Prediction of Gravity Anomalies Over the South China and Philippine Seas from Multi-satellite Altimeter Sea Surface Heights

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Abstract  Gravity anomalies on a 2.5 x 2.5 arc-minute grid in a non-tidal system were derived over the South China and Philippine Seas from multi-satellite altimetry data. North and east components of deflections of the vertical were computed from altimeter-derived sea surface heights at crossover locations, and gridded onto a 2.5 x 2.5 arc-minute resolution grid. EGM96-derived components of deflections of the vertical and gravity anomalies gridded into 2.5 x 2.5 arc-minute resolutions were then used as reference global geopotential model quantities in a remove-restore procedure to implement the Inverse Vening Meinesz formula via the 1D-FFT technique to predict the gravity anomalies over the South China and Philippine Seas from the gridded altimeter-derived components of deflections of the vertical. Statistical comparisons between the altimeter-derived and the shipboard gravity anomalies showed that there is a root-mean-square agreement of 5.7 mgals between them.

Keywords  satellite altimetry; sea surface heights; deflections of the vertical; gravity anomalies

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Introduction

Marine gravity anomalies over oceans are traditionally determined using shipboard point gravity measurements. The shipboard gravimetric surveys are time-consuming, sometimes inhomogeneous and expensive and, therefore, not regularly-carried out projects.[1]

Fortunately, with the advent of satellite altimetry, marine geodesists and geophysicists have been provided with a huge amount of homogeneous and near-global instantaneous sea surface heights that could be converted into deflections of the vertical, and subsequently, to high-resolution marine gravity anomalies by invoking the Inverse Vening Meinesz formula[2-4].

In this paper, the Inverse Vening Meinesz formula implemented to compute the gravity anomalies using altimeter-derived components of deflection of the vertical as input data follows Molodensky et al.[5], and is structurally different from the one used by Hwang[7], though Li[4] has proved that the two are mathematically equivalent.

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1 Theory

Following Molodensky et al., the Inverse Vening Meinesz formula implemented in this study to compute gravity anomalies using altimeter-derived components of deflection of the vertical as input data is given by\(^{(5)}\):

\[
\Delta g = -\frac{\gamma}{4\pi R^2} \int_{\sigma} \left( 3 \csc \psi - \csc \psi \csc \frac{\psi}{2} - \tan \frac{\psi}{2} \right) \frac{\partial N}{\partial \psi} \, d\sigma
\]

where the component of deflection of the vertical along the azimuth \( \alpha \) is related to the geoid slope \( \frac{\partial N}{\partial \psi} \) by:

\[
\frac{\partial N}{\partial \psi} = R(\xi \cos \alpha + \eta \sin \alpha)
\]

where \( R \) is the mean radius of the Earth, and \( \xi \) and \( \eta \) are the respective altimeter-derived north-south and east-west components of deflections of the vertical. Substituting Eq.(2) into Eq.(1) yields

\[
\Delta g(\varphi, \lambda_p) = -\frac{\gamma}{4\pi} \int_{\sigma} \left( 3 \csc \psi - \csc \psi \csc \frac{\psi}{2} - \tan \frac{\psi}{2} \right) (\xi \cos \alpha + \eta \sin \alpha) \, d\sigma
\]

To obtain the 1-D convolution form of Eq.(4), the kernel functions \( IV_\xi \) and \( IV_\eta \) are introduced, and Eq.(4) is expressed as:

\[
\Delta g(\varphi, \lambda_p) = -\frac{\gamma}{4\pi} \int_{\sigma} \left( \xi IV_\xi + \eta IV_\eta \right) \, d\sigma
\]

where

\[
IV_\xi = \cos \alpha \left( 3 \csc \psi - \csc \psi \csc \frac{\psi}{2} - \tan \frac{\psi}{2} \right)
\]

\[
IV_\eta = \sin \alpha \left( 3 \csc \psi - \csc \psi \csc \frac{\psi}{2} - \tan \frac{\psi}{2} \right)
\]

\[
= \left[ \frac{\cos \varphi \sin \varphi - \sin \varphi \cos \cos(\lambda_p - \lambda)}{4 \sin^2 \frac{\psi}{2} \left( 1 - \sin^2 \frac{\psi}{2} \right)} \right].
\]

\[
\left( -2 \sin \frac{\psi}{2} + 3 \sin^2 \frac{\psi}{2} - 1 \right)
\]

2 Methodology

2.1 Data-editing and computing corrected sea surface heights

Multi-satellite altimeter sea surface heights comprising 11 years of T/P merged geophysical data records (392 cycles), 9.4 years of ERS-2 35-day-repeat data (96 cycles), 1.25 years of ERS-1 35-day-repeat data (13 cycles), 3.2 years of GEOSAT ERM data (63 cycles), and the 1.5 years of GEOSAT GM data were
subjected to rigorous editing criteria as recommended in the user handbooks of the various satellite altimeter missions[7-10] and by Ohio State University. Out of the valid global data points of 633 651 949, five million, three hundred and forty two thousand, six hundred and seventy six (5 342 676) data points falling within the geographical domain of latitude 0 to 30°N and longitude 105°E to 135°E were extracted for further processing.

