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A comparison of predicted and observed ocean tidal loading displacements around the Puget Sound

Tanessa C. Morris
University of Montana, Missoula, tm158487@umconnect.umt.edu

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University of Montana Geoscience Department
Advisor: Dr. Hilary Martens, Geosciences

Ocean Tidal Loading

Introduction and Motivation

The Earth crust is commonly viewed as being a rigid entity; however, the crust is elastic and deforms due to loading on it. Tides moving ocean water cause the surface of Earth to deform due to the weight of the water. This is known as ocean tidal loading (OTL). Around coastlines and in shallow oceans, models of OTL are not highly accurate and can create sources of error in OTL analysis. In this study, forward-modelled predictions of OTL are compared to observations from Global Positioning System (GPS) data to explore the elastic deformation response of Earth to OTL around the Puget Sound.

The motivation behind this work is to quantify the differences in data surface displacements between the models of surface displacement due to OTL and observations of OTL. I am very interested in complex coastlines and unique geographic regions, such as the Puget Sound. The Puget Sound has a complex coastline and any existing models of how ocean tides impact this area have not been at a high enough resolution to accurately capture the tidal effects in the Puget Sound. Many of the existing global tidal models do not reach into the Puget Sound. When the model does not cover the Puget Sound and extend into these waters, the OTL models around the Puget Sound are likely not accurate. With a higher resolution of the impact ocean tides have in this area, OTL models can be refined and improved.

Setting

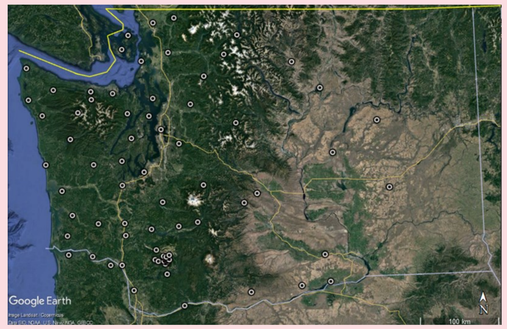


Figure 1: The Puget Sound area as well as the Pacific Ocean and major cities in Washington to provide a context as to where this research is being performed. The Puget Sound has a complex coastline. Credit: Google Earth Pro.

Hypothesis and Research Objectives

I hypothesized that there would be residual differences between the tide model used (FES2014b) and the observed OTL in the Puget Sound area. I also hypothesize that limitations in coverage in the FES2014b tide model within the Puget Sound contribute significantly to the residuals in that area and the residual values can be used in future works. The main objective of this work is to compare displacements of the solid Earth induced by the weight of ocean tides from the FES2014b model with the observed OTL around the Puget Sound.

Methods

Data from 75 Global Navigation Satellite Systems (GNSS) stations were processed to yield position estimates at intervals of 5 minutes for a year. The OTL model used for comparison was the FES2014b ocean-tide model loading a spherically symmetric, non-rotating, elastic, and isotropic (SNREI) Earth model. The three tidal frequency bands used were the semidiurnal (M_2), diurnal (O_1), and fortnightly (M_f). The M_2 tide is the largest and M_f the smallest.

The time series data of the stations was considered to determine which stations should be used in the analysis of the Puget Sound. Figure 2 a is an example of a station used in the analysis. There is continuous data, clear harmonic behaviour in the time-series data, and the residuals between the data and a tidal-harmonic fit exhibit a smooth bell curve. Figure 2 b shows an example of data that was unusable. The data are more choppy and the bell curve of residuals has a large peak and is uneven on either side of the peak.

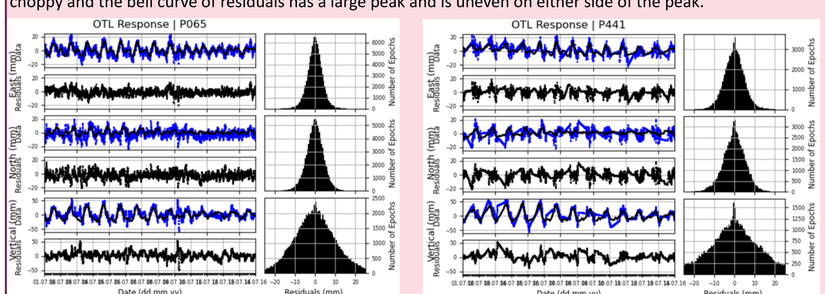
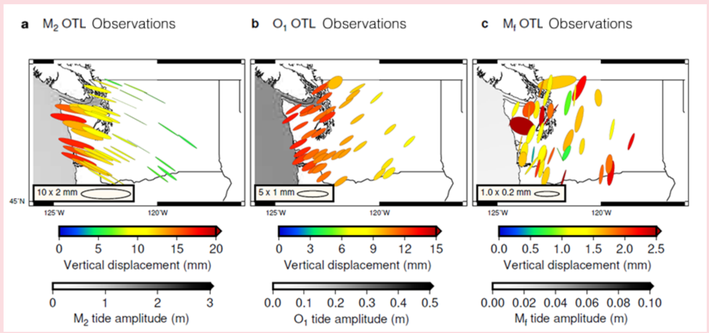


Figure 2: a) time series plots for Station P437, which is located nearest the Puget Sound. This station has good data, as is evident by the clear tidal sine waves and clean distribution. b) Time series plots for Station 441, which is a station with poor data and a significant amount of missing data. The normal distribution has sharp peaks, indicating poorer quality data.

