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Determination of semi-diurnal ocean tide loading constituents using GPS in Alaska

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Abstract.
During the past years, the accuracy of relative positioning using differential GPS (DGPS) has been improved significantly. The present accuracy of DGPS allows us to directly estimate the differential amplitudes and Greenwich phase lags of the main semi-diurnal ocean tide loading constituents (S_2, K_2, M_2 and N_2). For this purpose a test is carried out using two GPS stations in Alaska. One station, Chi3, is located on an island in the Gulf of Alaska, while the second station, Fair, is located far away from the coastal areas. Processing hourly GPS solutions for the baseline between Fair and Chi3 during 49 days gives differential amplitudes of 23.21 mm and 4.71 mm for M_2 and N_2, respectively, while the theoretically differential amplitudes of M_2 and N_2 are 20.90 mm and 4.21 mm, respectively (using the GOT99.2 ocean tide model). The diurnal ocean tide loading constituents are not considered, because unmodeled troposphere effects increase the noise level near the diurnal frequency band and prevent us from obtaining significant results.

Introduction

The sun and the moon exert tidal forces causing deformations of the earth. These deformational effects, also known as the solid earth tide effect and the ocean tide loading effect, are rather large and measurable by various geodetic techniques e.g. GPS and VLBI [Scherneck, 1983]. The solid earth tide effect, which is dependent on the global structure of the earth, is very well modeled, while the ocean tide loading effect is more dependent on the locally variable properties of the lithosphere [Farrell, 1972] and the oceanic tides still need improvements, especially near coastal areas.

In order to predict the ocean tide loading effect an ocean tide model and an earth model are required. The ocean tide model describes the distribution of the surface mass load by the oceans while the earth model (or more precisely the load love numbers) describes how the earth reacts to the surface mass load. The surface load may be determined by usage of global ocean tide models, such as the AG95 [Andersen, 1994], GOT99.2 [Ray et. al, 1999] or FES95.2 [Le Provost et. al, 1995], which are all delivered on a global 0.5° x 0.5° grid (in degrees). However, this coarse grid resolution is not able to provide us with precise ocean tide loading displacements near irregular coastlines. In order to improve the loading predictions, Lambert [Lambert et. al, 1998] reduces the cell-size to 0.125° x 0.125° in the nearshore waters. But, with the increasing accuracy of differential GPS (DGPS), we can also use DGPS to directly estimate the amplitude and phase lags of the main ocean tide loading constituents.

The purpose of this study is to observe the main semi-diurnal differential vertical ocean tide loading constituents using DGPS. Hence, the observed values may tell us how well we are able to predict the loading effect near an irregular coastline using a global ocean tide model. When using DGPS, we are able to process the baseline vector between two GPS sites. Hence, we are able to observe relative heights between sites. In addition, this paper considers the differential ocean tide loading effect between sites.

Analysis

We have chosen two GPS stations in Alaska, in order to compute the differential vertical ocean tide loading effect. The choice of the area is based upon the extremely large oceanic tides in the Gulf of Alaska (according to the GOT99.2 ocean tide model). One station, Chi3 (Cape Hinchinbrook 3), is located on an island that separates Prince William Sound from the Gulf of Alaska, while the second station, Fair (Fairbanks), is located far away from the coastal areas. Chi3 produces the largest response to loading, while Fair is less affected. Thus, by computing the baseline between Chi3 and Fair, we can obtain a relatively large differential loading effect. The baseline length between Fair and Chi3 is approximately 530.014 km. (see figure 1)

We use the KMSLOAD software for the computation of the vertical displacements caused by the ocean tide loading effect. According to the GOT99.2 model, we may obtain vertical displacements of almost 20 cm in the Gulf of Alaska. This is a huge effect, nearly 30 percent of the solid earth tide effect. Figure 1 shows the maximum obtainable vertical ocean tide loading effect around Alaska with contour intervals of 1 cm. The figure is based on the main diurnal and the semi-diurnal constituents K_1, O_1, P_1, Q_1, M_2, S_2, K_2 and N_2. The figure shows that the loading effect is very large near the coastal areas with values around 9 to 14 cm, while the values decrease to only 3 cm in the deep continental areas.

We analyzed the GPS data using the Bernese 4.2 software [Beutler et al, 2000]. The data used here were sampled during the period of 13 June to 31 July, 2000. The data was processed by usage of the precise IGS GPS satellite orbit solutions. Furthermore, solid earth tide and pole tide corrections were applied in the processing. FAIR was kept as fixed reference station and double difference L3 phase solutions were used . Moreover, the phase ambiguities were resolved and kept fixed for each day. Finally, hourly solutions were carried using the pre-determined ambiguilities and using the Saastamoined troposphere model (using fixed temperature, pressure and humidity). Loading corrections were not applied instead we will estimate that from the hourly solutions.

We have not estimated the tropospheric ZD (zenith delay) i.e. for hourly intervals, because it would absorb and eliminate the loading signal [Dragert et. al, 2000].

