Temporal-spatial distribution of oceanic vertical deflections determined by TOPEX/Poseidon and Jason-1/2 missions

Jin Yun Guo1,2*, Yi Shen1, Kairhua Zhang1,3, Xin Liu1, Qiaoli Kong1,2, Feifei Xie1,2
1 College of Geodesy and Geomatics, Shandong University of Science and Technology, Qingdao 266590, China
2 State Key Laboratory of Mining Disaster Prevention and Control, co-founded by Shandong Province and Ministry of Science & Technology, Qingdao 266590, China
3 Tianjin Survey and Design Institute for Water Transport Engineering, Tianjin 300456, China
* Corresponding author: JinyunGuo, E-mail: jinyunguo1@126.com

Abstract

Deflections of the Vertical (DOV) are essential data in the geodetic observation reduce, the earth gravity field and geoid model refinement, and the mass earth change. The meridional and prime vertical components of global oceanic DOVs are estimated from altimetry data of TOPEX/Poseidon, Jason-1, and Jason-2, through 1992 to 2013 with the crossover method, to analyze the temporal-spatial distribution of marine DOVs. Comparing with the EGM2008-modelled DOVs, precisions of meridional and prime vertical components can be up to 0.98" and 1.02", respectively. The time series of annual mean DOVs from 1992 to 2013 are studied to get the annual variation law. Annual changes of meridional and prime vertical components are small over most oceans. But the annual changes are significant over oceans with large submarine topography undulations. The spatial distribution of oceanic DOVs is also analyzed. The absolute DOVs over oceans around lands, islands, and large oceanic trenches are greater than those over the other oceans. The meridional and prime vertical components are consistent with the longitude and latitude directions, respectively.

Keywords: Deflection of the Vertical (DOV), satellite altimetry, temporal-spatial distribution, crossover point, marine gravity field.

Resumen

Las Desviaciones de la Vertical (DOV, del inglés Deflections of the Vertical) son información esencial en la simplificación de la observación geodésica, el campo gravitatorio terrestre y el perfeccionamiento del modelo geoid, y el cambio de la masa terrestre. Se estimaron los componentes meridional y principal vertical de las desviaciones de la vertical oceánica global con la información altimétrica de TOPEX/Poseidón, Jason 1 y Jason 2, de 1992 a 2013, con un método de cruce para analizar la distribución espacio-temporal de las desviaciones de la vertical marinas. Comparadas con las desviaciones de la vertical obtenidas con el modelo EGM2008 (Modelo de Gravitación de la Tierra), la precisión de los componentes meridional y principal vertical puede aumentarse 0.98" y 1.02", respectivamente. Se estudiaron las series temporales de la media anual de las desviaciones de la vertical desde 1992 a 2013 para obtener la ley anual de variación. Los cambios anuales de los componentes meridional y principal vertical son muy pequeñas en la mayoría de los océanos. Sin embargo, los cambios anuales son mayores en aquellos océanos con una topografía submarina de grandes ondulaciones. También se analizó la distribución espacial de las desviaciones de la vertical oceánicas. Las desviaciones de la vertical absolutas alrededor de los continentes, islas y fosas oceánicas mayores son superiores a aquellas sobre los otros océanos. Los componentes meridional y vertical principal son consistentes con las direcciones de la longitud y la latitud, respectivamente.

Palabras clave: Desviación de la vertical (DOV), altimetría satelital, distribución espaciotemporal, punto de cruce, campo de gravitación marino.
1. Introduction

The Deflection of the Vertical (DOV) is one basic research topic in geodesy and geophysics. It can characterize the direction of gravity vectors and provide one tight local tie among space geodetic techniques (Shen et al., 2015). The traditional methods to measure DOV include the astronomical geodetic surveying, gravimetry, combination of astronomical geodetic and gravimetry, and global navigation satellite system (GNSS). Based on the astronomical geodetic principle, the automatic measurement system integrating GNSS and CCD zenith telescope can precisely measure DOVs (Guo, Song, Chang, & Liu, 2011; Hirt & Seebert, 2008; Tian et al., 2014, Peng & Xia, 2015). These measurement methods of the vertical deflection are applicable to lands (Ning, Guo, Wang, & M. Wang, 2006), but are unable to measure practically the oceanic vertical deflection due to limitations of these techniques under effects of ocean dynamic environment over open oceans (Guo, Chen, Liu, Zhong, & Mai, 2013; Guo, Liu, Chen, Wang, & Li, 2014). DOVs over open oceans are commonly calculated from the Earth gravity field model at present (Jekeli, 1999; Pavlis, Holmes, Kenyon, & Factor, 2012). Ship-borne gravity data can also be used to estimate the oceanic vertical deflections. But the ship-borne gravimetry can mostly be carried out over coastal seas, and most of the oceans are short of gravity field data. With the rapid development of satellite altimetry, altimeter data can widely be used to estimate the oceanic vertical deflection (Fu and Cazenave, 2000; Guo, Hu, Wang, Chang, & Li, 2015).

