Journal of Geodesy (2002) 76: 419–427
DOI 10.1007/s00190-002-0272-7

Journal of Geodesy

GPS measurements of ocean loading and its impact on zenith tropospheric delay estimates: a case study in Brittany, France

S. Vey[1], E. Calais[1], M. Llubes[2], N. Florsch[2], G. Woppelmann[2], J. Hinderer[3], M. Amalvict[3], M. F. Lalancette[4], B. Simon[4], F. Duquenne[5], J. S. Haase[6]

[1] CNRS Géosciences Azur, Sophia Antipolis, France
[2] Université de La Rochelle, France
[3] Ecole et Observatoire des Sciences de la Terre, Strasbourg, France
[4] Service Hydrographique et Océanographique de la Marine, Brest, France
[5] Ecole Supérieure des Géomètres Topographes, Le Mans, France
[6] ACRI-ST, Sophia Antipolis, France

Received: 16 July 2001 / Accepted: 25 April 2002

Abstract. The results from a global positioning system (GPS) experiment carried out in Brittany, France, in October 1999, aimed at measuring crustal displacements caused by ocean loading and quantifying their effects on GPS-derived tropospheric delay estimates, are presented. The loading effect in the vertical and horizontal position time series is identified, however with significant disagreement in amplitude compared to ocean loading model predictions. It is shown that these amplitude misfits result from spatial tropospheric heterogeneities not accounted for in the data processing. The effect of ocean loading on GPS-derived zenith total delay (ZTD) estimates is investigated and a scaling factor of 4.4 between ZTD and station height for a 10° elevation cut-off angle is found (i.e. a 4.4-cm station height error would map into a 1-cm ZTD error). Consequently, unmodeled ocean loading effects map into significant errors in ZTD estimates and ocean loading modeling must be properly implemented when estimating ZTD parameters from GPS data for meteorological applications. Ocean loading effects must be known with an accuracy of better than 3 cm in order to meet the accuracy requirements of meteorological and climatological applications of GPS-derived precipitable water vapor.

Keywords: Ocean loading – Zenith tropospheric delay – Global positioning system – Absolute gravity – Brittany

Correspondence to: E. Calais,
Department of Earth and Atmospheric Sciences,
Purdue University, West Lafayette, IN 47907-1397, USA.
e-mail: ecalais@purdue.edu
Tel. : + 1-765-496-2915; Fax: + 1-765-496-1210

1 Introduction

The periodic motion of the Earth's surface due to the forcing from ocean tides, referred to as 'ocean loading', is the second largest periodic motion of the Earth's crust after the solid Earth tides in areas with energetic ocean tides, such as the Atlantic coast of Europe. Their frequency content is dominated by semi-diurnal (M_2, S_2, N_2, K_2) and diurnal (O_1, K_1, P_1, Q_1) constituents. The amplitude of the Earth's surface motion due to ocean loading can reach several centimeters in the vertical component and one-tenth to one-third of this in the horizontal component in coastal regions. Such displacements are large enough to be measured with space geodetic techniques such as the global positioning system (GPS) (Baker et al. 1995; Dragert et al. 2000; Khan and Tscherning 2001).

Ocean loading is usually described by the convolution of a surface load derived from a barotropic ocean tide model using the Green function describing the elastic response of the Earth's crust to that load (see e.g. Farrell 1972; Scherneck 1991; Agnew 1997). Ocean tide models agree well with each other and with observations over most of the open oceans (see e.g. Shum et al. 1997), but still need improvements in particular in certain coastal areas. The main limitations of current coastal tide models include the bathymetry accuracy, non-astronomical effects (e.g. river outflows), a shallow continental shelf and coastal lines, and the baroclinic effects which are not assumed in these models. In addition, the elastic response of the Earth's crust depends on spatial variations of its rheology and structure, whereas loading models use a spherically symmetric PREM (preliminary earth model) (Dziewonski and Anderson 1981). However, this approximation has a minor impact on ocean loading predictions, which are usually accurate except in some coastal areas and shallow seas. In such cases, direct geodetic measurements of ground motion may provide useful constraints for improving the modeling of ocean loading (Khan and Tscherning 2001).

Accurate models of ocean loading are important for precise geodetic positioning, in particular for sub-daily positions (Baker et al. 1995), and for the determination of polar motion and UT1 parameters (Scherneck and Haas 1999). In addition, because of the potential use of GPS-derived tropospheric delays for meteorological and climatological applications (see e.g. Bevis et al. 1992; Duan et al. 1996), ocean loading must be accurately modeled in order to provide tropospheric delay estimates that meet the accuracy requirements imposed by these new applications (Dach et al. 2000; Dragert et al. 2000).

This paper presents the results from a GPS experiment carried out in Brittany, France, in October 1999, aimed at measuring crustal displacements caused by ocean loading and at quantifying their impact on GPS-derived precipitable water vapor (PWV).

2 GPS measurement and data analysis

The study area is Brittany, northwestern France, a 200-km-long peninsula advancing westward into the Atlantic ocean, where ocean tides can reach up to 10 m. Figure 1 shows the predicted vertical crustal displacements using the CSR4.0 ocean tide model, which has the best fit for Europe (Eanes 1999) with eight principal diurnal and semi-diurnal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2) over a 12-hour period. Vertical ground motion caused by the M_2 constituent reaches up to 9 cm peak-to-peak at Brest, at the westernmost tip of Brittany, during our study. It still reaches 3 cm peak-to-peak 150 km inland at Le Mans. In addition, horizontal motions are also significant, with a predicted peak-to-peak amplitude of 3 cm at Brest, for instance.

