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Ocean Loading Tides For, In, and From VLBI

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Abstract

The general problem of predicting surface displacements due to ocean tide loading is reviewed. This includes the procedures in the IERS Conventions and suggestions for their next issue. In order to increase modeling accuracy we focus on the tides in the Gulf of Maine. This area is difficult to represent in global tide models. The VLBI station of Westford is located close enough to open up a model inversion opportunity. We have revived an ocean tide model to compute fully time-dependent solutions; in one run we included forcing by air pressure using ECMWF pressure fields and the corresponding geostrophic wind. We show observed ocean loading parameters and discuss the remaining discrepancies with respect to the model results.

1. Introduction

Ocean loading tides have become a significant process in VLBI observations. We can show that amplitudes regularly exceed the resolution capability of larger databases tenfold. It is therefore indicated to address the problem with renewed scrutiny.

The article is organized into three parts, each a little article in its own right. We first review the current situation with supply of loading parameters **for** space geodesy and VLBI in particular. Then we discuss how the tidal processes are implemented **in** VLBI analysis software and come up with suggestions for improvement. Finally we show the high resolution of sub-millimeter harmonic processes possible to obtain **from** utilizing most of the available VLBI data bases.

1.1. For

At present a range of ocean loading files with coefficients are available from the ftp server at Onsala Space Observatory. The following ocean tide models have been used to generate ocean loading coefficients: Schwiderski (1980) [1], Le Provost et al., (1994) [2], CSR3 and CSR4 by Eanes and Bettadpur (1996, 1999) [3], and GOT99.2 by Ray [4]. Of these, only the Le Provost et al. (1994) model is completely numerical, the others using empirical tide information: The Schwiderski (1980) model is numerically driven by tide gauge observations, and the remaining models on the list utilize TOPEX/POSEIDON (T/P) satellite altimetry.

The demand in application for ocean loading is a good global coverage, good spatial resolution, representation of many partial tides, and good coverage of the shelves and smaller basins. The T/P based models fill in the Le Provost et al. (1994) tide in the high latitude regions not sensed by the satellite. As regards spatial resolution the Schwiderski (1980) model is inferior with its 1×1 deg to the others (0.5×0.5 deg); however, it is still the only one that provides the long-period partial waves M_f (fortnightly), M_m (monthly), and S_{sa} (semi-annually). Since the S_{sa} tide in Schwiderski (1980) appears unreasonably different from an equilibrium tide, which would be expected to approximate the semi-annual hydrodynamic response of the ocean even better than

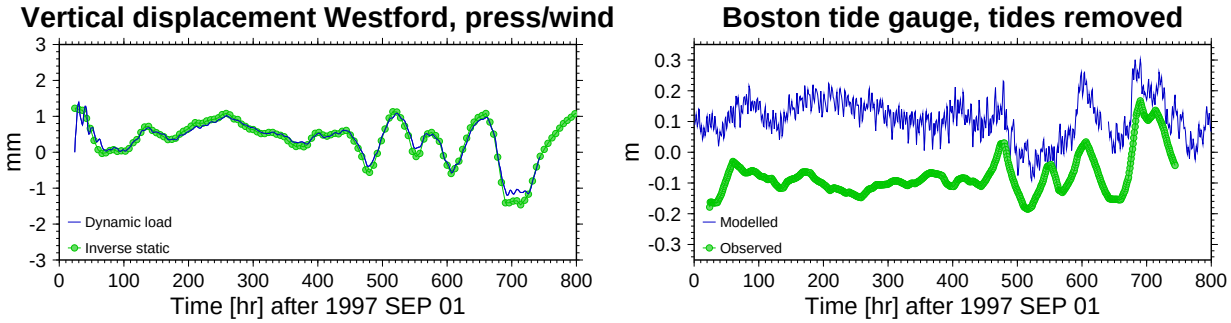

Figure 1. The left hand diagram shows the Gulf of Maine loading effect, vertical displacement at Westford, due to dynamic response to air pressure and wind (slight curve) and using an inverse barometer assumption (curve with circle symbols). The right hand diagram shows the modelled water level at Boston (curve with circle symbols) and a recording of the Boston tide gauge (slight curve), from which the luni-solar tides have been removed using a least-squares fit.

what seems to be evident in the case of the monthly tide, we regularly use an equilibrium tide to compute the loading effects at semi-annual period.

