicated by grey figures in the tables, were obtained in 64% of all combinations of loading models treated here. However, the average improvement is only at 3,9% never exceeding 11,5%. For some stations (ALGOPARK and WESTFORD) all various combinations of loading models yield improved repeatabilities. Considering all of the stations there is not one combination of the loading models that seems to be superior to the others. Similar conclusions can be drawn for the baseline lengths (Table 3). From this, it can be concluded that the existing mass loading models that were described in section 3 and were used for this study still have deficiencies on several regions of the globe.

5.3 Radial Displacements Determined by Doris

Doris is a satellite tracking system based on a dense network of around 50 beacons that have been deployed in the early 1990s. We have analyzed seven years (1993-1999) of Doris data on Spot-2, Spot-3, Spot-4 and Topex/Poseidon. Details on the Doris data processing can be found in Crétaux et al. (1998).

For the current study we have used a software developed at the GRGS which is based on the dynamical computation of satellite orbits, simultaneously with determination of station coordinates and velocities as well as polar motion. For this analysis we have computed monthly 3-D coordinates of the beacons of the Doris network and used the vertical time series. Ocean tide loading effect has been computed for each site and removed during the orbital computation, but not the atmospheric, the non-tidal oceanic, and continental water loading. Among the 50 beacons of the Doris network, only 16 of them have presented significant vertical fluctuations (with respect to noise) at the seasonal time scale. Then for each of the selected stations an annual signal was adjusted which is supposed to reflect surface loading. This was then compared to the annual signal predicted by the different surface loading models.

The first aim was to check the coherence between the Doris system and the model predictions, then if possible, to use the comparisons to discriminate between the models. Table 4 gives the comparison made between Doris annual vertical displacements and three combinations of the models, based on different models for continental waters (soil moisture + snow). It indicates that globally, the model Huang + ISLCP is closer to Doris in amplitude as GSWP but less coherent in phase. The Milly model does not show any evident improvement. The same comparison was also made for the non-tidal oceanic contribution, and this showed without any doubt that the POCM model underestimates the annual vertical deformation of the crust. We have also tried to compare the discrepancies observed in Table 4 with the locations of the stations, but there is no clear geographical correlation. It is certainly too premature to draw any final conclusion about the discrimination between models. A more reliable comparison needs to be performed with more geodetic stations.

Table 1. Sum of loading effect

sum of loading effects	atmospheric loading effect	snow cover loading effect	soil moisture loading effect	non-tidal oceanic loading effect
sum 1	van Dam IBH	MILLY	MILLY	T/P
sum 2	van Dam IBH	GSWP	GSWP	T/P
sum 3	van Dam NIBH	ISLSCP	HUANG	T/P
sum 4	van Dam NIBH	ISLSCP	HUANG	POCM
sum 5	Crétaux	MILLY	MILLY	T/P
sum 6	Scherneck	MILLY	MILLY	T/P
sum 7	Scherneck	GSWP	GSWP	T/P
sum 8	Scherneck	MILLY	MILLY	POCM
sum 9	Scherneck	GSWP	GSWP	POCM

Table 2. Repeatabilities of the mean station heights in [cm]; improvements in grey figures.

VLBI station	reference (no loading effect)	sum of loading effects applied a-priori sum 1	sum 2	sum 3	sum 4	sum 5	sum 6	sum 7	sum 8	sum 9
ALGOPARK	1,30	1,28	1,29	1,29	1,28	1,28	1,26	1,27	1,26	1,27
FORTLEZA	1,96	1,96	1,96	1,96	1,96	1,96	1,97	1,96	1,96	1,96
GILCREEK	1,08	1,08	1,08	1,11	1,10	1,12	0,98	0,98	0,98	0,98
KOKEE	1,52	1,52	1,52	1,51	1,52	1,52	1,52	1,52	1,52	1,52
MATERA	1,33	1,27	1,28	1,29	1,34	1,25	1,29	1,31	1,33	1,35
NRAO20	1,66	1,66	1,67	1,68	1,67	1,66	1,65	1,66	1,64	1,65
NYALES20	1,40	1,37	1,38	1,39	1,41	1,36	1,34	1,34	1,35	1,35
WESTFORD	0,66	0,59	0,60	0,59	0,58	0,61	0,60	0,61	0,59	0,60
WETTZELL	1,14	1,16	1,16	1,14	1,14	1,16	1,08	1,08	1,08	1,08

Table 3. Repeatabilities of the baseline lengths in [cm]; improvements in grey figures.