2.2 Computing deflections at crossover locations

Single-satellite and dual-satellite crossovers were performed, and at the crossover positions, north(ξ) and east(η) components of deflections of the vertical were determined using Sandwell’s computational philosophy, and expressed as[11]:

\[
\begin{align*}
\eta &= -\frac{1}{2\lambda R \cos \phi} (\dot{H}_a + \dot{H}_d) \\
\xi &= -\frac{1}{2|\dot{\phi}| R} (\dot{H}_d - \dot{H}_a)
\end{align*}
\]

where \(\dot{H}\) denotes the derivative of the corrected sea surface height, subscripts \(a\) and \(d\) represent the ascending and descending tracks, respectively; \(\lambda\) and \(\phi\) are the respective longitudinal and latitudinal components of the satellite’s ground track velocity, and \(R\) is the mean radius of the Earth.

2.3 Gridding components of deflections of the vertical

Using Shepard’s interpolation procedure[12], the altimeter-derived components of deflections of the vertical were then gridded onto a 2.5′ × 2.5′ resolution grid. Employing GMT programs, the altimeter-derived components of the deflections of the vertical were “contoured” at 1″ intervals and 5′ × 5′ spatial resolution (for display purposes), as exemplified in Fig.1.

2.4 Applying remove-restore procedure

2.5′ × 2.5′ grids of EGM96-derived gravity anomalies and components of deflections of the vertical, depicted in Figs.2, 3 and 4, were then used as reference global geopotential model quantities in a remove-restore procedure to implement the Inverse Vening Meinesz formula via 1D-FFT technique to predict the 2.5′ × 2.5′ gravity anomalies from the gridded altimeter-derived components of the deflections of the vertical.

The EGM96-derived components of deflections of the vertical \(\xi^{GM}\) and \(\eta^{GM}\) were first subtracted from the altimeter-derived components of the deflections of the vertical to obtain the residual north \(\delta \xi\) and east \(\delta \eta\) components of the deflections of the vertical as:
$$
\delta \xi_q = \xi^{4\it{th}}_q - \xi^{\text{GM}}_q \quad \delta \eta_q = \eta^{4\it{th}}_q - \eta^{\text{GM}}_q \tag{11}
$$

With the residual components of vertical deflection as input data, the Inverse Vening Meinesz was invoked to compute the residual gravity anomalies through the 1D-FFT technique, following Haagmans et al., as\textsuperscript{[13]}:

$$
\delta g_{\phi, \lambda_p}(\phi, \lambda) = \frac{\Delta \gamma}{4\pi} F^{-1}_i \sum_{i=1}^{i=1} \{ F_i[\delta \xi(\phi, \lambda) \cos \phi] F_i[IV_\xi(\phi, \phi, \lambda_p - \lambda)] + F_i[\delta \eta(\phi, \lambda) \cos \phi] F_i[IV_\eta(\phi, \phi, \lambda_p - \lambda)] \} \tag{12}
$$

where the kernel functions $IV_\xi$ and $IV_\eta$ are defined as:

$$
IV_\xi = \begin{cases} 
IV_\xi, & \text{if } \psi \leq S \\
0, & \text{if } \psi > S
\end{cases} \\
IV_\eta = \begin{cases} 
IV_\eta, & \text{if } \psi \leq S \\
0, & \text{if } \psi > S
\end{cases} \tag{13}
$$

and $F_i$ and $F_i^{-1}$ are the 1-D FFT operator and its inverse, respectively; $\gamma$ is the Earth’s mean gravity; $\phi$ is the latitude along which gravity anomalies are computed; $\phi_p$ and $\phi_n$ are the southernmost latitude and northernmost latitude, respectively, within a spherical cap of size $S$; $\alpha_{\phi_p}$ is the azimuth from $q$ to $p$, $\Delta \lambda_{\phi_p} = \lambda_p - \lambda$, is the difference in longitude between $q$ and $p$, and $IV_\xi$ and $IV_\eta$ are as defined in Eqs.(6) and (7).

After getting the residual gravity anomalies $\delta g$ from the above step, the gravity anomalies computed from the EGM96 geopotential model $\Delta g^{\text{GM}}$ were restored to them (i.e. added to the residual anomalies) to obtain the final altimeter-derived gravity anomalies $\Delta g$ at the grid nodes as:

$$
\Delta g = \delta g + \Delta g^{\text{GM}} \tag{14}
$$

Table 1 gives the descriptive statistics of the altimeter-predicted gravity anomalies (excluding the EGM96-derived gravity anomalies on land) over the study area via 1D-FFT, while Fig.4 and Fig.5 present examples of the predicted gravity anomalies over the study area.