1.1.1. Computation of Surface Displacements

The method to compute the coefficients is by means of a point load Green's function, with which the tidal mass is convolved in a discrete approximation of a surface integral. The problem here is to resolve the coast fine enough when the field point, the location of a VLBI antenna, is at close distance. Experience shows that the five arc minute resolution of the TerrainBase or ETOPO5 topographic files are sufficient for loading induced displacements. The coastal refinement is carried out when a station is within 150 km from the coast and involves manual, interactive work to correctly edit the binary mask that distinguishes land and sea.

For the limited number of VLBI stations in the world, this work load is acceptable. Larger efforts are required for the ever increasing number of stations where satellite receivers are installed.

1.1.2. Tide Modelling on the Continental Shelves

We have also investigated the impact of a nearby body of water that possesses a profound resonance in the tidal band on load induced displacement of the Earth surface. We chose the Gulf of Maine as it is near the Westford site. A hydrodynamic model was created to model the shallow water tides of the area, including the Bay of Fundy and the Gulf of Saint Lawrence. The model was excited with either a large frequency set of tides (39 simultaneous waves) or with air pressure and wind fields from the European Centre for Medium Range Weather Forecast (ECMWF).

In short our results indicate that the dynamics of the area can be simulated by the model accurate enough to be used for loading effects. Most interesting, however, is an account of the dynamic response of the basin to excitation by weather conditions and the comparison of ensuing loading effects with the much simpler assumption of an inverted barometer response even on the continental shelf. Figure 1 shows the comparison of dynamic loading effects to the inverted barometer response. The effective net loading effect, equal to the difference between both, is

regularly less than 0.1 of the total, and much less than one millimeter.

The result is encouraging in so far as atmospheric loading for most stations will be accurately represented using an inverse barometer assumption for the ocean response. A small and over the oceans spatially uniform load will arise only due to the water mass budget constraint.

1.1.3. Atmospheric Loading Time-series

Time-series for predicted atmospheric loading displacements can be retrieved from our http server `http://www.oso.chalmers.se/~hgs/apload.html`. The time series comprise of three-dimensional displacements, vertical, east and north, in meter units, one sample per six hours for most VLBI stations used in geodetic experiments.

1.2. In

Ocean loading displacement of a site at time t can be specified using harmonics

$$\vec{\mathbf{u}} = \sum_j \hat{\mathbf{x}}_j \mathcal{R}eal \sum_k \mathcal{Z}_j^*(\omega_k)\gamma(\omega)H_k e^{i\omega_k(t-t_0)+i\phi_k} \tag{1}$$

where ϕ_k is the astronomical argument of partial tide k, and its angular speed at time t_0 is $\omega_k = d\phi/dt$. The sum involves those partial tides that belong to the same spherical harmonic degree of the astronomical potential H_k, and it is only harmonic degree two that is considered in the present context to have important oceanic tides. Thus, equation (1) is a first order Taylor expansion in time of a time convolution process of astronomical tides and solid earth tides driving the ocean that generates elastic deformation. The frequency domain function $\mathcal{Z}_j^*(\omega_k)$ is the ocean loading admittance. In each frequency band (long-period, diurnal, semi-diurnal) it is assumed to be a smooth function of frequency, especially if the core resonance, $\gamma(\omega)$, in the tide generating potential is factored out (but this requires that the ocean tide model has been generated with the core factor instituted; this is only rarely encountered). A method recently revived in TOPEX/POSEIDON tidal altimetry is termed Orthotides [5], [3]. It should be noted that the spectrum domain-based formulation of the ocean loading tide of equation (1) would work well together with a spectral domain formulation of the solid Earth tide as suggested in [6].

