# Chapter 2
# Ocean Tidal Loading Effects to Displacements at GNSS Sites

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**Abstract** Ocean tidal loading (OTL) effects to displacements should be considered during GNSS precise positioning. Especially, along with the shift of geodesy from mainland to ocean, the OTL corrections to displacements play more and more important roles in precise positioning. The approaches to resolve OTL effects in precise GNSS data processing software GAMIT are that, either directly reading out the amplitudes and phases of several main tidal constituents (also called tidal coefficients) at site from file station.oct, or interpolating the site's tidal coefficients from global grid file grid.oct. It's not ideal to modify the OTL effects in China mainland (especially in coast areas, islands and reefs) using GAMIT directly, because of tidal coefficients' errors or the limitations of tracking stations' distribution. This paper detailed describes the OTL effects theories to displacements based on convolution integration approach about OTL and Green's functions. Numerical integration of OTL is performed using the Gauss quadrature method and the integration areas are separated to inner zone and outer zone. A newest $2' \times 2'$ resolutions local ocean tidal model of the East China Sea and South China Sea was adopted for inner zone, and a global model TPXO7.2 for the outer zone. Some OTL corrections to displacements at coast GNSS sites were computed, and which were applied to the GNSS data processing. The estimation of amplitudes and phases for the main tidal constituent M2 were acquired at some sites, variation functions changed with time for displacement were constructed. Numerical tests show that, the displacements at coast sites are bigger than those at inland sites, amplitudes of local loading on displacements reach the order of centimetre. If the amplitudes and phases of tidal constituents calculated by this method are appended into the station.oct file, the baselines' accuracies will be improved greatly for GAMIT software. Not only the OTL corrections but also suitable ocean tidal models and tide constituents should be taken into account in GNSS data analyses.

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## 2.1 Introduction

Researches indicated that the ocean tidal loading effects to displacements can be up to several centimetre in magnitude, even to dm in some parts of our Earth and during some periods, especially in rapidly changing ocean [1–6]. With the developments of national surveying and mapping projects of islands and reefs, China's geodetic measurements are being extended from inlands to oceans, thus the OTL effects can't be ignored.

With the developments of satellites altimetry technologies, so many ocean tidal models were released one after another, such as CRS3.0, CRS4.0, AG95, GOT, NAO, FES2004, and TPXO7 et al. [4, 5]. The GAMIT software used for precise positioning corrects OTL displacements by means of using OTL grid file created by Swedish Onsala Space Observatory (OSO), which was based on global fundamental GNSS stations. OTL grid file created by National Astronomical Observatory of Japan (NAO) was also added to GAMIT for candidate from ver. 10.2 then on. Ocean tidal model FES2004 was selected to correct OTL displacements from GAMIT ver. 10.3 then on, which was released by French Tidal Group (FTG) and was established on the formula of tidal hydrokinetics and the technologies of data fusion. The approaches to resolve OTL effects in GAMIT are that, either directly reading out the amplitudes and phases of several main tidal constituents (also called tidal coefficients) at sites from file station.oct, or interpolating the site's tidal coefficients from grid file grid.oct. The file station.oct comprises lots of tidal coefficients at global 465 tracking stations (including GPS, SLR and VLBI). If the distance between the unknown site and a tracking station is less than 10 km, then the tidal coefficients for the tracking stations are used for this unknown site, otherwise by the mean of interpolating from grid.oct file. It's not ideal to modify the OTL effects in China mainland (especially in oceans) because of tidal coefficients' errors and the limitations of interpolations methods.

## 2.2 Theories and Computation of Loading Effects

OTL effects to displacements at GNSS sites are usually calculated by the convolution integrals of tidal heights and mass loading Green's functions [1, 7–9]:

$$L(\theta,\lambda,t) = \rho R^2 \iint H(\theta',\lambda',t)G(\psi,A)ds \tag{2.1}$$

where, $\theta$ and $\lambda$ are colatitude and longitude for computing point, $\theta'$ and $\lambda'$ are colatitude and longitude for loading point, $\rho$ is the average density of sea water (1.03 g $\text{cm}^{-3}$), $R$ is the average Earth radius, $L(\theta, \lambda, t)$ is the OTL effects, $H(\theta', \lambda', t)$ is the tidal height of loading point, $A$ is the azimuth from computing point to loading point, $\psi$ is the spherical distance between computing point and loading point, which can be calculated from below equation.

$$\cos\psi = \sin\theta \sin\theta' + \cos\theta \cos\theta' \cos(\lambda - \lambda')$$