| Satellite altimeter data type | Data points | Maximum | Minimum | Mean | RMS | STD | CPU time mins:sec |
|------------------------------|-------------|---------|---------|------|-----|-----|------------------|
| ERS1                         | 394 655     | 340.252 | -335.905| 13.623| 51.272| 49.429| 11:23            |
| ERS2                         | 400 671     | 340.880 | -342.407| 13.843| 51.534| 49.640| 11:35            |
| GEOSAT                       | 407 331     | 342.934 | -359.424| 13.554| 50.379| 48.521| 11:04            |
| T/P                          | 327 006     | 331.565 | -311.709| 14.763| 54.354| 52.498| 10:49            |
| ERS1-ERS2                    | 400 696     | 340.931 | -339.977| 13.847| 51.534| 49.639| 11:27            |
| GEOSAT-ERS(1+2)              | 408 032     | 343.453 | -374.354| 13.642| 50.715| 48.845| 11:07            |
| T/P- ERS(1+2)                | 334 961     | 344.420 | -307.959| 14.965| 54.739| 52.654| 10:48            |
| T/P-GEOSAT                   | 343 609     | 345.014 | -318.540| 15.157| 54.931| 52.799| 11:20            |
3 Results analyses and discussions

3.1 Comparisons between altimeter-derived and EGM96-derived gravity anomalies

The satellite altimeter-predicted gravity anomalies were compared with the EGM96-derived gravity anomalies. Table 2 gives the descriptive statistics of the comparisons, while Fig. 9 presents the colour-shade map of the differences.

The differences between the altimeter-predicted gravity anomalies and the EGM96-derived gravity anomalies are equal to the residual gravity anomalies computed using the Inverse Vening Meinesz formula. From Fig.7, it can be seen that higher differences occur in areas associated with tectonically active structures.

3.2 Comparisons between altimeter-derived and shipboard gravity data

The altimeter-derived gravity anomalies were externally checked using shipboard recorded point gravity data provided by the National Geophysical Data Center (NGDC). A total of three hundred and thirty four thousand, one hundred and sixty five (334 165) ship-track gravity observations were extracted and converted to gravity anomalies. The altimeter-derived gravity anomalies were then interpolated into the positions of the randomly distributed ship-track gravity observations for point-to-point comparisons to be effected. Table 3 presents the statistics of the differences between the altimeter-derived and shipboard gravity anomalies for each of the single- and combined-satellite missions, while the spatial distribution of the differences is shown in Fig. 8.

4 Conclusions

A 2.5×2.5 arc-minute grid of gravity anomalies in a non-tidal system over the South China and Philippine Seas is derived from multi-satellite altimeter sea surface heights. The results indicate that relatively smaller differences exist between the altimeter-derived gravity anomalies and the EGM96-derived gravity anomalies.

Table 2 Statistics of the differences between EGM96- and altimeter-derived gravity anomalies/mgals

| Mission       | Data points | Maximum | Minimum | Mean    | RMS    | STD    |
|---------------|-------------|---------|---------|---------|--------|--------|
| ERS1          | 394 655     | 115.246 | -110.473| 0.209 743| 14.908 3| 14.906 9|
| ERS2          | 400 671     | 114.142 | -100.083| 0.228 285| 15.184 6| 15.182 9|
| GEOSAT        | 407 331     | 104.533 | -116.745| 0.015 092| 13.442 1| 13.442 2|
| T/P           | 327 006     | 109.917 | -115.586| 0.110 606| 16.888 6| 16.888 2|
| ERS(1+2)      | 400 696     | 120.253 | -102.541| 0.229 940| 15.189 0| 15.187 3|
| GEOSAT-ERS(1+2)| 408 032   | 112.060 | -109.000| 0.118 894| 14.024 9| 14.024 4|
| T/P-ERS(1+2)  | 334 961     | 107.513 | -131.359| 0.195 247| 16.632 5| 16.631 4|
| T/P-GEOSAT    | 343 609     | 111.214 | -147.589| 0.266 445| 16.427 1| 16.425 0|

Table 3 Statistics of the differences between altimeter-derived and shipboard gravity anomalies/mgals

| Mission       | Data points | Mean   | RMS    | STD    |
|---------------|-------------|--------|--------|--------|
| ERS1          | 774 47      | -0.415 3| 5.668 3| 5.653 1|
| ERS2          | 777 85      | -0.435 9| 5.658 0| 5.641 3|
| GEOSAT        | 751 08      | -0.530 1| 5.682 1| 5.657 3|
| T/P           | 763 98      | -0.320 0| 5.636 8| 5.627 7|
| ERS(1+2)      | 777 09      | -0.429 9| 5.658 7| 5.642 4|
| GEOSAT-ERS(1+2)| 766 43     | -0.405 6| 5.701 9| 5.687 5|
| T/P-ERS(1+2)  | 761 13      | -0.324 2| 5.639 4| 5.630 1|
| T/P-GEOSAT    | 764 90      | -0.402 9| 5.676 3| 5.662 7|
anomalies over regions where no tectonically active geological structures exist. However, over tectonically active zones, higher differences were observed. It was also shown that there is a root-mean-square agreement of about 5.7 mgals between the altimeter-derived and the ship-track gravity anomalies over the study area.

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