Originally, Schwiderski (1980) specified 11 tide waves. This might have inspired early programmers to limit the ocean loading formula in analysis software to these 11 terms. This went well along hand in hand with the storage efficiency of the solid Earth tide formula being based on the direct gravity action, knowing the ephemerides of the tide raising bodies. The major effect of the solid Earth core was accounted for using one correction for the K_1 tide, the argument of which is the sidereal hour angle. Thus, the most important effects were conveniently programmed.

With the 1996 issue of IERS Conventions [7] some additional terms were introduced (modulation of primary tides due to lunar node revolution in the loading tides). With steadily increasing sensitivity, more and more correction terms to the tide formulas are required, and they typically turn out as terms of a frequency domain formula like equation (1). The time may soon come when a revision of the presently used tide formulas is inevitable. For further discussion see [6].

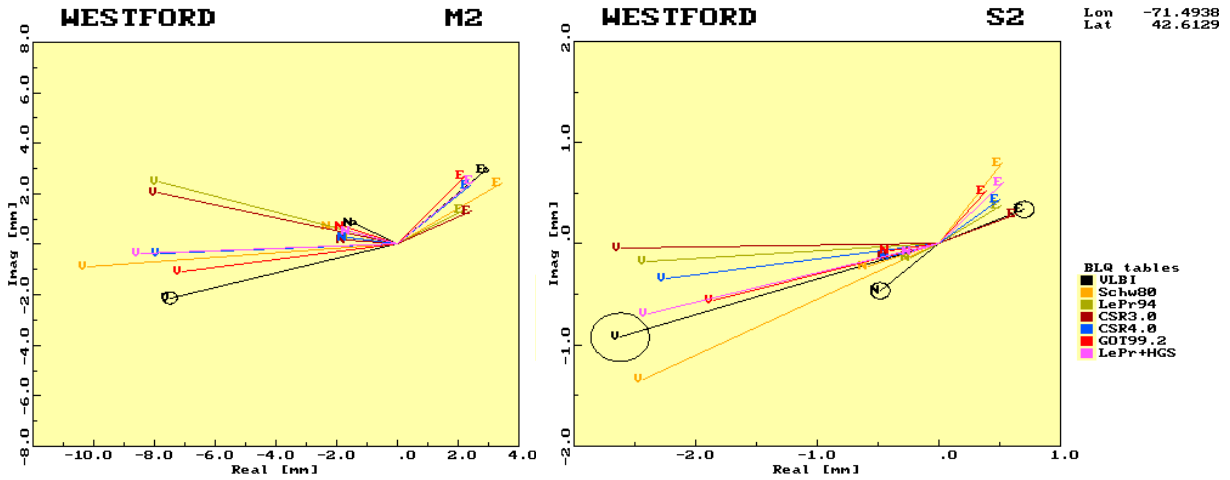

Figure 2. Plots of tidal phasors, observed (black and with circle showing a one-sigma limit) and predicted using a range of tide models. The model labeled LePr+HGS is composed of a regional model of the Gulf of Maine and the global Le Provost et al. (1994) model. Left hand diagram shows M_2, right S_2 vertical displacement at Westford.

1.3. From

Using data bases from 1979 on, we have estimated ocean loading parameters from VLBI observations. The method works as follows (also refer to [8]): The ocean loading tides are predicted using the standard model. At a set of target stations, pairs of signals in phase and at quadrature phase with respect to the eight most important solid earth partial tides are added in each spatial component, and the amplitude coefficients are adjusted in the least-squares stage.

In the most favorable cases we obtain one-sigma formal errors of 0.2 mm (vertical) and 0.1 mm (horizontal). Comparison with models show that a greater part of the observations are explained. Only the K1 tide seems to be offset by some perturbation, affecting both the vertical and the horizontal components at almost all stations, see Figure 3. As of now we have not found the systematics behind the perturbation.