We performed a GPS campaign in Brittany over 3 days (24–27) October 1999 (Fig. 1). We installed eight dual-frequency GPS receivers sampling at 30-s intervals, in addition to those continuously operating at the permanent sites of Brest and Le Mans. We processed the GPS data using the GAMIT Software, release 9.7 (King and Bock 1999). In order to obtain precise coordinates for the GPS sites, we first processed the pseudorange and phase GPS data in 24-hour sessions. We included six core IGS stations (International GPS Service; Graz, Matera, Villafranca, Kootwijk, Zimmerwald, Onsala) in order to serve as ties to the 1997 International Terrestrial Reference Frame (ITRF97; Boucher et al. 1999), and decorrelate the tropospheric estimates (Tregoning et al. 1998). We solved for regional station coordinates, satellite state vectors, 13 tropospheric zenith delay parameters per site and day, and phase ambiguities using doubly differenced GPS phase measurements. We used the IGS final orbits and IERS (International Earth Rotation Service) Earth orientation parameters. We used a 10° cut-off angle and elevation-dependent antenna phase center models following the tables recommended by the IGS. We applied solid Earth and polar tide corrections following the IERS standards (IERS 1996), as well as ocean loading corrections using the CSR4.0 ocean tide model (Eanes and Shuler 1999) and the eight principal diurnal and semidiurnal tidal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2). We then combined our loosely constrained solution with the daily global SINEX files produced by Scripps Institution of Oceanography and finally implemented the terrestrial reference frame (ITRF97) using a seven-parameter transformation. Using session day-to-day repeatabilities (weighted RMS of the scatter to the weighted mean over the whole time series) as a statistical indicator, we found that the precision of our GPS measurements was 2–3 mm horizontally and 5–10 mm vertically, which are typical values for such networks.

In order to detect periodic ground motion due to ocean loading, in particular the vastly predominant M_2 harmonic of period 12.42 hours, we tested various processing strategies. Indeed, it is well known that the accuracy of GPS measurements deteriorates with decreasing session length, mostly because of multipath and satellite constellation geometry effects that average out over 24-hour periods (see e.g. Bock et al. 2000). In

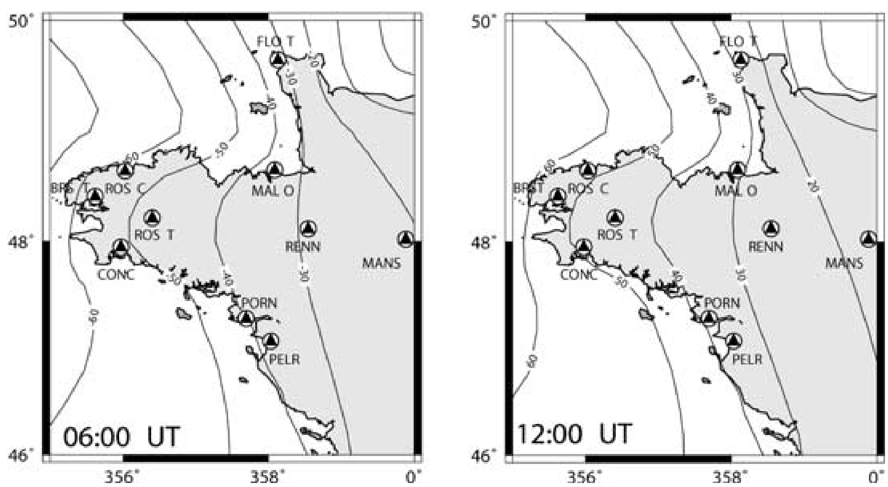


Fig. 1. Location of the GPS sites in Brittany. Contour lines represent the vertical displacement in millimeters predicted using the CSR4.0 ocean tide model and the eight principal diurnal and semi-diurnal tidal constituents (O_1, P_1, Q_1, K_1, M_2, S_2, N_2, K_2) for 24 October 1999

addition, the ratio of the number of parameters to observables decreases and it becomes difficult to simultaneously solve for integer ambiguities, together with the position and tropospheric delay parameters. We found that the best results were obtained with 3-hour sessions, a 10° cut-off angle, without estimating tropospheric delay parameters. The averaging introduced by this rather coarse sampling (3 h) of the ~12 hour period M_2 tidal component results in an error of less than 5% of the measured signal, i.e. about 4 mm in the vertical and 1.5 mm in the horizontal component at Brest, where the M2 signal is the largest. These errors are small enough not to be a factor in the rest of the analysis.

We also used ground meteorological values of temperature, pressure, and humidity at the GPS sites and a Saastamoinen atmospheric model (Saastamoinen 1972). In an another strategy, we fixed a priori zenith tropospheric delays extracted from the HIRLAM numerical weather prediction model in analysis mode (H. Vedel, pers. comm. 2000). Both strategies result in similar horizontal position estimates (within 1–3 mm) across the network but vertical position estimates vary within about 1 cm. The 3-hour solutions are a compromise between shorter but noisier sessions, and longer sessions that would undersample the M_2 tidal loading signal. Using this strategy, we were able to fix nearly 100% of the integer ambiguities. Using session repeatabilities (weighted RMS of the scatter to the weighted mean over the whole time series) as a statistical indicator, we find that the precision of the GPS measurements using 3-hour sessions is 1.5 cm for the horizontal and 4 cm for the vertical baseline components.

An important aspect of our data processing strategy is that we did not fix any of the station positions to their a priori values, but rather used a priori constraints of 10 cm in the horizontal component and 20 cm in the vertical. Fixing the positions, together with the orbits and Earth orientation parameters, would result in propagating errors into other estimated parameters in the least squares (LS) inversion process. We chose the a priori constraints to be 50% higher than the maximum predicted ocean loading effect in Brittany at the time of the experiment.

3 Position estimates

Figure 2 shows the baseline component time series for two baselines derived from the GPS measurements without correcting for ocean loading together with the predicted ocean loading signal. Both baselines show a good overall agreement between the model and the measurements. The GPS measurements show a 12-hour periodic signal with peak-to-peak amplitudes of 9 cm in the vertical component and 3 cm in the horizontal component, well correlated in phase and amplitude with the ocean loading model. We compared the GPS measurements with the ocean loading prediction based on the Le Provost et al. (1998) and the GOT99.2 (Ray 1999) ocean tide models and found differences no larger than 0.9 cm. The precision of GPS measurements over 3-hour sessions for long baselines (>50 km) is not sufficient to discriminate between these models.

