Improving Gravity Anomalies Over China Marginal Sea from Retracked Geosat and ERS-1 Data

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Abstract
The quality of altimeter data and ocean tide model is critical to the recovery of coastal gravity anomalies. In this contribution, three retracking methods (threshold, improved threshold and Beta-5) are investigated with the aim of improving the altimeter data over a shallow water area. Comparison indicates that the improved threshold is the best retracking method over China Sea. Two ocean tide models, NAO99b and CSR4.0, are analyzed. Results show that different tide models used in the processing of altimeter data may result in differences more than 10 mGal in recovered coastal gravity anomalies. Also, NAO99b is more suitable than CSR4.0 over the shallow water area of China Sea. Finally, gravity anomalies over China Sea are calculated from retracked Geosat/GM and ERS-1/GM data by least squares collocation. Comparison with shipborne gravimetry data demonstrates that gravity anomalies from retracked data are significantly superior to those from non-retracked data. Our results have the same order as the other two altimeter-derived gravity models: Sandwell&Smith(V16) and DNSC08.

Keywords satellite altimetry; waveform retracking; gravity anomaly; tide model; China marginal sea

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Introduction
Satellite altimeter data are arguably the most important marine geology and geophysics data set collected over the past decades[1]. The combination of these high-density data sets provided the first detailed view of the global marine gravity field. The global marine gravity anomaly models have been constructed by several scientific groups[1-3]. Current satellite altimeters have typical 1-s averaged range precision of 3-4 cm resulting in gravity field accuracies of 4-6 mGal in open oceans. However, altimeter data quality over shallow waters can be seriously degraded due to (1) bad tidal correction, (2) contaminated altimeter waveforms, (3) large sea surface variability and (4) bad wet tropospheric correction because of corruption in radiometer measurements[4, 5]. Inferior or erroneous altimeter data will lead to gravity anomalies containing artifacts and in turn false interpretations of the underlying geophysical phenomena. This limits the recovery of coastal gravity anomalies.

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and other coastal applications. In order to improve the accuracy of the altimetry-derived gravity anomalies over the shallow waters, the range precision of the existing measurements should be improved. There are two ways to improve the range precision. One is waveform retracking, which is proved very efficiently to improve the data quality and extend data closer to the coast. The other is to select optimal geophysical correction models.

The continental shelves of the China Sea are typical shallow-water areas, defined as water with a depth less than 200 m in this paper. And the coastal sea-surface state is very complicated over the China marginal sea. This causes the difficulty to accurately recover the gravity anomalies from altimeter data. The objective of this study is to improve altimetry gravity in these areas, including Bohai, Yellow Sea, East Sea and Taiwan Strait, where more than 60% of waters are shallower than 200 m. Three waveform retrackers are compared to choose an optimal retracking scheme. Two tide models are tested for the ocean tide correction.

1 Comparison of waveform retracking methods

It is well known that the precision of satellite-altimeter-measured sea surface heights (SSHs) is lower in coastal regions than in open oceans, due to the complex sea state and the contamination of the radar return from land topography. The error caused by altimeter waveform contamination can be mostly removed by using waveform retracking. There are numerous methods for waveform retracking. For example, the conventional methods are the offset center of gravity (OCOG) arithmetic [6], the threshold method [7] and the Beta-5 method [8]. OCOG is a simple waveform retracker with low accuracy since its model is based on the statistics of waveform. Therefore, OCOG is often used to calculate initial values for other methods. The threshold method is also a statistical approach with no physical meaning, but has higher accuracy than OCOG. The Beta-5 method is based on mathematical fitting. It uses a 5-parameter function to fit the waveform with least squares method. Usually, the Beta-5 method can get a more accurate tracking gate if the reflecting surface has Gaussian distribution. However, the surface of coastal water is not Gaussian. According to the features of waveform from coastal water, Hwang et al. [9] developed a new retracking algorithm based on the threshold method, which is named improved threshold retracker (ITR). With the aim of selecting an optimal retracker for the study region, we will experiment with three retracking techniques: ITR, threshold and Beta-5.