Baselines	reference (no loading effect)	sum of loading effects applied a-priori sum 1	sum 2	sum 3	sum 4	sum 5	sum 6	sum 7	sum 8	sum 9
ALGOPARK FORTLEZA	0,98	0,98	0,98	0,98	0,98	0,99	0,99	1,00	0,99	0,99
ALGOPARK GILCREEK	0,63	0,62	0,62	0,63	0,63	0,62	0,62	0,63	0,62	0,63
ALGOPARK KOKEE	0,92	0,89	0,89	0,89	0,89	0,90	0,90	0,91	0,91	0,91
ALGOPARK MATERA	1,03	0,95	0,95	0,96	0,96	0,94	0,97	0,97	0,98	0,98
ALGOAPRK NRAO20	0,32	0,32	0,31	0,31	0,32	0,31	0,32	0,32	0,32	0,32
ALGOPARK NYALES20	0,55	0,54	0,55	0,54	0,54	0,55	0,54	0,55	0,53	0,54
ALGOPARK WETTZELL	0,67	0,65	0,66	0,65	0,65	0,65	0,64	0,65	0,64	0,65
FORTLEZA GILCREEK	1,50	1,50	1,50	1,52	1,52	1,50	1,40	1,41	1,40	1,40
FORTLEZA KOKEE	1,64	1,66	1,65	1,63	1,63	1,66	1,66	1,64	1,64	1,63
FORTLEZA NYALES20	1,39	1,39	1,39	1,38	1,39	1,38	1,39	1,38	1,38	1,37
FORTLEZA WESTFORD	0,70	0,66	0,66	0,66	0,67	0,66	0,67	0,66	0,67	0,67

FORTLEZA WETTZELL	1,02	1,05	1,04	1,03	1,04	1,05	1,04	1,04	1,04	1,04
GILCREEK KOKEE	0,59	0,58	0,57	0,57	0,56	0,60	0,58	0,57	0,59	0,58
GILCREEK NYALES20	0,52	0,49	0,50	0,53	0,53	0,46	0,51	0,52	0,51	0,52
GILCREEK WETTZELL	0,83	0,82	0,83	0,83	0,84	0,82	0,81	0,81	0,81	0,81
KOKEE MATERA	1,18	1,11	1,11	1,20	1,23	1,06	1,08	1,08	1,13	1,14
KOKEE NRAO20	1,16	1,16	1,17	1,17	1,17	1,16	1,15	1,16	1,15	1,16
KOKEE NYALES20	1,21	1,22	1,22	1,20	1,21	1,21	1,23	1,22	1,22	1,22
KOKEE WESTFORD	0,70	0,63	0,63	0,64	0,63	0,65	0,64	0,63	0,65	0,64
KOKEE WETTZELL	1,28	1,30	1,30	1,28	1,28	1,31	1,28	1,27	1,28	1,27
NYALES20 WETTZELL	0,40	0,40	0,40	0,40	0,40	0,40	0,39	0,39	0,39	0,39
WESTFORD WETTZELL	0,62	0,54	0,53	0,57	0,54	0,55	0,60	0,59	0,61	0,60

Table 4. Doris / loading model comparison (for ocean the Topex/Poseidon data were used, and NCEP gridded data sets were used for the atmospheric contribution). In parenthesis the correlation coefficients which are related to coherence in phase between the Doris time series and model's predictions are indicated. Amplitudes are expressed in mm/yr.

Stations	Doris annual Amplitude	Huang+ISLCP	Milly	GSWP
Reykjavik	3.5	2.0 (0.44)	0.7 (0.72)	0.8 (0.70)
Badary	4.4	4.8 (0.93)	2.8 (0.95)	3.9 (0.96)
Tristan	2.6	1.6 (0.99)	2.0 (0.97)	2.0 (0.98)
Dakar	3.6	2.4 (0.97)	2.0 (0.92)	1.9 (0.99)
Yellowknife	3.4	4.8 (0.63)	2.0 (0.90)	4.1 (0.97)
Fairbanks	9.9	4.0 (0.47)	4.2 (-0.15)	4.0 (-0.25)
Yarragadee	3.1	3.2 (0.79)	2.3 (0.44)	2.9 (0.49)
Noumea	1.8	1.4 (-0.81))	1.6 (-0.90)	1.4 (-0.89))
Ny-Alesund	3.0	2.4 (0.95)	2.7 (0.90)	1.9 (0.86)
Hartebeesthoek	4.2	3.0 (0.60)	1.9 (0.92)	1.9 (0.93)
Libreville	3.2	2.3 (0.99)	2.1 (0.99)	1.9 (0.92)
Ottawa	5.2	4.9 (0.99)	2.5 (0.99)	4.9 (0.96)
Kauai	1.7	1.4 (0.37)	1.7 (0.36)	1.6 (0.35)
Arequipa	1.8	2.6 (0.24)	2.8 (0.30)	2.1 (0.27)
Syowa	0.9	1.6 (0.88)	2.2 (0.93)	1.4 (0.91)
La-Reunion	8.0	2.5 (0.99)	2.3 (0.90)	2.5 (0.95)

6 Conclusions

The non-tidal loading effects are in the range of ±10 to 30mm and should be corrected when analyzing space geodetic data. So far, only weak correlation between VLBI station heights and modeled radial loading displacements (<0.3) can be observed. When applying a-priori corrections due to loading the scatter around the mean station heights and the baseline lengths decreases for most of the stations. However, further improvements of loading models are needed, in particular by using better global models for snow and soil moisture.

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