Both baselines also show a significant misfit on the vertical component between models and measurements during the second half of day 298, with a 6–7-cm residual, too large to be explained by differences between ocean tide models. The misfit is particularly evident for the FLOT–ROSC baseline. There are also noticeable misfits in the second half of day 300. We first thought

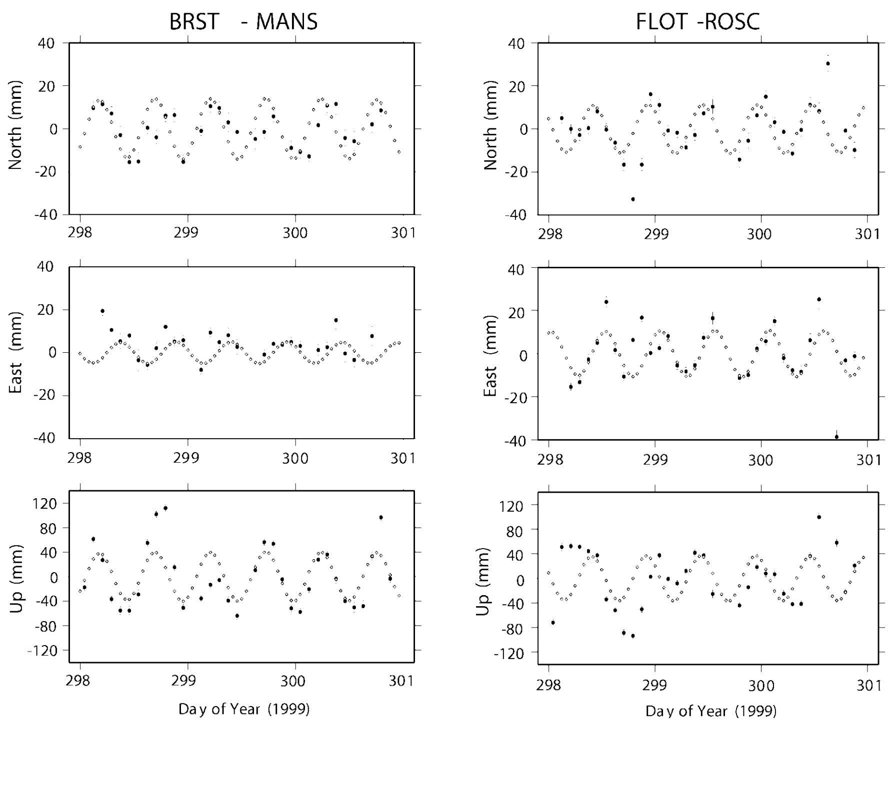


Fig. 2. Baseline components time series derived from GPS measurements (*black dots* with 1-sigma error bars, 3-hour sessions) and ocean loading predictions (*grey diamonds*) for the Brest–Le Mans and Flottemanville–Roscoff baselines. Ocean loading was computed using the CSR4.0 ocean tide model with eight diurnal and semi-diurnal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2). The GPS baselines were computed without solving for ZTD parameters

that the misfit on day 298 could be due to an exceptionally large tidal load caused by anomalous wind and/or atmospheric pressure conditions associated with a storm that passed over Brittany from west to east during the first two days of the experiment. However, the tide gauge record at Brest does not show any significant variations on day 298 (25 October 1999) compared to the prediction of ocean tide models (Fig. 3). In addition, we simulated the effect of a 1-m variation of water level over the area between latitudes 46°N and 51°N and longitudes 005.5°W and 002°E (area around Brittany and the English Channel) on crustal loading and found a maximum vertical motion of 15 mm at Brest and 13 mm at Saint Malo, which cannot explain the observed misfit.

Finally, the absolute gravity measurements performed at Brest during the GPS experiment show a good agreement with ocean loading predictions (Fig. 4). Assuming the Bouguer approximation, which incorporates the effect of vertical crustal motion (in an infinite plane of constant density approximation) in addition to the free-air correction, a change in gravity of 2 μGal corresponds to a height change of 1 cm. In reality, the relationship between height and gravity changes depends on the entire computation of the load and is more complicated (being time, latitude, and longitude dependent) than the single coefficient used above. However, we found that this factor was indeed close to 2.5 for the largest tide (10 μGal/4 cm due to M_2 load) at the Brest site. Consequently, the observed 6–7-cm GPS height residuals should correspond to a 15–17-μGal misfit in the gravity signal on day 298, which is not observed in the data (Fig. 4).

As already observed during a gravity experiment done in 1998 at the same location (Llubes et al. 2001), we also find that the observed gravity signal is larger than the model prediction by about 20%, with no noticeable phase-lag difference between measurement and model. This difference is too large to be accounted for by differences between existing ocean tide models and rather suggests that local effects near the coast, not accounted for in global ocean tide models, contribute to the gravity loading in Brittany (Llubes et al. 2001). In any case, the 20% misfit between observed and modeled gravity, which corresponds to 5-μGal RMS, shows that ocean loading corrections derived from the CSR4.0 model are accurate enough to describe crustal motion at the 2–3-cm level in our study area. Therefore, the misfit observed during the second half of day 298 is likely to be due to spatial tropospheric inhomogeneities caused by the passage of the storm over Brittany and not accounted for in the GPS data processing, rather than to inaccuracies in the ocean loading predictions.