Two criteria are used to assess the efficiency of each method. One is the success rate of retracking. Table 1 shows the success rates of the three retrackers. In theory, the success rate of the threshold method is 100%. However, if the retracked gate is less than 6 or greater than 58, the result is incredible. In this case, we will think the waveform retracking is failed. The results in Table 1 demonstrate that the success rates of ITR and threshold are very close to 100%. ITR has a slightly higher success rate than threshold where water depth is less than 100 m. The Beta-5 method has the lowest success rate, especially for ERS-1 data.

| Water depth(m) | Total No. | ITR (%) | Threshold (%) | Beta-5 (%) |
|---------------|-----------|---------|---------------|-----------|
|               | Geosat    | ERS-1   | Geosat        | ERS-1     | Geosat    | ERS-1     | Geosat    | ERS-1     |
| 0-50          | 207948    | 366807  | 99.97         | 99.31     | 99.94     | 99.29     | 93.84     | 74.52     |
| 50-100        | 208083    | 309363  | 99.96         | 99.92     | 99.93     | 99.92     | 96.35     | 82.17     |
| 100-150       | 100108    | 147015  | 99.99         | 99.98     | 100.00    | 99.98     | 97.41     | 84.75     |
| 150-200       | 25614     | 39966   | 100.00        | 99.94     | 100.00    | 99.94     | 96.96     | 84.75     |
| >200          | 342079    | 487281  | 99.99         | 99.95     | 99.98     | 99.95     | 98.45     | 86.82     |

The other is standard deviation of the differences between retracted SSHs and modeled geoidal heights. Table 2 compares the standard deviations of differences between non-retracted, retracted SSHs and geoidal heights. The standard deviation of each case is calculated only by using the points which can be
successfully retracked by all the three retrackers. For Geosat, retracking improves the accuracy of SSHs where water depth is shallower than 50 m, and ITR outperforms the other two retrackers. However, the non-retracked SSHs are better than retracked SSHs where water is deeper than 50 m. For ERS-1, all the three retrackers can improve the quality of SSH both over the shallow waters and over the deep open oceans, and ITR also performs the best.

Therefore, ITR is selected as the optimal retracker for the subsequent gravity derivation based on both the success rate and the standard deviation. All ERS-1 SSHs are corrected by retracking. For Geosat SSHs, only those over the waters shallower than 50 m are corrected, and non-retracked SSHs are used elsewhere.

| Water depth(m) | Non-retracted(m) NAO99b | CSR4.0 | ITR(m) NAO99b | CSR4.0 | Threshold(m) NAO99b | CSR4.0 | Beta-5(m) NAO99b | CSR4.0 |
|---------------|-------------------------|--------|---------------|--------|---------------------|--------|-----------------|--------|
| Geosat: 0-50 | 0.469                  | 0.563  | 0.458         | 0.557  | 0.465               | 0.560  | 0.464           | 0.559  |
| 50-100        | 0.340                  | 0.363  | 0.353         | 0.373  | 0.347               | 0.368  | 0.346           | 0.367  |
| 100-150       | 0.326                  | 0.335  | 0.343         | 0.353  | 0.340               | 0.349  | 0.339           | 0.347  |
| 150-200       | 0.439                  | 0.452  | 0.455         | 0.468  | 0.449               | 0.463  | 0.441           | 0.454  |
| >200          | 0.458                  | 0.459  | 0.463         | 0.464  | 0.460               | 0.462  | 0.462           | 0.463  |
| ERS-1: 0-50  | 2.101                  | 2.136  | 2.006         | 2.045  | 2.014               | 2.053  | 2.017           | 2.056  |
| 50-100        | 1.262                  | 1.277  | 1.233         | 1.250  | 1.235               | 1.251  | 1.232           | 1.248  |
| 100-150       | 0.774                  | 0.790  | 0.746         | 0.763  | 0.750               | 0.767  | 0.748           | 0.764  |
| 150-200       | 0.808                  | 0.823  | 0.770         | 0.785  | 0.773               | 0.787  | 0.770           | 0.784  |
| >200          | 0.805                  | 0.811  | 0.780         | 0.786  | 0.790               | 0.796  | 0.786           | 0.793  |

2 Effect of tide model error on altimetry gravity

The most important correction to the along-track gradient is the ocean tide. One μrad of tidal slope error will map into about 1 mGal of gravity anomaly error. Tidal slope corrections are usually small over the deep ocean, but can be up to 6 μrad over some continental margins\(^1\). Ocean tides over the China marginal sea are complex with high-frequency spatial variations in tidal amplitude and phase. The monsoon winds in winter and summer induce large waves over the East Sea and Taiwan Strait, resulting in a large sea surface variability. Therefore, the noise level of altimeter measurements in these areas is higher than that over a calm sea.