$G(\theta, A)$ is mass loading Green's functions, which come from the Earth model parameters. $ds = \sin\theta' d\theta' d\lambda'$ stands for surface element. Instantaneous tidal height $H(\theta', \lambda', t)$ can be described as a sum of harmonic oscillations:

$$\begin{aligned} H(\theta', \lambda', t) &= \sum_{p=1}^{N} \zeta_p(\theta', \lambda') \cos(\varpi_p t + \chi_p - \delta_p) \\ &= \sum_{p=1}^{N} \left[H_{cp}(\theta', \lambda') \cos(\varpi_p t + \chi_p) + H_{sp}(\theta', \lambda') \sin(\varpi_p t + \chi_p)\right] \end{aligned} \tag{2.2}$$

where,

$$\begin{aligned} H_{cp}(\theta', \lambda') &= \zeta_p(\theta', \lambda') \cos\delta_p \\ H_{sp}(\theta', \lambda') &= \zeta_p(\theta', \lambda') \sin\delta_p \end{aligned}$$

$\zeta_p$, $\delta_p$, $\chi_p$ and $\varpi_p$ is the amplitude, initial phase, astronomical argument and angular velocity of the $p$th tidal constituent at loading point, respectively. $t$ is UT, $N$ is the count of tidal constituent. Submit Eqs. (2.2) to (2.1):

$$\begin{aligned} L &= \sum_{p=1}^{N} \left[LC_p(\theta, \lambda) \cos(\varpi_p t + \chi_p) + LS_p(\theta, \lambda) \sin(\varpi_p t + \chi_p)\right] \\ &= \sum_{p=1}^{N} \left[L_p(\theta, \lambda) \cos(\varpi_p t + \chi_p - \beta_p)\right] \end{aligned} \tag{2.3}$$

where [10],

$$\begin{aligned} LC_p(\theta, \lambda) &= \rho R^2 \iint H_{cp}(\theta', \lambda') G(\psi, A) \sin\theta' d\theta' d\lambda \\ LS_p(\theta, \lambda) &= \rho R^2 \iint H_{sp}(\theta', \lambda') G(\psi, A) \sin\theta' d\theta' d\lambda' \end{aligned} \tag{2.4}$$

and that,

$$\begin{aligned} L_p(\theta, \lambda) &= \sqrt{LC_p^2 + LS_p^2} \\ \tan\beta_p &= LS_p / LC_p \end{aligned} \tag{2.5}$$

Thus, the key question to OTL effects lies in the integrations of Eq. (2.4), through which the amplitudes $L_p$ and phases $\beta_p$ who describe the loading response for the chosen site can be worked out. There exists four different open sources programs including CONMODB, GOTIC2, NLOADF and OLFG/OLMPP in the world at present, which can complete the convolution integrals of Eq. (2.4) successfully, and the difference between the four results from these programs is not more than 5 % [8]. Agnew [11] developed a method and its corresponding program for calculating loading tides named after NLOADF, which is based on the Green's functions by Farrell [7], and is capable of combining regional ocean tide model with a global ocean tide model, so that users can use more accurate coastal models to improve the loading tide results.

Now, only two unkown parameters including angular velocity $\varpi_p$ and astronomical argument $\chi_p$ are left in Eq. (2.3). Conventionally, the tide is decomposed into a series of harmonics which frequencies lie in semidiurnal, diurnal and long-period three bands, including the semidiurnal waves M2, S2, N2, K2, the diurnal waves K1, O1, P1, Q1 and the long-period waves Mf, Mm and Ssa. More than 95 % of the tidal signal is characterized by these 11 tidal constituents, whose angular velocities are listed in Table 2.1 [10].

The argument $\chi_p$ is the linear combination of astronomical argument, which can be computed from below equation [10].

$$
\begin{aligned}
\chi_{M2} &= 2h - 2s \\
\chi_{S2} &= 0 \\
\chi_{N2} &= 2h - 3s + q \\
\chi_{k2} &= 2h \\
\chi_{K1} &= h + 90^\circ \\
\chi_{O1} &= h - 2s - 90^\circ \\
\chi_{P1} &= -h - 90^\circ \\
\chi_{Q1} &= h - 3s + q - 90^\circ \\
\chi_{MF} &= 2s \\
\chi_{MM} &= s - q \\
\chi_{SSA} &= 2h
\end{aligned}
$$

where, $h$, $s$ and $q$ respectively stands for mean longitude of sun, mean longitude of moon and mean longitude of lunar perigee at beginning of a day, which can be detailed deduced from reference [10].

