Bathymetric Inversion of South China Sea from Satellite Altimetry Data

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1 Introduction

To develop the ocean widely and deeply, we need abundant ocean information. As an essential part of such information, seafloor topography plays a very important role in a variety of marine activities. However, the high cost for ocean bathymetric surveying limits the application of this technology. To meet the needs of the society, more effective methods, which can fit various deep oceans with complex bottom, are expected to be brought out.

Fortunately, many scientists of oceanography have paid attention to this situation and have found many methods and theories[1]. And a method based on the relationship between the earth interior mass and the external gravitational field is regarded as an effective way. As Dorman and Lewis (1970) pointed out that the relationship between the Bouguer anomalies and the seafloor topographic height (ocean bathymetric height) was simply linear, the ocean bathymetric inversion from the gravity anomalies had been based on this assumption[2,3]. Furthermore, the impending LEO (Low Earth Orbit) satellite missions including satellite altimetry mission, satellite gravity mission, satellite ocean current mission and so on will be brought into effect. They will give geoscience field more detailed ocean information and make the methods of bathymetric inversion from gravity anomaly widely be used.

2 Model and methodology

Ocean gravity anomaly is caused by many reasons including the mass deficiency of seawater, the earth crust density ano -
mally, the structure of the sea depth and so on. The gravity anomalies from the compensation and the mass anomalies in the earth crust are smoothed by upward continuation. The mass deficiency of seawater is the dominant source, which causes of the short and medium wavelength part of the ocean gravity anomaly.

Fig. 1 shows that the potential derives from the seawater anomaly mass:\(^{41}\)

\[
\delta V = G \int_{V} \frac{dm}{l} (1)
\]

where \(G\) is the constant of universal gravitation; \(l\) is the distance between the mobile point and the fixed point; \(dm\) is the particle. We can make an approximate process. If the sphere surface is regarded as a limited plane the equation can be obtained as

\[
\delta V = G \Delta \rho \int_{E} \frac{d(z - z_{p})}{l} dxdy (2)
\]

where \(l = \sqrt{(x - x_{p})^2 + (y - y_{p})^2 + (z - h)^2}\); \(\Delta \rho = \rho_{0} - \rho_{w}\); \(H \geq 0\) is the sea depth; \(E\) is a two-dimensional plane; \(x, y\) and \(z\) is a right-hand local coordinate and their orientations are north, east and up, respectively; \(\rho_{0}\) is the mean density of the earth crust; \(\rho_{w}\) is the mean density of the sea water. Then the gravity anomaly value which is caused by seawater mass deficiency is

\[
\delta g = \frac{-3H}{8} \left[ \frac{H^2}{(l_0^2 + H^2)^{3/2}} \right] dxdy (3)
\]

As Eq. (4) shows, the relationship between the depth and gravity anomaly is not a simple linear one even in first approximation. After getting rid of the items which is greater than order 2 and replacing the denominator’s \(H\) with \(\bar{H}\) which is the mean depth of an appointed ocean area, we can obtain

\[
\delta g \approx \frac{1}{2} G \Delta \rho \int_{E} \frac{H^2}{(l_0^2 + H^2)^{3/2}} dxdy (5)
\]

Making a Fourier transformation:

\[
f_{\delta g} = \frac{1}{2\omega} G \Delta \rho f_{H} \exp(-2\pi \omega \bar{H}) (6)
\]

where \(f_{\delta g}\) and \(f_{H}\) are Fourier transformation of \(\delta g\) and the square of sea depth; \(\omega\) is the scale wave number. Eq. (6) represents the linear relationship between \(\delta g\) and the square of the sea depth in the frequency domain.