Fig.1 shows the difference of tidal gradients at a selected epoch between the NAO99b tide model\(^{10}\) and the CSR4.0 tide model\(^{11}\). The NAO99b and CSR4.0 tide models are derived from the TOPEX/
Poseidon (T/P) altimeter data. To some extent, the differences from the two models can be considered as a reference of the tide model error. Fig.1 indicates that the differences over the deep ocean are close to zero. However, the differences near the coasts are very large, with the magnitude larger than 10 μrad. Those areas with large differences in Fig.1 are just where NAO99b and CSR4.0 produce inaccurate tidal heights. Use of these inaccurate tidal heights to correct for the tidal effects in altimeter data will inevitably lead to degraded SSHs, and creates large standard deviations. Table 2 lists the standard deviations of SSHs corrected by the two models. It shows that SSHs corrected by NAO99b have a smaller standard deviation than those corrected by CSR4.0. That is, the NAO99b tide model outperforms the CSR4.0 tide model in the study area. The reason is that NAO99b is a local model that contains local tide gauge data.

3 Improved altimetry gravity in China Seas

3.1 Data processing and methods

To recover gravity anomalies, all Geosat/GM and ERS-1/GM GDR data are used. Waveforms of these data are retracted by using the retracking scheme proposed in section 2. Applying the retracted range correction and all environmental corrections to GDRs, the retracted SSH can be obtained. All the environmental corrections except ocean tide correction are the default value in GDR data. The value from the NAO99b tide model is substituted for the default ocean tide correction. Although many corrections have been applied to the observed SSHs, there are still many outliers in the corrected SSHs. Several procedures are performed in order to remove the outliers. First, if the difference between SSH and geoidal height is greater than 3 m, this point is rejected. Then a Gauss filter is used to interpolate an SSH each 4 km along-track from 10 Hz (Geosat) and 20 Hz (ERS-1) data. The point whose deviation is more than 3 times the rms will be removed in the interpolation procedure.

Gravity anomalies can be computed by least-squares collocation (LSC) or the Inverse Vening Meinesz (IVM) formula from the altimeter data. Hwang et al. concluded that the LSC always outperforms the IVM by a few mGal in the accuracy of computed gravity anomaly [9]. So the LSC is employed to derive the gravity anomalies, and the remove-restore procedure is used in the LSC derivation of gravity anomalies. The reference gravity model is EIGEN-GL04c[12].

The model is a combination GRACE and LAGEOS mission plus 0.5×0.5 degrees gravimetry and altimetry surface data. The input data type of the LSC is the along-track residual geoid gradient, which is computed by

\[ e_{\text{res}} = e_{\text{obs}} - e_{\text{model}} \]  

where \( e_{\text{obs}} \), \( e_{\text{model}} \) and \( e_{\text{res}} \) are observed, long-wavelength from the reference model and residual gradients, respectively. The observed geoid gradients are calculated from the corrected SSHs with the assumption that the sea surface topography is equal to zero. To make the gradient data clear, a similar action as the process of SSH was performed to remove outliers in the residual along-track gradients. Any residual gradients greater than 50 μrad are rejected in the study areas. Specially, a larger threshold value (100 μrad) is adopted for the eastern sea of Taiwan because the strong Kuroshio Current will cause large gradients in this area. Subsequently, a median filter with a 20 km window is used to remove gradients greater than 3 times RMS.