With the development of satellite altimetry technique, oceanic DOVs are mainly utilized to determine oceanic gravity field models with high precision. DOVs on crossover points can be calculated from altimeter data by the crossover method (Sandwell, 1984). Altimeter data of ERS-1 and Geosat were processed to estimate DOVs of crossover points from which gravity field over Antarctic oceans was estimated by the Laplace equation (Sandwell, 1992). Sandwell et al. (1997) used ERS-1 and Geosat altimetry data to compute DOVs of crossover points which are interpolated to get DOVs of grids and then estimated the gravity anomalies over seas with the Fast Fourier transformation (FFT). Differences of sea surface height along the track and corresponding track azimuths are used to calculate oceanic DOVs along the track (Olgiati, Balmino, Sarraillh, & Green, 1995). Altimetry data from multi-satellite altimetry missions can be integrated to process DOVs along tracks which are interpolated to calculate DOVs of grids used to estimate marine gravity anomalies. Gravity anomalies along tracks with the along-track DOVs are more accurate than those determined by FFT with the inverse Stokes formula. The inverse Vening Meinesz formula is derived to calculate DOVs with the grid method (Hwang, 1998). The geoid and gravity anomalies over China seas has been calculated from oceanic DOVs with the crossover method (Li, Ning, Chen, & Chao, 2003). DOVs from the crossover method are more accurate than those from the grid method and the along-track method, and the grid method is optimal to determine the high-resolution precise marine gravity field using altimeter data (Peng & Xia, 2004). DOVs over China coastal seas are calculated from Geophysical Data Records (GDRs) of EnviSat with the grid method (Xing, Li, & Liu, 2006). Comparing with EGM96 (Lemoine et al., 1998), precisions of the prime vertical and meridional components are 6 µm and 3 µm, respectively. Multi-altimeter data are processed to calculate global DOVs with the grid method. Comparing with EGM96, precisions of the prime vertical and meridional components over global oceans are 1.97 µm and 1.12 µm, respectively.

TOPEX/Poseidon (T/P) launched in 1992, Jason-1 initiated in 2002 and Jason-2 initiated in 2008 can together measure oceans. Jason-1 follow on runs the same track of T/P and continuously surveys oceans. The precision of single observation is estimated to be near to 3 cm (Beckley et al., 2010; Fu and Cazenave, 2000; Tunini et al., 2010). T/P and Jason-1/2 provide altimetry data with high precision which are processed by the crossover method. Global oceanic DOVs are estimated and then the temporal-spatial distribution of global oceanic DOVs is studied in the paper.
2) Determination of crossover point. The quadratic polynomials are used to fit the ascending and descending arcs on geodetic latitude and longitude based on the positioning information in altimetry data, respectively. The quadratic equations of ascending and descending arcs are combined to solve coordinates of the crossover point.

3) Unification of time and space datum. There exist systematic biases between different altimeter data under effects of a different ellipsoid, time-varying sea surface height, satellite orbit determination error, altimeter error and geophysical correction error. Corrections of coordinate frame biases for different altimetry data are calculated to unify the time and space datum for T/P, Jason-1, and Jason-2.

4) Sea surface height of crossover point. Sea surface height of crossover point is interpolated from the ascending and descending arcs’ data based on coordinates with the distance weight method.

5) DOV determination of crossover point. 8-10 altimetry points around crossover point are selected based on the position of the crossover point. The quadratic polynomial on latitude and longitude, and the quadratic curves of latitude and longitude with respect to time are fitted based on information about sea surface height, latitude, longitude and time of altimetry point, respectively. Then derivatives of these quadratic polynomials are made to get, and which are substituted for equations (1) and (2) to calculate the prime vertical and meridional components of DOV on crossover point.

6) Repeat step 5) to calculate all DOVs of all crossover points. The same pass may be different for all cycles and the farthest distance of crossover points for the same ascending and descending arcs may be up to 1 km for T/P, Jason-1 and Jason-2 (Fu and Cazenave, 2000; Luz Clara, Simionato, D’Onofrio, & Moreira, 2015). So the mean position of crossover point for the same ascending and descending arcs should be determined.

7) Reduce DOVs of crossover points to the mean position with the inverse distance weighted interpolation method within the studied time span. We can get oceanic DOVs of crossover points from altimetry data from 1992 to 2013. So the temporal-spatial distribution of oceanic DOVs can be obtained.

Altimetry data should be edited and corrected before DOV calculation because of contamination of many kinds of errors. The same editing criteria are used to modify and correct altimetry data to get precise results. To check the precision of oceanic DOVs from altimetry data, it was selected T/P data of cycle 17 to compute oceanic DOVs of crossover points in the global area (-60°S~60°N, 0°~360°), which are compared with the modeled DOVs from EGM2008 (Pavlis, Holmes, Kenyon, & Factor, 2012). Table 1 lists the statistical results. From Table 1, it can be seen that the precisions of prime vertical and meridional components are 1.02° and 0.98° comparing with EGM2008-modelled components, respectively, which indicates that oceanic DOVs of crossover points from altimetry data are reliable.