Ignoring the estimation of the tropospheric ZD has an advantage and a disadvantage. The advantage is that the semi-diurnal loading constituents are estimated without any absorption of the loading signal into the tropospheric estimation. Troposphere effects do not disturb the semi-diurnal ocean tide loading signal. The disadvantage is that it is difficult to estimate the diurnal loading constituents, because we have to treat the tropospheric effects as noise and some of these effects have nearly diurnal variations, e.g. the daily temperature variations. Hence, the noise level around the diurnal tidal frequency band is too large and may not give precise loading constituents.

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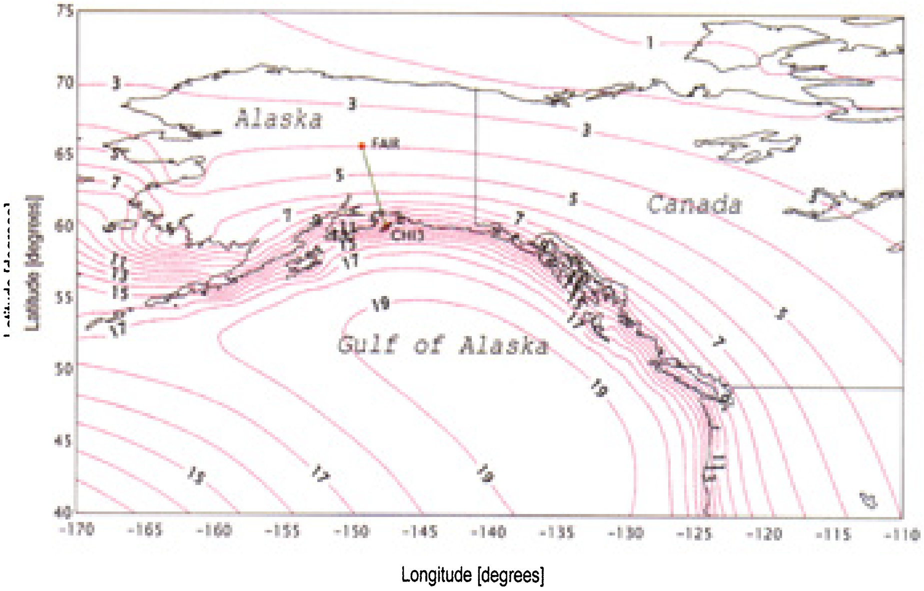

Figure 1. The figure shows the sum of the amplitudes of the main ocean tide loading constituents (or the maximum ocean tide loading displacements) in Alaska and Gulf of Alaska with contour interval of 1 cm. The included waves are P_1, K_1, O_1, Q_1, K_2, S_2, M_2 and N_2.

Estimation of the ocean tide loading amplitudes and phase lags include usage of the FFT (Fast Fourier Transform) algorithm, which allows no gaps in the data. Therefore, we have interpolated the gaps using cosine functions. In total 3.5 days of data out of 49 days were interpolated.

Results

The hourly solutions of the relative height differences between Chi3 and Fair are displayed in Figure 2A. The figure shows some large height variations with periods near 2 to 10 days. These vari-