The short-wavelength bathymetry produces the short-wave length gravity anomalies, while the long-wavelength bathymetry is compensated\(^{5}\). The processing of inversion from gravity anomalies to ocean bathymetry is a downward continuation processing. So if we calculate the sea depth directly, the processing may cause strong surge and the results can be far from the actual sea depth. On the other hand, because of the deflections of the geological data and the mantle data below the sea floor, directly using the equation to calculate the sea depth will be of a failure. To ensure the successfully calculating, we must use a filter to get rid of the long-wavelength bathymetry, then calculate the short and medium-wavelength bathymetry, and then restore the actual bathymetry. In this way, the results will show the detailed bathymetric compared with the prior ocean bathymetry model.

In this paper, the free-air gravity anomalies are derived from the satellite altimetry. The inversion of bathymetry is based on the EGM96 globe gravity model and the TBASE globe bathymetric model. The approach is described as follows:

1) Calculating the residual gravity anomalies:

\[
\Delta g^{res} = \Delta g^{ref};
\]

2) Calculating the residual ocean bathymetry \(H^{res}\) by using \(\Delta g^{res}\) with the function which represents the relationship between the depth and the gravity
3) Then the actual calculated ocean bathymetry (same as in Fig. 1) \( H = H_{\text{ref}} + H_{\text{rd}} \);

4) Comparing the inversed value with that by the ship-board bathymetry, and determining the system error;

5) Inversing the bathymetry again, where \( \Delta g_{\text{rd}} \) is the reference gravity anomaly model (EGM96 2.5' x 2.5' globe gravity model in this paper); \( \Delta g \) is the free-air gravity anomalies derived from various satellite altimetry data; \( \Delta g_{\text{ref}} \) is the residual gravity anomalies; \( H_{\text{ref}} \) is the referenced ocean bathymetric model (TBASE 5' x 5' globe bathymetric model in this paper); \( H_{\text{ms}} \) is the residual bathymetry.

3 Data

In the research on the seafloor topography, some data sources, such as the earth gravity field information, the information of the sea floor sediment, ocean current, the geological structure of the ocean floor and bathymetric data are necessary. The earth gravity field is high related to the physical character of seawater, seafloor crust and mantle. Other data, e.g. sediment, will directly affect the inversion processing. Hence the data used in this paper should be described here.

The earth gravity information is derived from the satellite altimetry data (GEOSAT, ERS-1/2, T/P, etc.). These data are useful to determine the ocean gravity anomaly in high precision, and the processing flow is below: firstly, editing the altimetry data; secondly, calculating the crossover points, at the same time calculating the deflection of the vertical; thirdly, calculating the grid gravity anomalies with inverse Venning-Menaz formula[5]; finally, we get the grid free-air gravity anomalies whose resolution is the 2.5' x 2.5' and the mean gravity anomaly precision is better than 8 mGal.

In this paper, the basic inversion method needs a global gravity model and a global ocean bathymetric model. The 360-degree global gravity model EGM96 and TBASE bathymetric model are used.

In a very important respect, the seafloor sediment is affected by the ocean current, the meteorology and the sea floor topography. When the thickness of the sediment is more than 200 m, it will affect the inversion processing considerably. And up to now, there is not any appropriate global ocean sediment model, so it is difficult to get rid of the effects of the thick sediment. In this paper, the seafloor sediment which has low density is regarded as a thinner one, which has the same density as seafloor lithosphere. Through adjusting the system error and using the basic inversion method, we can improve the precision and reduce the effects of the thick sediment.

Ocean currents and seafloor geological structures have synthetical affects. All of these effects are included in the gravity anomaly information. Further researches are needed to extract such information.

Up to now, some factors which affect the bathymetric inversion are still difficult to process well, but they contain much ocean information. It is foreseeable that the research about the seafloor and ocean bathymetry will be improved rapidly with the new theories, impending LEO satellite ocean and gravity missions and all new technique improvements.

4 Result analyses and Conclusions

4.1 The improvement for TBASE model

By comparing Fig. 2 and Fig. 3, nearby 22.5°N 126°E, it is found that there is a seamount, which could be found in the TBASE model, and nearby 10°N 115°E, the inversion model is more exact than the TBASE model.

Furthermore, in Fig. 4, the TBASE model and the inversion model are in good agreement. And the residual errors are all less than ±250 m.