Table 1. Statistical results of oceanic DOVs from T/P, Jason-1, and Jason-2

<table>
<thead>
<tr>
<th>Component</th>
<th>Max (°)</th>
<th>Min (°)</th>
<th>Mean (°)</th>
<th>STD (%)</th>
<th>RMS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meridional</td>
<td>4.89</td>
<td>-4.86</td>
<td>0.07</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Prime vertical</td>
<td>4.98</td>
<td>-4.99</td>
<td>0.00</td>
<td>1.02</td>
<td>1.02</td>
</tr>
</tbody>
</table>

4. Temporal variations of oceanic DOVs

The earth gravity field not only changes in space but also changes in time. The temporal-spatial variation of the earth gravity field is one important part of geodynamics (Ding, Li, & Ding, 2006). The gravity field change containing the abundant geophysical information of interior earth can be studied through the DOV variations.

Oceanic DOVs of crossover points for each cycle are calculated from altimetry data of T/P, Jason-1, and Jason-2 with the crossover method. The mean position of crossover point is determined by averaging positions of crossover points from the same ascending and descending arcs in one year. DOVs from the altimetry data of about 37 cycles in one year are used to get the mean DOV of the average position with the inverse distance weighted interpolation method. So itis possible to get a group of DOVs of annual mean crossover pointson a global scale, which can make up a time series of annual mean DOVs from 1992 to 2013. The time series can be analyzed to study the interannual variations of oceanic DOVs. Figures 2 and 3 show annual variations of meridional and prime vertical components of oceanic DOVs determined by the crossover method, respectively.

From figure 2, it can be found that the annual change of meridional component over most oceans is slight in 1992-2013, and the annual change in most oceans in the north hemisphere is greater than that in the south region. The annual change over open oceans far away from islands and lands is small and apt to convergence, such as the middle Pacific Ocean and the Middle Indian Ocean. The annual variation over coastal seas is great, such as the Bering Sea, the Indonesian Sea, the New Zealand Sea, and the Caribbean Sea. On the one hand, the mass over these coastal seas changes greatly. On the contrary, the variation can reflect the lower altimetry data quality over coastal seas than that over open oceans.

Figure 3 shows the annual changes in prime vertical components. Annual variations are small and apt to convergence over most oceans except for the eastern oceans of the North American, the Bengal Bay, and the China coastal seas. Also, the annual variation is significant over some oceans around islands in the Pacific Ocean.

5. Spatial variation of oceanic DOVs

The Marine gravity field is mainly determined by the oceanic lithosphere and the deep mass distribution and geological structure. It shows the basic geographic information of oceanic lithosphere structure and the submarine topography (Chao, Yao, Li, & Xu, 2002). The uneven distribution of vast oceanic gravity affects the direction of the marine plumb line, which makes the spatial distribution of marine DOVs inconsistent. The marine gravity field can be analyzed by studying the spatial distribution of global oceanic DOVs. DOVs of crossover point for the same ascending and descending arcs in all cycles are interpolated to the mean position with the inverse distance weighted interpolation method. So the average DOV of each crossover point in 1992-2013 can be obtained. Figures 4 and 5 show the global distribution of oceanic DOVs.
large and the altimetry precision over coastal seas may be lower. Absolute DOVs over oceans around lands, islands and vastocean trenches are bigger than those over the other oceans. This is mainly due to the obvious gravity change of interior earth and the severe submarine topography undulation. The meridional and prime vertical components of DOVs are consistent with the longitude and latitude directions, respectively.

The spatial resolution of oceanic DOVs determined from altimetry data with the crossover method is limited by theexact repeating period of altimetry satellite. The combination of more satellite altimetry missions can improve the resolution of oceanic DOVs.

Acknowledgments:

This study is supported by the National Natural Science Foundation of China (Grant No.41374009), the Shandong Natural Science Foundation of China (Grant No. ZR2013DM009), the Public Benefit Scientific Research Project of China (Grant No. 201412001), and the SDUST Research Fund (Grant No. 2014TDJH101).

References:


6. Conclusions

Marine DOVs are determined from altimetry data of T/P, Jason-1, and Jason-2 in 1992-2013 with the crossover method. The temporal-spatial distribution of oceanic DOVs is studied. Comparing with the EGM2008-modelled DOVs, the precisions of prime vertical and meridional components determined from one-cycle altimetry data of T/P, Jason-1, and Jason-2 can be up 0.98° and 1.02°, respectively, which indicates that DOVs of crossover points estimated from altimetry data are very reliable.

Annual changes of meridional and prime vertical components of DOVs over most open oceans are small. But the annual variations over most coastal seas are significant because mass changes over coastal ocean may be consistent with the longitude and latitude directions, respectively.