Excepting the K_1 tide from an analysis of goodness of fit, Figure 4, we can show that the ocean loading models do explain 50 to 90 percent of the observed effects. The residual normalized chi^2 is found between 5 and 20. In the case of Wettzell, where ocean loading effects are small and the standard error is extremely small because of the great number of experiments, the goodness of fit looks a bit pessimistic. Translated into displacements, the discrepancy for the largest loading tide at Wettzell, M_2, is 2 mm of a loading effect of 5 mm.

There are no substantial differences between different ocean loading models. The general trend is that more recent models perform slightly better. Their greatest advantage is that the coverage of the models, GOT99.2 [4] in particular, extends over practically all important and interesting tidal waters, and that even difficult areas, like the Gulf of Maine, are represented with high accuracy.

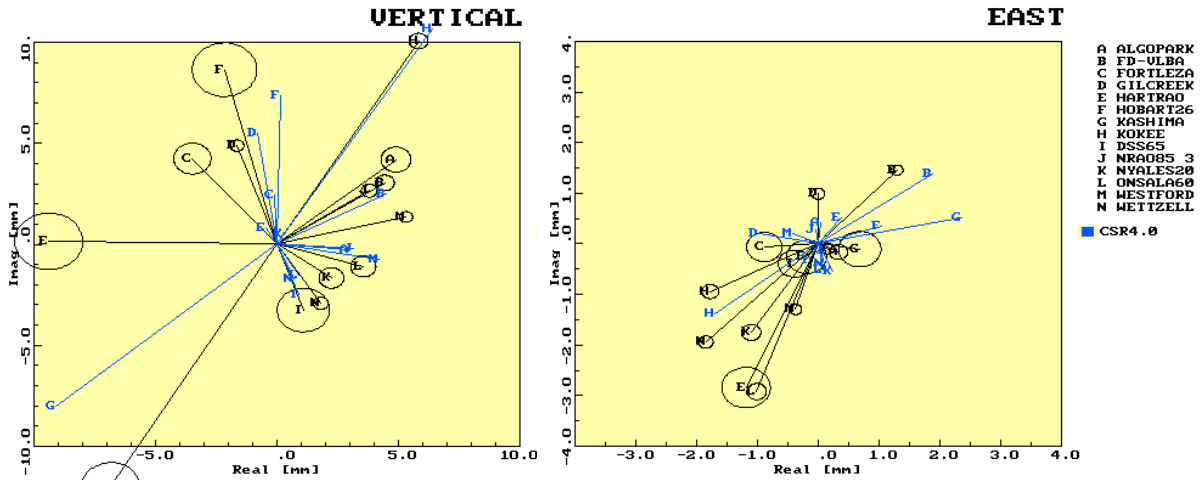

Figure 3. Plots of tidal phasors for the K_1 tide, observed (black and with circle showing a one-sigma limit) and predicted (grey) using the CSR4.0 model [3]. The discrepancies between observations and model are much larger than what could be explained by uncertainty in the ocean tide. All components are affected at practically all stations.

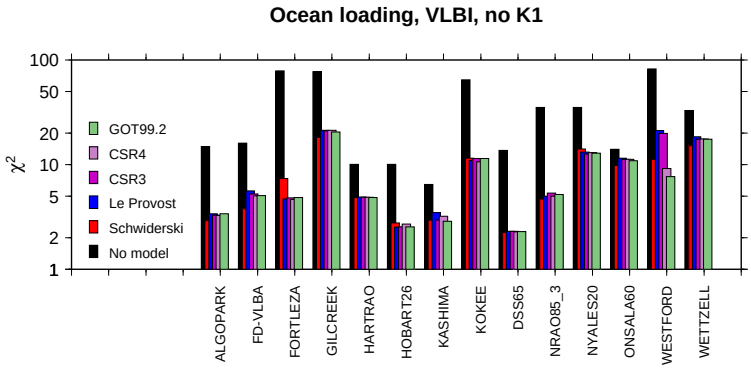

Figure 4. Goodness of fit

2. Conclusions

We showed that ocean loading tides are a significant phenomenon in VLBI observations of station motion. Currently available models predict the effects with approximately 90 percent agreement. Future work is indicated regarding the formulation of the process in the VLBI software.

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