The residual gravity anomaly is computed by the LSC formula [9] :

\[ \Delta g_{\text{res}} = C_{\Delta g} (C_{\Delta g} + C_n)^{-1} e_{\text{res}} \]  

where \( \Delta g_{\text{res}} \) is the residual gravity anomaly; \( e_{\text{res}} \) is a vector of residual geoid gradients; \( C_{\Delta g} \), \( C_{\Delta g} \) and \( C_n \) are covariance matrices for gravity anomaly-gradient, gradient-gradient and noise of gradient, respectively. The \( C_n \) is a diagonal matrix holding the noise variances of geoid gradients, which can be estimated from the error of SSH. Empirical standard deviation errors for Geosat and ERS-1 SSH are set to 5 and 6 cm, respectively. At the final stage, the residual gravity anomalies are filtered by using Gauss filter with 16 km filter-width to remove short wavelength noise. Also, the long-wavelength gravity anomaly is restored to acquire the results.
3.2 Results

Following the procedure described in the previous section, we computed the gravity anomalies over the China marginal sea. To assess the ability of retracking to improve the accuracy of altimeter-derived gravity anomaly, two sets of gravity anomalies were computed. One is from non-retracked data. The other is from retracked data. The two sets of gravity anomalies were then compared with shipborne gravity anomalies around Taiwan and over the East Sea. Totally, 4048 shipborne gravity points around Taiwan and 4939 points over the East Sea were used in the comparison. Also, other two altimeter-derived gravity anomaly models, DNSC08\textsuperscript{[13]} and Sandwell&Smith (V16)\textsuperscript{[14]} were compared.

Table 3 shows the statistics of the differences between the altimeter-derived gravity anomalies and the shipborne gravity anomalies. From Table 3, we can see that the accuracy of gravity anomalies derived from the retracked SSHs is improved by 2.1 mGal around Taiwan, and by about 0.1 mGal over the East Sea. Because the shipborne gravity data over the East Sea are distant from the coasts and there is no landmass to affect the waveforms, it is difficult to reflect the effectiveness retracking. However, a considerable amount of data is near the coasts around Taiwan. Retracking has been shown to improve the accuracy of altimeter-derived gravity anomalies in this area. Compared with the shipborne gravity anomalies, the DNSC08 model has the highest accuracy. The accuracy of our results is slightly better than that of Sandwell&Smith(V16). Fig.2 shows gravity anomalies derived from the retracked SSHs over the Taiwan Strait and the East Sea. It can be seen that there are still some spurious features or artifacts in the immediate vicinity of the coast where the tide error is very large.

| Gravity anomalies | Max  | Min  | Mean | RMS  |
|-------------------|------|------|------|------|
| Non-retracted     | 110.890 | -93.660 | -1.000 | 10.810 |
| Retracked         | 108.20 | -94.41 | 0.110 | 8.720 |
| DNSC08            | 103.49 | -90.29 | -0.590 | 7.060 |
| Sandwell&Smith    | 119.920 | -94.240 | -0.330 | 8.750 |

| Gravity anomalies | Max  | Min  | Mean | RMS  |
|-------------------|------|------|------|------|
| Non-retracted     | 21.35 | -17.92 | -1.600 | 3.490 |
| Retracked         | 20.67 | -18.81 | -1.370 | 3.410 |
| DNSC08            | 21.88 | -17.42 | -1.460 | 3.180 |
| Sandwell&Smith    | 21.51 | -19.20 | -1.400 | 3.830 |

Fig.2 Contours of gravity anomalies derived from retracked SSH
4 Conclusion

For the recovery of shallow-water gravity anomalies from altimeter data, waveform retracking is an important technique. Different retracking methods have different performance. Three waveform retrackers are tested in this paper. It is verified that the improved threshold retracker is the optimal one for the coastal zone of the China Sea. The accuracy of altimetry gravity can be improved by ~2 mGal around Taiwan using the retracked data.

The NAO99b and CSR4.0 tide models are experimented to access the effect of tide model error. We conclude that tide model error is the biggest contributor to error in altimeter-derived gravity anomaly over coastal zones. It is shown that the error of altimeter-derived gravity anomaly due to the tide model may be larger than 10 mGal in the coastal zone of the China Sea. Also, the NAO99b tide model outperforms the CSR4.0 tide model over the China marginal sea.

For future work, we recommend a procedure to improve the accuracy of altimeter-derived gravity anomalies: (1) retrack near-shore waveforms of altimeter to produce waveform-corrected SSHs, (2) use the corrected SSHs to improve tide model, (3) use improved tide model to correct for the ocean tide effect in SSH. Finally, the improved tide-corrected and waveform-corrected altimeter data will lead to an improved gravity field over shallow waters. Furthermore, including land gravity data in the vicinity of coasts might be a way to enhance the accuracy of altimeter-derived gravity anomalies.

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