Forward modelling was performed to compare a model for OTL to the observed OTL. The forward modelling predicts surface displacement in 3 dimensions. The 3 dimensions are up, east, and north, and they are caused by OTL. LoadDef software is used to produce the forward models of the surface displacement (Martens et al., 2019). The earth model used was the Preliminary Reference Earth Model (PREM) (Dziewonski & Anderson, 1981). PREM represents a spherically symmetric Earth. We assume isotropic and elastic properties. The ocean tide model used was FES2014b. The FES2014b model is highly accurate in deep waters (Carrère et al., 2015).

Results

a)



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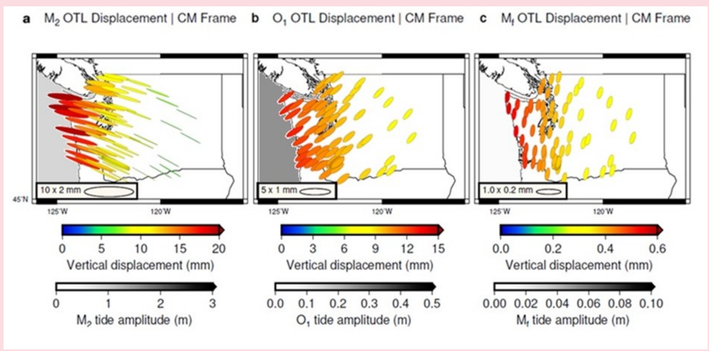

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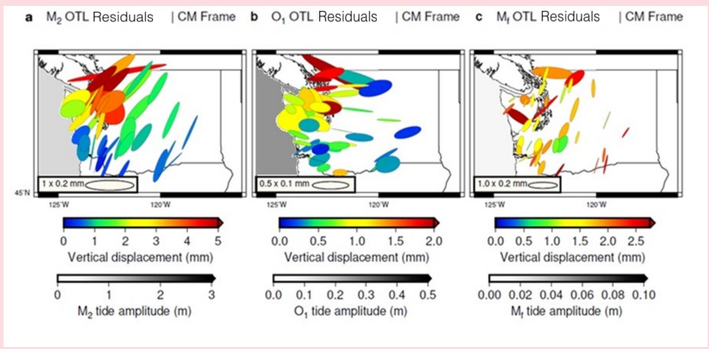

Figure 3: a) The observed OTL in the Puget Sound area. The plotted ellipses show the (scaled) ground track taken by the GNSS stations in response to the OTL in the area and the varying colours correspond to differing levels of vertical displacement in response to OTL. The redder an ellipse is, the more vertical displacement there is and bluer indicates less vertical displacement. The gray background shades in the ocean show the tidal amplitude. There is also a scale present, which shows what a plotted PME corresponds to in the real world, as the PMEs do not follow a path as large as the ones shown in the figure. Panel a shows the OTL due to the M_2 tide, panel b shows the OTL due to the O_1 tide, and panel c shows the OTL due to the M_f tide. b) Model predictions of OTL in the Puget Sound area. This figure assumes the FES2014b ocean-tide model and PREM structure to estimate the OTL displacements. Notably in this figure, the Puget Sound has no apparent impact on the OTL, as it shows a consistent change across the area. c) The residual displacements of OTL in the Puget Sound when comparing the observations to the predictions of OTL. These are the differences between the observations and the predictions of OTL. The GPS time series used to estimate the observed OTL were filtered for outliers based on a window of 14 days and a median absolute deviation filter of 10; no sidereal filter was applied. The predictions were computed using the LoadDef software assuming PREM structure and the FES2014b ocean-tide model.

The model and observations have the largest residual displacements of 5 mm for the M_2 tide, and the smallest 2 mm for the O_1 tide. The maximum residual for the M_f tide was 2.75 mm. These are relatively large values compared to the values seen in similar studies, albeit a harmonic common mode has not been removed here. Spatial coherency in the residuals, and relatively large residuals around the Puget Sound, suggest that there are flaws in the FES2014b tide model that was used in the analysis (particularly the model representation of tides in the Puget Sound), the PREM model for Earth structure, the observations of OTL, or all three. We hypothesize that limitations in coverage in the FES2014b tide model within the Puget Sound contribute significantly to the residuals in that area. This is thought because the largest residuals are seen in the immediate area of the Puget Sound. The FES2014b model does not extend far into the Puget Sound, so the tides here are not considered in the predicted OTL displacements. The model likely needs to be expanded to include the Puget Sound to have less residual displacement between the predictive model and the observations.