4.2 Compared with the ship bathymetry

As for checking, the bathymetric points play an important role: the GEODAS(r) database has 49 096 ship bathymetry points in this area (N 1°-24°, E104°-128°) (see Fig. 5). The calculated water depth values with TBASE model and the model presented in this paper are compared with those measured at ship bathymetry points, respectively.
(Table 1). Some conclusions can be drawn:

![Fig. 2](image1.png)

Fig. 2 TBASE model bathymetry

![Fig. 3](image2.png)

Fig. 3 Inversion model bathymetry

![Fig. 4](image3.png)

Fig. 4 Difference between TBASE model and inversion bathymetry

![Fig. 5](image4.png)

Fig. 5 Distribution of ship bathymetry

| Ranges of bathymetry | Elimination systematic error | GEODAS bathymetry point | TBASE model RMS | TBASE model STD | Inversion model RMS | Inversion model STD |
|----------------------|------------------------------|-------------------------|-----------------|-----------------|---------------------|---------------------|
| 1 000-2 000          | No                           | 1598                    | 249.68          | 249.19          | 252.99              | 250.66              |
|                      | Yes                          |                         |                 |                 |                     |                     |
| 2 000-3 000          | No                           | 6469                    | 245.85          | 244.16          | 258.15              | 242.77              |
|                      | Yes                          |                         |                 |                 | 251.86              | 251.86              |
| 3 000-4 000          | No                           | 9838                    | 350.87          | 349.81          | 374.32              | 350.82              |
|                      | Yes                          |                         |                 |                 | 361.76              | 361.76              |
| 4 000-5 000          | No                           | 27681                   | 231.09          | 190.56          | 207.22              | 189.67              |
|                      | Yes                          |                         |                 |                 | 187.17              | 187.17              |
| >5 000               | No                           | 32                      | 303.32          | 212.35          | 229.75              | 213.61              |
|                      | Yes                          |                         |                 |                 | 213.62              | 213.62              |

1) There is obvious systematic error between the TBASE model and ship data. It may be caused by the benchmark surface defining difference. After getting rid of the systematic error, the coherence between the model and ship data is improved.

2) The sea depth and the inversion precision are high correlated with each other. With the increase of the sea depth, the precision of the inversion val-
ues of the sea depth increase obviously.

3) The systematic error of the TBASE model and the sea depth are high correlated with each other as well. So the processing for getting rid of the systematic error needs connecting with the sea depth. On the other hand, there is a direct relationship between the sea depth and the seafloor geological characters.

4) In particular, in the area where the sea depth is more than 4000 m, the inversion model gives better results than the TBASE model. In other words, after introducing the ocean gravity data, the precision and resolution of the bathymetry model are very improvement.

5) In the area where the depths range from 1000 m to 4000 m, the precision of the inversed sea depth is low, that may be caused by the poor altimetry data precision and the complex geological conditions of the shallow sea and the area near shore. So in this kind of area, the inversion way is not suitable.

From above analysis, it can be concluded that the seafloor topography can be effectively inversed by using the ocean gravity data from satellite altimetry.

5 Suggestions

1) With the new LEO missions (CHAMP, GRACE and GOCE) which are designed for earth gravity field and ocean current observations, the earth gravity model and ocean current model and other oceanic information will be available. The main problem will be the need of good inversion mathematics model.

2) Through analyzing the relative dense ocean gravity data and the spare shipboard bathymetry, abundant seafloor sediment information can be obtained. As a method for the research of sediment, it is worthy of paying more attention.

3) With regard to the ocean current, the research is limited of by the degree of ocean current model of less than 25 degree. With the GRACE mission being put into practice (GRACE satellite has been launched on March 18, 2002), the tremendous breakthrough will open new insights and application areas. It will be helpful for the research of seafloor sediment.

4) The relationship between gravity anomaly and bathymetry is connected with the oceanic floor crust. But because of the complex situations, there are not any satisfying model and theories to solve this problem.

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