4 ZTD estimates

In a second step, we used the GPS data at Brest and Le Mans to estimate zenith total delay (ZTD) time series in order to test whether the misfit between the observed and modeled loading signal on the Brest–Le Mans baseline could be due to a spatial tropospheric inhomogeneity. We used two months of continuous data that included our three-day experiment period (30 September to 30 November 1999). We included the data from three

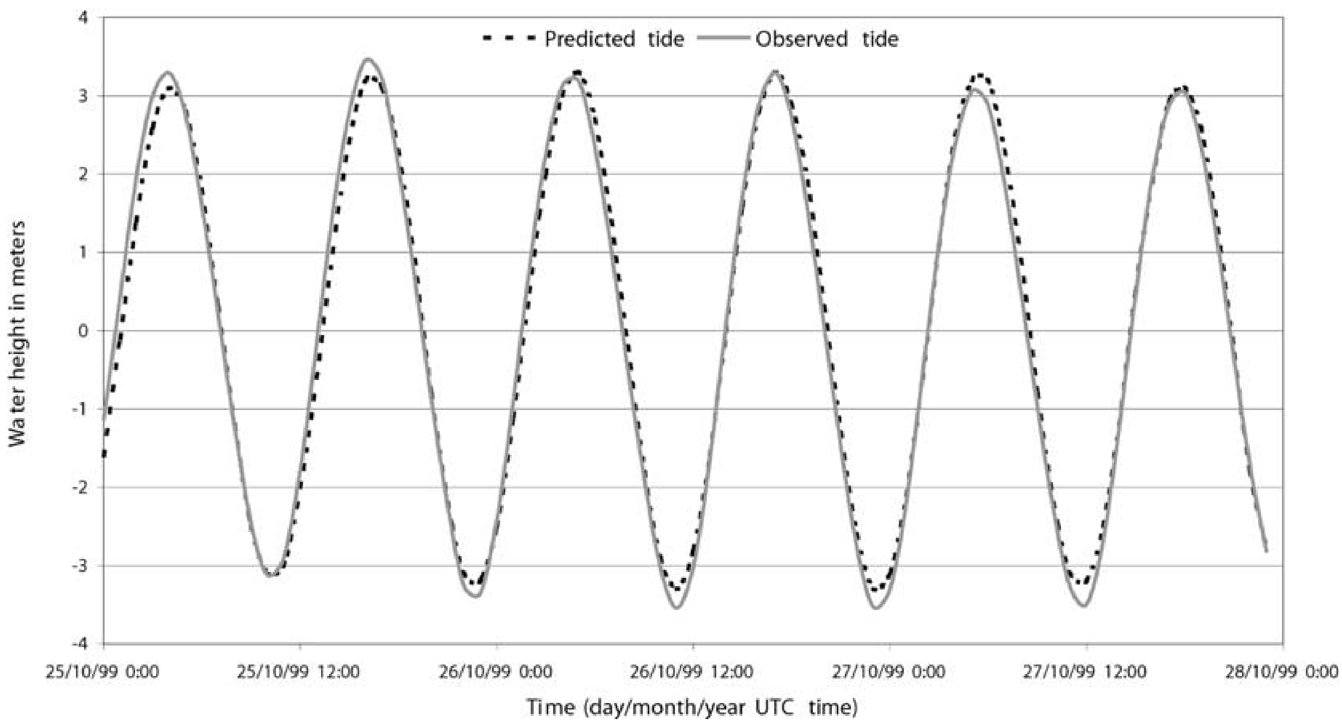


Fig. 3. Time series of tide gauge measurements at Brest (*solid grey line*) and predicted tide from the CSR4.0 model (*black dashed line*) during the 3 days of the GPS experiment. The bias and RMS between the two time series are −3.1 and 23 cm, respectively