**Table 2.1** Angular velocities of main tidal constituents

| Tidal constituent | Angular velocity (°/h) |
|---|---|
| M2 | 28.984 |
| S2 | 30.000 |
| N2 | 28.439 |
| K2 | 30.082 |
| K1 | 15.041 |
| O1 | 13.942 |
| P1 | 14.958 |
| Q1 | 13.405 |
| Mf | 1.098 |
| Mm | 0.544 |
| Ssa | 0.082 |

## 2.3 Tests and Computing

### *2.3.1 Choice of Global and Local Tidal Models*

In the numerical integration Eq. (2.4), the total OTL effects are the sum of inner zone and outer zone effects. The inner zone effect uses a refined grid of tidal heights and the outer zone uses a coarse grid. Ideally, tidal heights for the inner zone should be from a local tidal model and those for the outer zone should be from a global tidal model. In this paper, we chose osu.chinasea.2010 tidal model for inner zone which resolution was $2' \times 2'$ and comprised these 11 main constituents listed in Table 2.1, and TPXO7.2 tidal model for the outer zone which was the newest one at present and resolution reached $15' \times 15'$. M2 tidal constituent's amplitudes and phases in China East Sea and South Sea are shown in Fig. 2.1, where real lines stand for amplitudes (unit is centimetre) and broken line stand for phases (unit is degree).

### *2.3.2 OTL Effects to Displacements*

The standard "Gutenberg-Bullen A" Earth mean model was adopted to determine the OTL displacements effects at some sites. These results are compared to those from WU et al. [12], which only simply adopted NAO99b global tidal model. The displacements' amplitudes and phases in three directions [stands for Westward, Southward and Upward, separately, which is positive direction according to Eq. (2.1)] due to M2 and S2 tidal constituents are listed in Table 2.2, where two typical IGS stations are selected, including SHAO which is adjacent to coast and URUM which is far from sea. From Table 2.2, we obtain that the amplitudes of OTL displacements in the areas of nearby sea is obviously bigger than these far

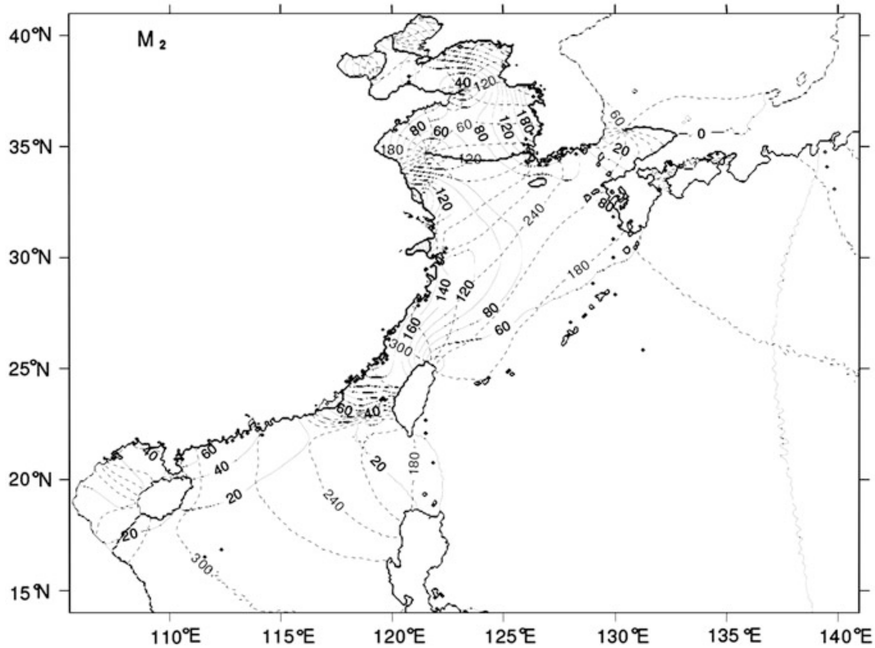

Fig. 2.1 M2 tidal constituents' amplitudes and phases in East China Sea and South China

away from sea. So, we must take into account the OTL effects when precision positioning projects are carried out nearby the coast.

The time series of total OTL corrections to displacements at SHAO station are shown in Fig. 2.2. The time is from August 1st to 31st in 2010. Figure 2.2 indicates that the effects in upward is obviously bigger than these in northward and eastward, which are up to 22 mm.