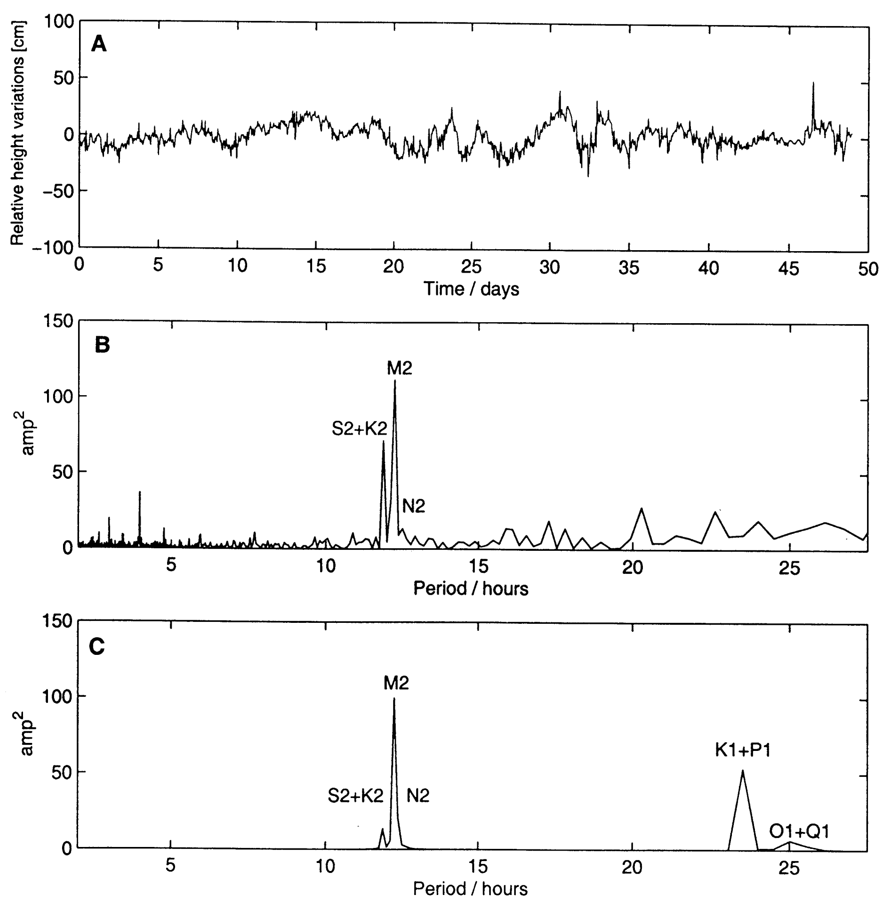

Figure 2. A) Relative height variations for the baseline between Fair and Chi3. The figure displays hourly GPS solutions for the period from 13 June to 31 July, 2000. B) Power spectrum based on observed relative height differences between FAIR and CHI3. C) Power spectrum based on modeled relative height differences caused by the ocean tide loading effect (modeled using GOT99.2). Both spectra (B and C) consider relative height changes during the period of 49 days.

Table 1. Modeled and observed differential amplitudes and related Greenwich phase lags of the baseline from Fair to Chi3.

Constituent	Amplitude [mm]	Phase lags [deg.]	Amplitude [mm]	Phase lags [deg.]
	Modeled loading effect (using GOT99.2)		Observed loading effect (using GPS)	
M_2	20.90	111.57	23.21 ± 0.12	85.11 ± 0.79
N_2	4.21	88.55	4.71 ± 0.12	144.44 ± 3.23
$S_2 + K_2$	5.26	138.58	8.60 ± 0.12	157.29 ± 0.98
S_2	7.01	144.35	NA	NA
K_2	1.81	140.46	NA	NA

ations are mainly caused by pressure and temperature variations in the troposphere, which affect the GPS signal propagation. Effects such as the atmosphere loading and non-tidal ocean loading are also included in the signal. Regarding atmosphere loading at Fair, it has a signal RMS of 5 mm [vanDam et. all, 1994], but these variations are mainly annual.

A power spectrum based on the observed relative height differences between Chi3 and Fair is displayed in figure 2B. Furthermore, a theoretical power spectrum of the relative height differences based on the GOT99.2 loading estimations is shown in figure 2C (the included waves are P_1, K_1, O_1, Q_1, K_2, S_2, M_2 and N_2). Both spectra show a significant peak at the M_2 period. Concerning the S_2 and K_2 loading waves, we have to considered these waves as one single wave. When using only 7 weeks of data, we are not able to separate S_2 from K_2. S_2 has a period of 12 hours 00 minutes and K_2 has a period of 11 hours 58 minutes, hence, more than 6 months of continuous data are required in order to separate these waves.

The spectrum based on GPS observations shows very low noise for the periods between 5 and 15 hours. Consequently, we are able to directly observe the semi-diurnal ocean tide loading signal. However, the noise level increases near the diurnal tidal frequency band, mainly caused by the unmodeled troposphere effects on the GPS signal propagation. Furthermore, effects caused by satellite orbit errors and perturbations due to multipath may appear with the K_1 and K_2 tidal frequencies, respectively. However, the orbit errors are neglectable, while perturbation due to multipath are unmodeled in this study and may have a significant contribution on our results.

Table 1 displays the main semi-diurnal differential vertical ocean tide loading amplitudes and Greenwich phase lags. Both observed and modeled values show that M_2 has the largest amplitude. Furthermore, there seems to be a relatively good agreement between observed and modeled M_2 differential amplitudes and phase lags. Also the small tide, N_2, shows relatively good agreement between observed and modeled amplitudes, while the phase lags deviate by nearly 55 degrees. Regarding the amplitude of $S_2 + K_2$, there is a relatively large disagreement between observations and predictions. According to GOT99.2, S_2 has an amplitude of 7.01 mm and K_2 has an amplitude of 1.81 mm. Moreover, S_2 and K_2 are almost in anti-phase during the considered period (according to GOT99.2). This gives a relatively small amplitude of only 5.26 mm for the sum S_2+K_2, while the observed S_2+K_2 amplitude is 8.6 mm. The relatively large disagreement is mainly caused by the multipath effect on S_2 and K_2.

Conclusions

Our study has demonstrated the possibility of evaluating the main semi-diurnal loading tides using GPS time series. This is a huge advantage in further modeling of the ocean tide loading effect. We can actually use GPS to improve the modeling of the loading, especially near complex coastal areas, where the global ocean tide models are less good because they are not able to include local phenomena e.g. wave interaction and bottom friction.

In order to obtain precise amplitudes and phase lags of the full loading spectra, including all the main diurnal and semidiurnal constituents (P_1, K_1, O_1, Q_1, K_2, S_2, M_2 and N_2), we have to consider the tropospheric effects carefully. The troposphere must be well modeled without any absorption of the loading signal. We suggest that meteorological observations be used for this purpose. Moreover, S_2 and K_2 has to be considered separately, because of the multipath effect.

The ocean tides in Alaska are unusually large. In addition, they may generate horizontal displacements measurable using GPS. We suggest that a similar study to that presented here be carried out for the horizontal loading displacements.

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http://research.kms.dk/~sak.
http://lox.ucsd.edu/

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