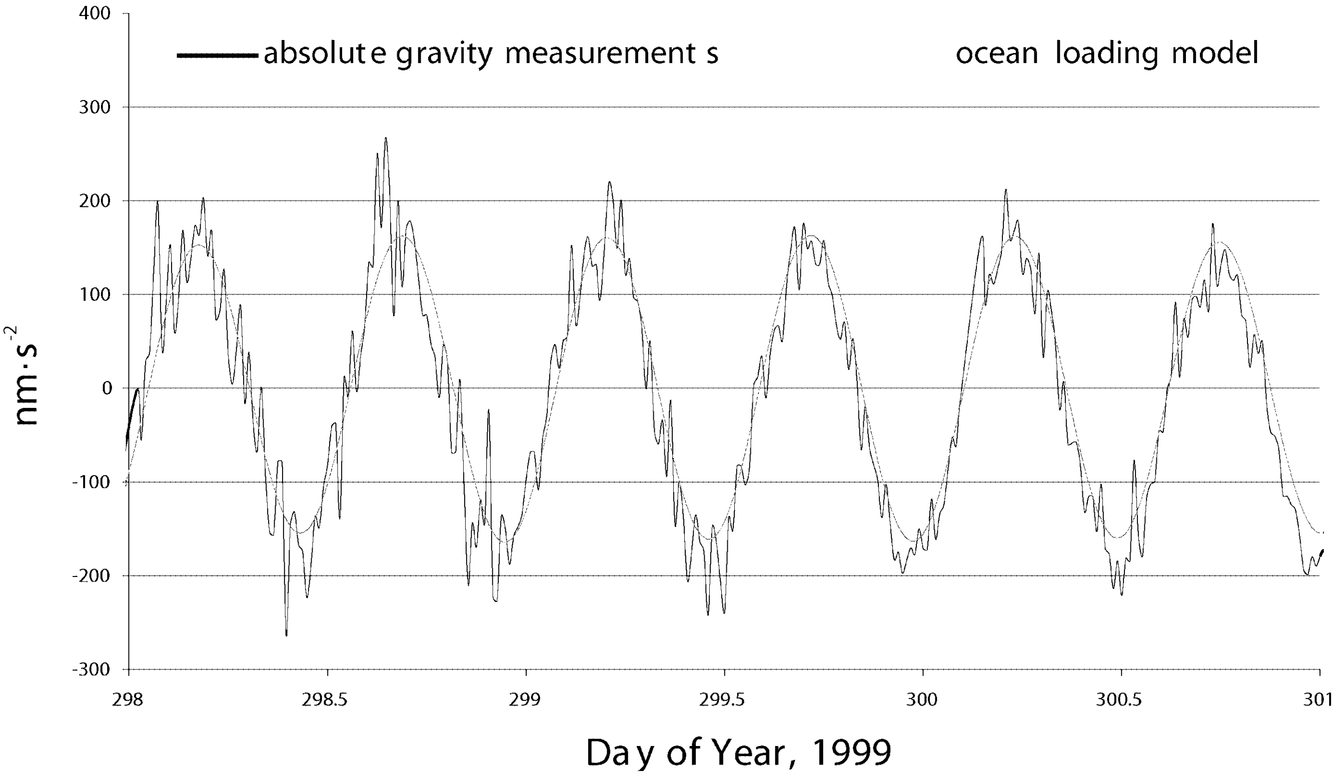


Fig. 4. Time series of absolute gravimeter (FG5) measurements (*black line*) and ocean loading predictions (*grey line*) at Brest during the 3 days of the GPS experiment

permanent GPS stations located at a large distance (greater than 1000 km) from Brittany (Villafranca, Spain; Kootwijk, The Netherlands; Wettzell, Germany) in order to decorrelate the tropospheric delays and estimate absolute values (Tregoning et al. 1998). We used a sliding window processing strategy with a 12-hour window length and a 6-hour forward shift (Ge et al. 2000). We processed the data with the GAMIT software, which parameterizes ZTD as a stochastic variation from the Saastamoinen model with piecewise linear interpolation. The variation is constrained to be a Gauss–Markov process with a given a priori power density of 2 $cm/\sqrt{h}$. ZTD parameters were estimated at each station every 15 minutes. In order to avoid border effects of the Gauss–Markov filter, we extracted the ZTD estimates from the central 6-hour period of each 12-hour session before moving the window forward. We computed two sets of ZTD estimates, one with ocean loading correction, the other without. The other processing parameters were the same as described above.

Figure 5 shows the time series of the resulting ZTD difference between Brest and Le Mans, with ocean loading corrections applied. We also plot on Fig. 5 the time series of the vertical component of the Brest–Le Mans baseline, computed with ocean loading corrections but without estimating ZTD parameters. We scaled the vertical baseline component time series by a factor of 4.4 in order to account for the relation between ZTD and vertical position (i.e. a 4.4-cm station height error maps into a 1-cm ZTD error, see discussion below). We observe a good correlation between the ZTD and vertical baseline component time series. In particular, the 3-cm peak on the ZTD time series observed during the second half of day 298 is correlated with a 16-cm peak in the vertical baseline component occuring at the time of the misfit mentioned above between the observed and modeled ocean loading signals (Fig. 2A).

Assuming that ocean loading corrections at Brest and Le Mans are accurate at the 2–3-cm level, as suggested by the agreement between observed and modeled water height and gravity at Brest (see discussion above), and that other loading effects (atmospheric and hydrological) are small compared to the M_2 constituent of the ocean loading signal, the good correlation between the two time series implies that variations of the vertical baseline component seen on Fig. 2 are essentially caused by spatial tropospheric inhomogeneities. Atmospheric and hydrological loading have been shown to cause inter-seasonal variations of vertical crustal motions of up to 1–2 cm in some areas, with smaller short-term effects (see e.g. van Dam et al. 1994, 2001).

We therefore conclude that the misfit between ocean loading predictions and observations during the second half of day 298 results from lateral tropospheric inhomogeneities not accounted for in the data processing strategy. The fact that the ZTD difference between Brest and Le Mans is close to zero during day 299 and the first half of day 300 (Fig. 5) probably explains the good fit between GPS measurements and ocean loading predictions during that time period (Fig. 2), even though ZTD parameters were not estimated in our solutions.

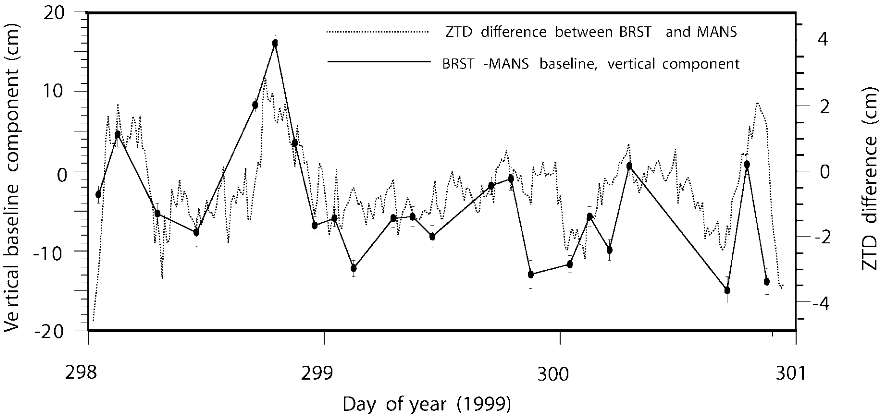
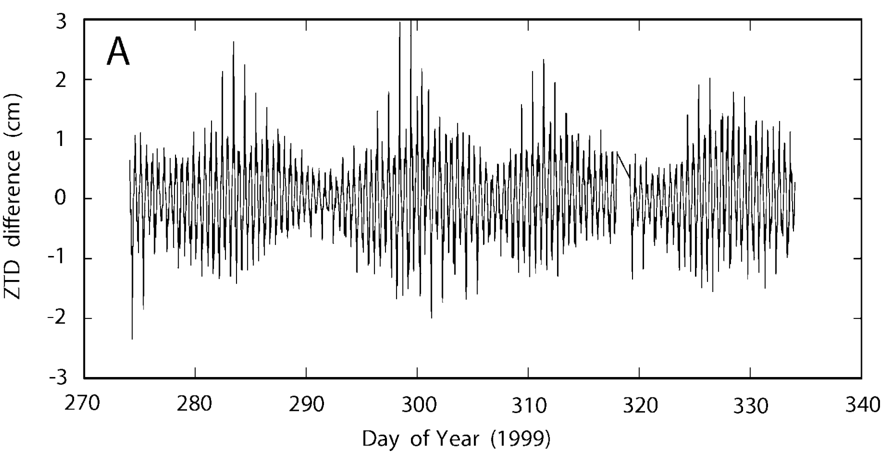