References and Acknowledgements

Carrère L., Lyard F., Cancet M., Guillot A., Roblou L., 2012. FES2012: a new global tidal model taking taking advantage of nearly 20 years of altimetry, in Proceedings of meeting "20 Years of Altimetry", Venice.

Dziewonski, A.M., and Anderson, D.L., 1981, Preliminary reference Earth model: Physics of the Earth and Planetary Interiors, v. 25, p. 297-356, doi: 10.1016/0031-9201(81)90046-7.

Martens, H.R., Rivera, L., and Simons, M., 2019, LoadDef: A Python-Based Toolkit to Model Elastic Deformation Caused by Surface Mass Loading on Spherically Symmetric Bodies: Earth and Space Science (Hoboken, N.J.), v. 6, p. 311-323, doi: 10.1029/2018EA000462.

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Sidereal Filter

Introduction and Motivation

Another element explored in this project was quantifying the difference in observed OTL when a sidereal filter is applied to the GNSS time series. A sidereal filter is used to remove multipath errors that occur every sidereal day when GNSS satellite orbits repeat.

It is important to quantify the effect a sidereal filter has on observations of OTL displacement because if the observations are modified by applying the filter (or by not applying the filter), then the comparison between the observations and predictive models will be changed as well. The sidereal filter can overlap in frequency space with the main tidal observations, so special care must be taken regarding the filter. If the observations are altered, then residuals between model and observations predictions and comparisons to the model are also altered.

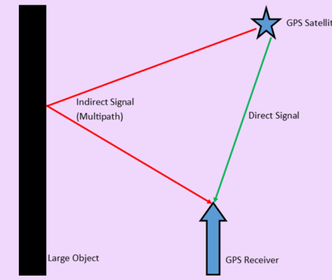
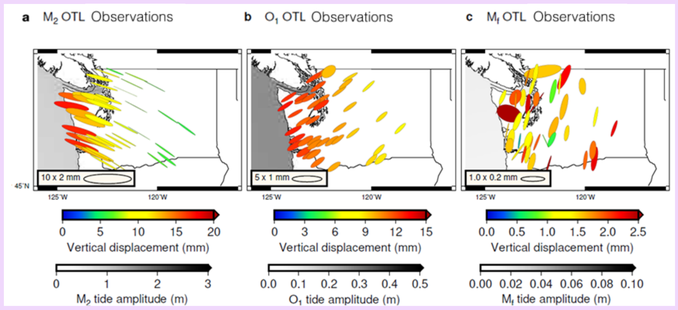


Figure 1: Multipath errors compared to a direct signal from a satellite. The multipath signal must travel much further than that of the direct signal, altering the recorded position of the receiver.

Results

a)



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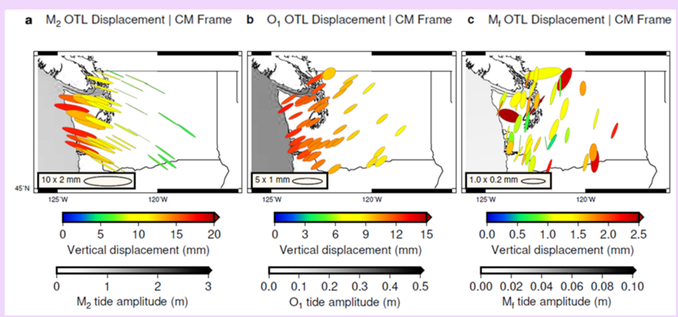

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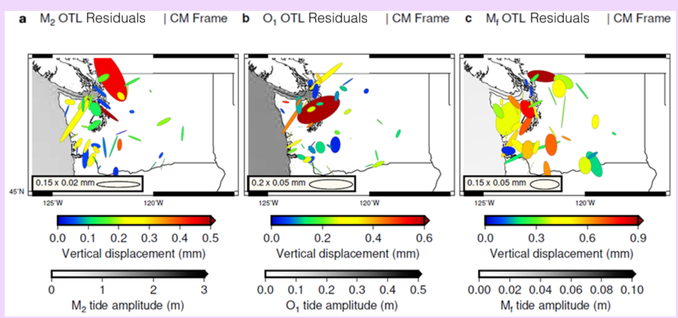

Figure 10: a) Observed surface displacements with settings of MAD-10, WIN-14, and no sidereal filter. b) Observed surface displacements with settings of MAD-10, WIN-14, and a sidereal filter applied. c) The residual difference between a lack of sidereal filter and a sidereal filter applied.

Also considered in this study was the use of a sidereal filter and quantifying the difference between the data produced when a sidereal filter is used versus when it is not. It was determined that the largest residual between the use of a sidereal filter and not in the M_2 tide was 0.5 mm, the O_1 tide was 0.6 mm, and the M_f tide was 0.9 mm. These values are smaller than the residuals between observed and predicted OTL but not insignificant, suggesting that OTL observations are sensitive to the application of a sidereal filter. The application of a sidereal filter should be further explored to determine precisely the impacts on OTL observations and the advantages and disadvantages of applying the filter.