Table 2.2 The effects to station displacements of M2 and S2 tidal constituent

| Station | Comp. | M2 | | | | S2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Ampl. (mm) | | Phase (°) | | Ampl. (mm) | | Phase (°) | |
| | | This | WU | This | WU | This | WU | This | WU |
| SHAO | W | 2.81 | 2.60 | −158.87 | −160.20 | 0.88 | 0.86 | −125.13 | −114.5 |
| | S | 3.42 | 3.98 | −25.20 | −31.70 | 1.43 | 1.62 | −4.23 | −7.5 |
| | U | 8.56 | 8.16 | −133.91 | −146.40 | 2.86 | 2.99 | −93.41 | −95.0 |
| URUM | W | 0.68 | 0.70 | −153.2 | −156.5 | 0.23 | 0.26 | −156.7 | −161.9 |
| | S | 0.49 | 0.44 | 145.3 | 141.1 | 0.16 | 0.13 | −136.2 | 132.5 |
| | U | 0.39 | 0.23 | −2.7 | −2.9 | 0.43 | 0.45 | 35.8 | 40.4 |

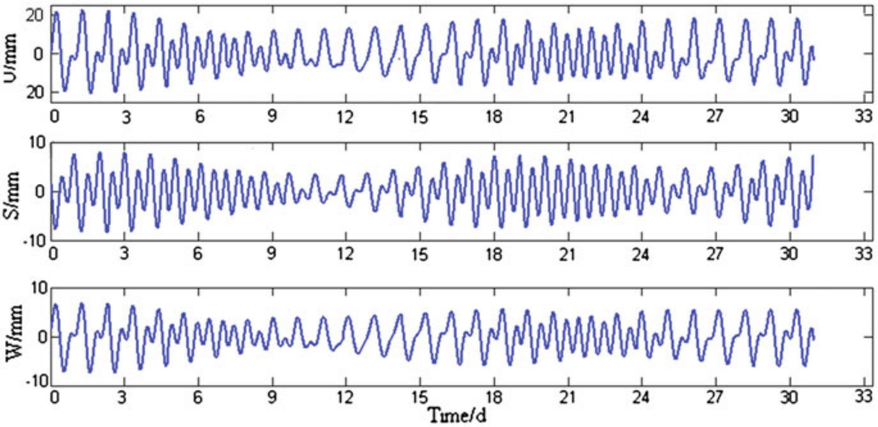

**Fig. 2.2** Time series of total OTL effects to displacements at SHAO

### 2.3.3 Coordinates Computing

There was a grade B GNSS network, which consists of sites located in either near coast or islands and reefs, and the GNSS data from Crustal Movements Observation Network of China were used for known values. Following are two schemes:

Scheme 1 Directly adopt FES2004 global tidal modelstation.oct file and grid.oct file from GAMIT software to determine OTL corrections

Scheme 2 First determine the OTL displacements' amplitudes and phases of every site by numerical integral using East China Sea local tidal model for inner zone and TPXO7.2 global tidal model for outer zone. Then, append these amplitudes and phases to station.oct file in GAMIT software

A statistics about adjustment results from above two schemes were listed in Table 2.3. After corrections of scheme 2, accuracies of baselines are improved greatly, and both standard deviations of coordinates and overlaps with baselines are obviously decreased, and the overlaps with baselines in upward are bigger than those in horizontal directions, which disclaim that OTL corrections do bigger contribution to improving the accuracies in radial direction.

**Table 2.3** A statistics about adjustment results to coordinates at GNSS sites

| | Avg Std (cm) | | | Max Std (cm) | | | Baseline Accu. (mm + ppb) | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | E | U | N | E | U | N | E | U |
| Sch. 1 | 0.22 | 0.55 | 1.26 | 0.37 | 0.89 | 2.27 | 0.4 + 0.6 | 0.3 + 0.6 | 0.2 + 0.8 |
| Sch. 2 | 0.18 | 0.41 | 0.83 | 0.31 | 0.73 | 1.82 | 0.3 + 0.5 | 0.3 + 0.5 | 0.2 + 0.5 |

## 2.4 Conclusions

The OTL displacements corrections are computed by means of Green's functions convolution integral. Some conclusions are drawed through theory analyses and numerical tests:

1. The OTL displacements effects are bigger near coast, even reach several centimeter in magnitude, however, it is up to only several mm in inland. So, in order to improve GNSS positioning accuracy, the OTL effects at sites near coastlines must be considered using various global ocean tidal models and numerical algorithms.
2. Employ higher accuracy and higher resolution ocean tidal model to determine the displacements' amplitude and phase at sites, which will be applied to OTL corrections computing. For GAMIT users, what needed to do is only appending the amplitudes and phases into stations.oct file.
3. Even if the newest ocean tidal model also can't describe the tidal movement characters in our nearby seas, because the continental shelf and geologic structures are very complicated. So, it's better to employ the observed tidal data from gauge during the course of accuracy positioning.

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