Fig. 5. Time series of the ZTD difference between Brest and Le Mans (*dotted line*) and of the vertical component of that baseline (*solid line*, no ZTD parameters estimated). Ocean loading corrections were applied. The *y*-axis scale of the ZTD difference was multiplied by 4.4 in order to match the vertical position variations

5 Impact of ocean loading on ZTD estimates

We continue the analysis of the impact of ocean loading corrections on ZTD estimates by differencing the ZTD times series obtained with ocean loading corrections from the ones obtained without ocean loading corrections. At a given site, this operation removes the signal of non-tidal origin common to the two solutions, leaving a residual that corresponds to the effect of ocean loading on the ZTD estimates. As expected, the resulting ZTD difference time series at BRST, for instance (Fig. 6A), shows a periodic signature with a frequency content similar to the predicted ocean loading effect on the vertical component of the site position (Fig. 6B).

Figure 7 shows the quasi-linear relation between the ZTD difference and the predicted height of the site, with a slope of 4.4. When accounting for this scaling factor of 4.4 between ZTD and height, we find an 88% correlation between height and ZTD. Beutler et al. (1988) first showed that this scaling factor, dependent on the elevation cut-off angle α used in the GPS data processing, can be approximated by $1/\cos(\alpha)$. Using $\alpha = 10°$ gives a scaling factor of 5.8. Santerre (1991) refined this analysis by taking into account the satellite sky distribution and found a scaling factor of 4.1 at mid latitudes and for $\alpha = 10°$. More recently, Dach and Dietrich (2000), using a GPS data set collected in Antarctica, found a scaling factor of 4.8 for $\alpha = 10°$. The value of 4.4 found here is consistent with these previously published ones. However, the shape of the correlation on Fig. 7 suggests that the relation between ZTD and height may not be linear, but that the scale factor is greater for larger ZTD values and lower for smaller ones.



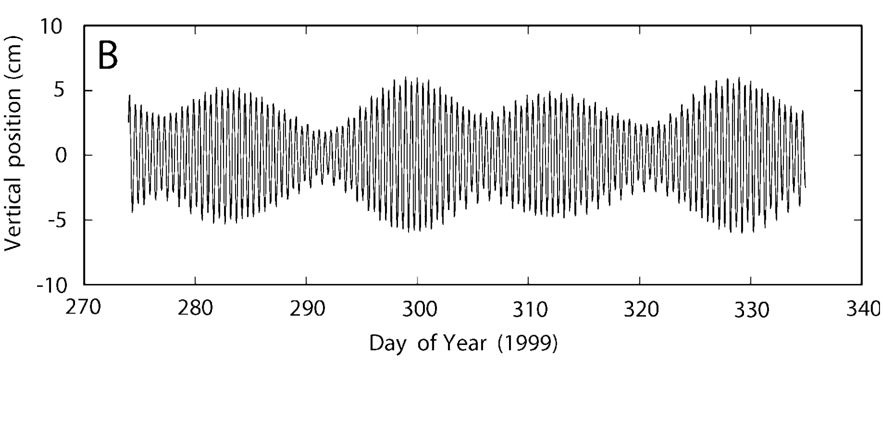


Fig. 6. A Time series of the ZTD difference estimated at BRST between a solution in which ocean loading corrections are applied and a solution in which ocean loading corrections are not applied. B Time series of the modeled vertical position variations due to ocean loading at BRST

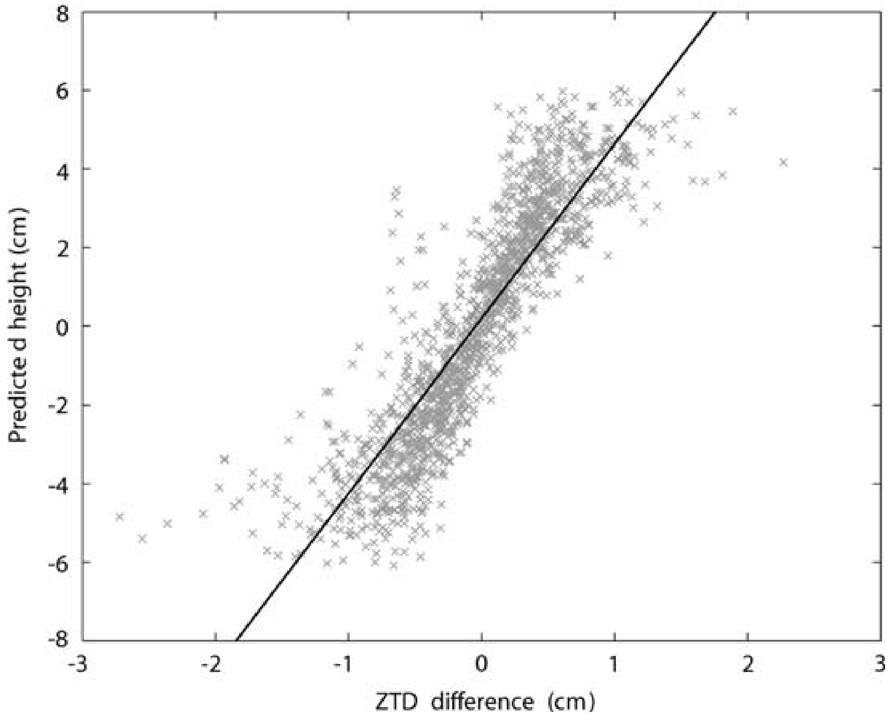


Fig. 7. ZTD difference between a solution with ocean loading correction and a solution without ocean loading correction, as a function of the vertical component of the predicted site position computed using the CSR4.0 ocean tide model

