Journal of Geodynamics 68 (2013) 29–36

Contents lists available at SciVerse ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Precise determination of ocean tide loading gravity effect for absolute gravity stations in coastal area of China: Effects of land–sea boundary and station coordinate

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A R T I C L E I N F O

Article history:
Received 30 October 2012
Received in revised form 12 March 2013
Accepted 12 March 2013
Available online 21 March 2013

Keywords:
Absolute gravity
Integrated Green's function
Land–sea boundary
Ocean tide loading
Tide gauge record

A B S T R A C T

Gravity effect due to ocean tide loading (OTL) is an important signal and correction in various gravimetric applications. In this paper, we assessed the OTL gravity effects at four absolute gravity (AG) stations in coastal China from several perspectives. The integrated Green's function of the Newtonian part was derived analytically and that of the elastic part was computed based on the PREM earth model. Ocean tide (OT) records near the four AG stations were used to enhance the accuracy of the global ocean tide model of NAO99b and the regional model of NAO99jb for the innermost field (<0.02°). The high-resolution digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) was used to define the land–sea boundary in the optimized near field (<1.0°). Results show that the high-resolution land–sea boundary is indispensible for OTL gravity modeling when the shoreline near a coastal station is complex. The SRTM-based OTL model outperforms the GMT-based model shoreline in terms of the agreement between modeled and observed gravity residuals at the four stations. The final gravity residuals, corrected for OTL, at the four stations are significantly smaller than those without OTL corrections. We give examples of accuracy requirements in coordinates at Qingdao for different station heights. At a station height of 80 m and to ensure a 0.1 μgal accuracy in OTL modeling, the required accuracies in the horizontal and vertical coordinate are 2.5 and 1. 3 m, respectively. For a new coastal station and an expected OTL accuracy, one should inspect the variation of OTL due to coordinate variation to find a best strategy to determine the required accuracy of coordinate.

1. Introduction

Ocean tide loading (OTL) is caused by the ocean tide-induced mass redistribution. OTL gives rise to gravity change and surface deformation, which are increasingly important for investigations of many geodetic and geophysical problems. For example, OTL gravity effect should be removed from observed gravity tidal parameters to set up a gravity reference (Hsu et al., 2000), to detect the translational oscillation of the Earth's inner core (Courtier et al., 2000; Sun et al., 2004; Xu et al., 2010), to evaluate the eigen-period of the Earth's free core nutation (Sun et al., 2002, 2003; Xu et al., 2004; Ducarme et al., 2007), and consequently to evaluate the viscosities of the core-mantle boundary (Sun et al., 2009; Cui et al., 2012). Some of these applications use gravity data from a global network of superconducting gravimeters, under the Global Geodynamics Project (GGP; Crossley et al., 1999). Many of the GGP stations, e.g., Syowa, Hsinchu and Concepcion, are located in coastal areas. In addition, absolute gravimetry has become increasingly an effective tool in monitoring phenomena ranging from sea level change to mass transfer of geodynamic origins (Larson and van Dam, 2000; van Dam et al., 2000; Lysaker et al., 2008; Llubes et al., 2008). Many such measurements are made in coastal zones.

It is widely known that OTL gravity effect in a coastal zone is more difficult to model in comparison to inland areas. In general, the OTL gravity effect will decrease with increasing distance from the ocean. In order to adequately utilize gravity observations in a coastal zone, OTL gravity effects must be modeled with a great care. According to the theory of OTL (Longman, 1962, 1963; Farrell, 1972; Goad, 1980; Agnew, 1997), Green's function and ocean tide are two dominating factors for OTL modeling. Green's function is based on

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http://dx.doi.org/10.1016/j.jog.2013.03.003

the earth model (Farrell, 1972; Pagiatakis, 1990; Wang et al., 1996). Ocean tide for OTL computation is mostly based on a combination of global and a regional tide model, but there have been attempts to enhance OTL accuracy by direct use of tidal records near gravity stations (Neumeyer et al., 2005; Sun et al., 2006; Lysaker et al., 2008).

In addition to Green's function and ocean tide, the land–sea boundary also plays an important role in OTL modeling (Bos et al., 2002; Bos and Baker, 2005; Lysaker et al., 2008). The coastline dataset of Wessel and Smith (1996) is widely used in many OTL programs to define the land–sea boundary (Agnew, 1997; Matsumoto et al., 2001; Bos and Baker, 2005; Scherneck and Bos, 2006). With a spatial resolution up to 90 m, the SRTM DEM is believed to better define the land–sea boundary than the coastline dataset of Wessel and Smith (1996). Several other factors also contribute to OTL accuracy when a gravity station is very close to sea (within several hundreds of meter). For example, Bos et al. (2002) and Hwang and Huang (2012) showed that the OTL gravity effect also depends on the height of a gravity station sufficiently close to sea. Also, for a coastal station, it is not clear how the horizontal coordinate accuracy will affect the OTL accuracy.

With the above background, the objective of this paper is to assess the sensitivities of land–sea boundary and station coordinates on OTL model accuracy. Absolute gravity data and tide gauge records collected at four coastal stations along the coastal area of China will be used in these investigations.

2. Time- and frequency-domain modeling of OTL gravity effect

According to the theory of Farrell (1972), the OTL gravity effect, L, can be expressed by the convolution

$$L(\theta, \lambda, t) = R^2 \rho \int_0^{2\pi} \int_0^{\pi} H(\psi, \alpha, t) G(\psi) \sin\psi d\psi d\alpha \quad (1)$$

where θ and λ are co-latitude and longitude of the location of interest, respectively, t is time. R is the mean radius of the Earth (about 6371 km), ρ is the density of sea water (about 1025 kg/m^3), H is the instantaneous tidal height at t, ψ and α are the spherical distance and azimuth between the location and differential spherical surface area ($\sin\psi\, d\psi\, d\alpha$), and G is the Green's function for gravity effect. The two quantities ψ and α form the spherical surface coordinate system. The latest version of SPOTL uses a density model that accounts for the spatial variation of sea water density (Agnew, 2012).

The tidal height can be expanded into a series of harmonic functions with known tidal frequencies. Hence, we can compute OTL for each constituent (harmonic) with known frequency and omit the time dependence. For example, Goad (1980) used the integrated Green's function method for numerical convolution based on Eq. (1). Other examples are SPOTL developed by Agnew (1997) and SGOTL developed by Hwang and Huang (2012). In the frequency domain, Eq. (1) can be numerically implemented by

$$\begin{pmatrix} L_\omega \cos\varphi_\omega \\ L_\omega \sin\varphi_\omega \end{pmatrix} = \rho \sum_i \sum_j \begin{pmatrix} H_\omega \cos\phi_\omega \\ H_\omega \sin\phi_\omega \end{pmatrix} I(\psi_i) \delta\alpha \quad (2)$$

where ω is a tidal frequency, L_ω and φ_ω are the amplitude and phase of OTL at ω, which are the functions of station coordinates (θ, λ). H_ω and ϕ_ω are the amplitude and phase of ocean tidal height at ω, which are the functions of tidal ocean mass coordinates (ψ, α), and

$$I(\psi_i) = R^2 \int_{\psi_i - \delta\psi/2}^{\psi_i + \delta\psi/2} G(\psi) \sin\psi d\psi \quad (3)$$

is the integrated Green's function (Goad, 1980; Agnew, 1997), $\delta\psi$ and $\delta\alpha$ are the step sizes of integrated Green's function and azimuth. In practice, the step size should be variable. In general, it increases with the increasing angular distance (Agnew, 1996).

The Green's function for the OTL gravity effect consists of two parts, i.e., the Newtonian part and the elastic part. The integrated Green's function for Newtonian part can be derived according to Agnew (2012). Neglecting station height, the formula of Green's function for the elastic part is

$$G^E(\psi) = \frac{f}{R^2} \sum_{n=0}^{\infty} \{(n+1)k'_n - 2h'_n\} P_n(\cos\psi) \quad (4)$$

where h'_n and k'_n are load Love numbers and P_n is the Legendre polynomial, and n is the degree. The derivation of the integrated Green's function of the elastic part involves an infinite series of the integral of the Legendre polynomial. According to the recursive formula of the Legendre polynomial (Heiskanen and Moritz, 1985), the integral of the Legendre polynomial is

$$\int_{\psi-\delta/2}^{\psi+\delta/2} P_n(\cos\psi) \sin\psi d\psi = -\int_{\cos(\psi-\delta/2)}^{\cos(\psi+\delta/2)} P_n(x) dx = \frac{P_{n+1}(x) - P_{n-1}(x)}{2n+1} \Bigg|_{\cos(\psi+\delta/2)}^{\cos(\psi-\delta/2)} \quad (5)$$

Eq. (5) shows that the integral of the Legendre polynomial decreases as $1/n$. Therefore, the infinite series of integrated Legendre polynomial converges faster than that of Legendre polynomial and can be truncated beyond a certain degree under a desired numerical accuracy.

In this paper, Eq. (3) is first used to compute the integrated Green's function and then Eq. (2) is used to calculate OTL for selected leading constituents (each with a frequency), and finally the OTL effect at any time t due to the leading constituents is computed as

$$g(t) = \sum_\omega L_\omega \times \cos[\omega(t - t_0) + \chi_\omega - \varphi_\omega] \quad (6)$$

where the sum is over the leading constituents, and χ_ω is the astronomic argument of that constituent with respect to a reference time t_0. This is the OTL effect in the frequency domain.

If a regional ocean tide model is available, it should be used to enhance the OTL modeling. If a gravity station is near the sea, incorporating nearby tidal records will also improve the OTL model accuracy (Neumeyer et al., 2005; Sun et al., 2006; Lysaker et al., 2008). Because the gravity stations in this paper are all near the sea, we use the tide gauge record as the mean value in a circle with a radius of 0.02° (the innermost field) centered at the stations for each epoch to improve the ocean tide models. Because the ocean tide records (parallel with the gravity records) in this paper are given in the time domain and are not long enough to extract the harmonic constants, we carried out the OTL computation in the time and frequency domains using the following steps:

(a) Calculate the OTL effect by considering the integration area of $0.02 \le \psi \le 180°$ and $0 \le \alpha \le 360°$. In the integral, the step $\delta\psi$ increases with ψ. Table 1 shows $\delta\psi$ with respect to ψ. The step of azimuth remains unchanged for all ψ. In this step the integration is divided into the integrations over the near field ($0.02 \le \psi \le 1°$) and the far field ($1 \le \psi \le 180°$), and the land–sea boundaries for these two fields are different, but are optimized (see Section 4).
(b) Within the innermost field ($\psi \le 0.02°$), calculate the transfer coefficient, C, from tidal height to OTL gravity effect by setting