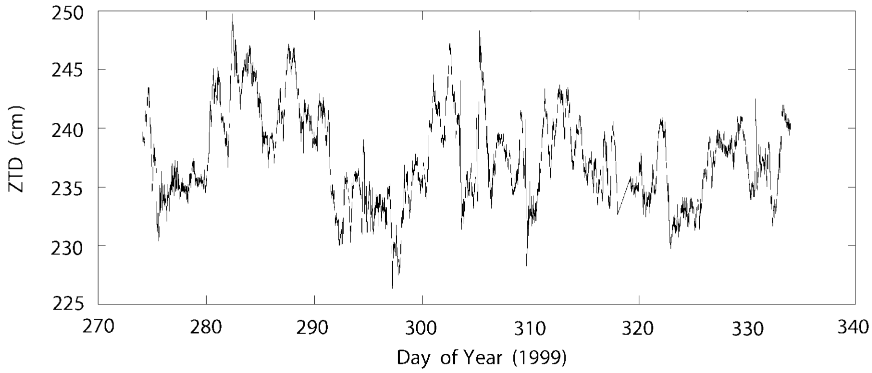
In any case, the results presented here imply that ZTD estimates derived from GPS measurements can be significantly biased if ocean loading effects are not properly accounted for. For instance, an unmodeled 9-cm peak-to-peak ocean loading effect on the vertical position component at Brest will result in a ZTD error of 2 cm, which translates into about 3 mm (or kg/m^2) of precipitable water vapor (PWV), assuming a scale factor of 0.15 between the zenith delay and PWV (Bevis et al. 1992). Meteorological applications of GPS-derived PWV currently require that PWV parameters are estimated with an accuracy of 1 mm PWV or better. Several studies have shown that this goal is achievable (Duan et al. 1996; Tregoning 1998). The ability to provide ZTD estimates with this level of accuracy implies that ocean loading effects must be modeled with an accuracy of about 2.6 cm or better.

Since unmodeled ocean loading effects essentially propagate into ZTD estimates, and since ZTD parameters can be accurately estimated much more frequently than positions, ZTD estimates can be used as an observable to quantify the efficiency of ocean loading models. We computed the power spectrum of the ZTD time series using 2 months of continuous data sampled at 15 min intervals (Fig. 8). When ocean loading corrections are not implemented in the GPS data processing (*solid line*), we observe two main peaks at semi-diurnal and diurnal frequencies. When ocean loading corrections are implemented (*dotted line*), we observe a strong reduction of the semi-diurnal peak, whereas the diurnal one is barely affected. Since we have shown above that absolute gravity and water height measurements are in good agreement with model predictions at Brest during our experiment, we conclude that the diurnal peak in the ZTD spectra is not caused by unmodeled ocean loading effects. This residual diurnal signal in the ZTD time series could be due to diurnal variations of tropospheric water vapor. It could also be caused by geodetic artifacts of quasi-diurnal periods such as site multipath or satellite geometry effects.

6 Conclusion

We have shown that GPS measurements in Brittany during a period of large ocean tide amplitude can be used to measure the corresponding crustal loading effect. For the E–W-trending baseline between Brest and Le Mans (350 km), we measure peak-to-peak displacements of 9 cm in the vertical component and 3 cm in the horizontal component at the frequency of the M_2 tidal constituent. The GPS measurements are usually in good agreement with ocean loading model predictions in phase, whereas the agreement in amplitude is usually fair but not as good as that in frequency. We have shown that the amplitude misfits are mostly caused by unmodeled tropospheric heterogeneities.

We have shown that unmodeled ocean loading effects translate into significant errors in ZTD estimates, with a scaling factor of 4.4 between ZTD and height for a 10° elevation cut-off angle. This effect increases approximately as the cosine of the elevation cut-off angle, as shown by Beutler et al. (1988). It is therefore important that ocean loading modeling is properly implemented when estimating ZTD parameters from GPS measurements for meteorological and climatological applications. These applications require an accuracy of 1 mm in PWV, which implies that ocean loading effects must be modeled with an accuracy of 2.6 cm or better. This level of accuracy is currently reached by most ocean loading models.



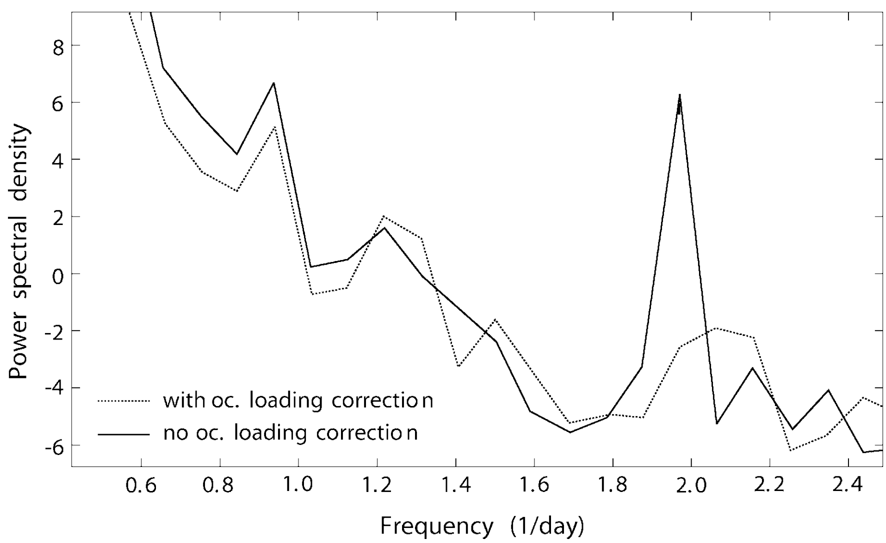


Fig. 8. Power spectrum of the ZTD time series at station BRST, based on 2 months of continuous data sampled at 15 min intervals (*dotted line*: ocean loading corrections applied; *solid line*: no ocean loading corrections)

More generally, if site positions are fixed in the data analysis (which is usually the case for PWV estimation), our results imply that the a priori height component of site positions must be known with an accuracy of about 3 cm or better in order to guarantee a 1-mm accuracy on PWV estimates (assuming that all loading effects are properly modeled). In order to separate ZTD and ocean loading effects on the station position, we may consider solving for the amplitudes and phases of the eight major tidal constituents instead of station coordinates, in that way reducing the number of parameters to be estimated.

Acknowledgments. The authors are grateful to H.G. Scherneck for fruitful discussions and for his help with the ocean loading calculations. They thank H. Vedel for making the HIRLAM data available; D. Jerett for helpful discussions; and the city of Rostrenen, the Laboratoire d'Océanographie of Concarneau, and the Institut de Protection et de Sûreté Nucléaire (BERSSIN) for their support during the GPS measurement campaign. Reviews by C.K. Shum and two anonymous referees significantly improved this paper. This work was carried out in the framework of the MAGIC project (http://www.acri.fr/magic), funded by the European Commission, Environment and Climate Program (EC Contract ENV4-CT98–0745).

References

Agnew DC (1997) NLODF: a program for computing ocean tide loading. J Geophys Res 102: 5109–5110

Baker TF, Curtis DJ, Dodson AH (1995) Ocean tide loading and GPS. GPS World 6(3): 54–59

Bevis M, Businger S, Herring TA, Rocken C, Anthes RA, Ware RH (1992) GPS meteorology: remote sensing of the atmospheric water vapor using the global positioning system. J Geophys Res 97(D14): 15 787–15 801

Bock Y, Nikolaidis RN, de Jonge PJ, Bevis M (2000) Instantaneous geodetic positioning at medium distances with the global positioning system. J Geophys Res 105: 28 223–28 253

Boucher C, Altamimi Z, Sillard P (1999) Results and analysis of the ITRF97. IERS Tech note 27, Int Earth Rotation Service, Paris

Dach R, Dietrich R (2000) Influence of the ocean loading effect on GPS derived precipitable water vapor. Geophys Res Lett 27(18): 2953–2957

Dragert F, Janes TS, Lambert A (2000) Ocean loading corrections for continuous GPS: a case study at the Canadian coastal site Holberg. Geophys Res Lett 27(14): 2045–2048

Duan J, Bevis M, Fang P, Bock Y, Chiswell S, Businger S, Rocken C, Solheim F, van Hove T, Ware R, McClusky S, Herring TA, King RW (1996) GPS meteorology: direct estimation of the value of precipitable water. J Appl Meteorol 35(6): 830–838

Dziewonski A, Anderson DL (1981) Preliminary reference Earth model. Phys Earth Planet Int 25: 297–356

Eanes RJ, Shuler A (1999) An improved global ocean tide model from TOPEX/Poseidon altimetry: CSR4.0, in European Geophysical Society, 24th General Assembly, The Hague

Farrell WE (1972) Deformation of the Earth by surface load. Rev Geophys Space Phys 10(3): 761–797

Ge M, Calais E, Haase J (2000) Reducing satellite orbit error effects in near real-time GPS zenith tropospheric delay estimation for meteorology. Geophys Res Lett 27: 1915–1918

Khan SA, Tscherning CC (2001) Determination of semi-diurnal ocean tide loading constituents using GPS in Alaska. Geophys Res Lett 28: 2249–2252

King RW, Bock Y (1999) Documentation for the GAMIT GPS software analysis, release 9.7. Scripps Institution of Oceanography, University of California, San Diego

Le Provost C, Lyard F, Molines JM, Genco ML, Rabilloud F (1998) A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set. J Geophys Res 103: 5513–5529

Llubes M, Florsch N, Amalvict M, Hinderer J, Lalancette MF, Orseau D, Simon B (2001) Observation gravimétrique des surcharges océaniques: premières expériences en Bretagne. C R Acad Sci Paris 332: 77–82

Ray R (1999) A global ocean tide model from T/P altimetry: GOT99.2. NASA Tech Mem NASA/TM-1999-209478, National Aeronautics and Space Administration, Goodard Space Flight Center, Greenbelt, MD

Saastamoinen J (1972) Atmospheric corrections for the troposphere and stratosphere in radio ranging of satellites. In: Henriksen et al. (eds) The use of artificial satellites for geodesy, Geophys Monograph Ser, vol 15. American Geophysical Unioned Washington, DC, pp 247–251

Santerre R (1991) Impact of GPS satellite sky distribution. Manuscr Geod 16: 28–53

Scherneck HG (1991) A parametrized solid Earth tide model and ocean tide loading effect for global geodetic baseline measurements. Geophys J Int 106: 677–694

Scherneck HG, Haas R (1999) Effect of horizontal displacements due to ocean tide loading on the determination of polar motion and UT1. Geophys Res Lett 26(4): 501–504

Shum CK, Woodworth PL, Andersen OB, Egbert GD, Francis O, King CK, Le Provost CL, Molines J-M, Parke ME, Ray RD, Schlax MG, Stammer D, Tierney CC, Vincent P (1997) Accuracy assessment of recent ocean tide models. J Geophys Res 102: 25 173–25 194

Tregoning P, Boers R, O'Brien D (1998) Accuracy of absolute precipitable water vapor estimates from GPS observations. J Geophys Res 103: 28 701–28 710

van Dam TM, Blewitt G, Heflin M (1994) Detection of atmospheric pressure loading using the global positioning system. J Geophys Res 99: 23 939–23 950

van Dam T, Wahr J, Milly PCD, Shmakin AB, Blewitt G, Lavallée D, Larson KM (2001) Crustal displacements due to continental water loading. Geophys Res Lett 28: 651–654