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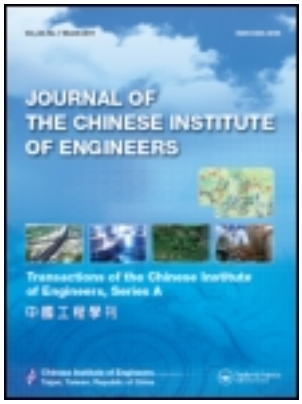


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# Shallow-water gravity anomalies from satellite altimetry: Case studies in the east china sea and Taiwan strait

Cheinway Hwang [a] & Hsin-Ying Hsu [b]

[a] Department of Civil Engineering , National Chiao Tung University , 1001 Ta Hsueh Road, Hsinchu 300, Taiwan, R.O.C. Phone: 886-3-5724739, 0953092239 Fax: 886-3-5724739, 0953092239 E-mail:

[b] Department of Civil Engineering , National Chiao Tung University , 1001 Ta Hsueh Road, Hsinchu 300, Taiwan, R.O.C.

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# SHALLOW-WATER GRAVITY ANOMALIES FROM SATELLITE ALTIMETRY: CASE STUDIES IN THE EAST CHINA SEA AND TAIWAN STRAIT

Cheinway Hwang* and Hsin-Ying Hsu

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## ABSTRACT

The differences between two global satellite altimeter-derived gravity anomaly grids over the East China Sea and the Taiwan Strait are investigated and the causes of the differences are discussed. Difference of gravity anomaly is correlated with tide model error, standard deviation of sea surface heights (SSHs) and ocean depth. We present two new SSH-derived observations of altimetry (differenced height and height slope) for gravity derivation. An iterative method for removing altimeter data outliers is used, and differenced height is found to be most sensitive to this method. For altimeter-gravity conversion, we used three altimeter-derived observations, i.e., deflection of the vertical, differenced height and height slope, in two conversion methods, i.e., the least-squares collocation (LSC) and the inverse Vening Meinesz method. Use of differenced heights in LSC produces the best result when comparing altimeter-derived and shipborne gravity anomalies. Use of land gravity data in the vicinity of coasts enhances the accuracy of altimeter-derived gravity anomalies.


***Key Words:*** satellite altimetry, gravity anomaly, East China Sea, Taiwan Strait.

## I. INTRODUCTION

Satellite altimetry over shallow waters has been very useful in geodetic, geophysical and oceanographic applications. Recent compilations of such altimetric applications are, among others, Fu and Cazenave (2001) and Hwang *et al*. (2004). One example of geodetic application is coastal gravity field modeling: use of combined coastal altimetry data with terrestrial gravity anomalies has resulted in gravity field models that outperform models using only terrestrial gravity data (Li and Sideris, 1997; Andersen and Knudsen, 2000). Furthermore, the potential of satellite altimetry in determining coastal sea surface topography has also been exploited in Hipkin (2000). Sea surface topography is the essential parameter for a world vertical datum (Rapp and Balasubramania, 1992). For oceanographic applications, shallow-water altimetry has been used to derive M-2 internal tides (Niwa and Hibiya, 2004) and variations of surface ocean circulations (Yanagi *et al*., 1997). Examples of geophysical applications of altimetry are abundant in the literature; we refer interested readers to Cazenave and Royer (2001) for a comprehensive review.

Altimeter-gravity conversion is one of the most important aspects in the geodetic and geophysical applications of satellite altimetry. Currently, the achieved accuracies of altimeter-derived gravity anomalies vary from one oceanic region to another, depending on gravity roughness, altimeter data quality and density (Sandwell and Smith, 1997; Hwang *et al*., 2002; and Andersen *et al*., 2005). Accuracy analyses associated with global gravity anomaly grids have been mostly made over the open oceans. However, altimeter data quality over shallow waters can be seriously degraded due to (1) bad tidal correction, (2) bad wet tropospheric correction because of corruption in radiometer measurements (for altimeter mission with a radiometer; Geosat does not carry a radiometer so radiometer errors are not a significant error source), (3) large sea surface variability, and (4) contaminated altimeter waveforms (Hwang

*Corresponding author. (Tel: 886-3-5724739, 0953092239; Fax: 886-3-5716257; Email: cheinway@mail.nctu.edu.tw)

C. W. Hwang and H. Y. Hsu are with the Department of Civil Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan, R.O.C.

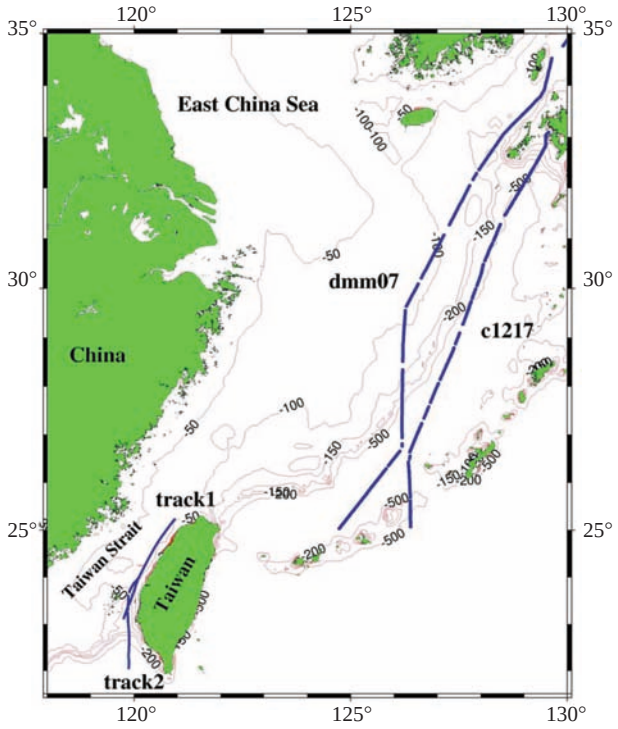


Fig. 1 Bathymetry (dashed lines) in the East China Sea and Taiwan Strait. Lines represent shipborne gravity data for comparison with altimeter-derived gravity anomalies

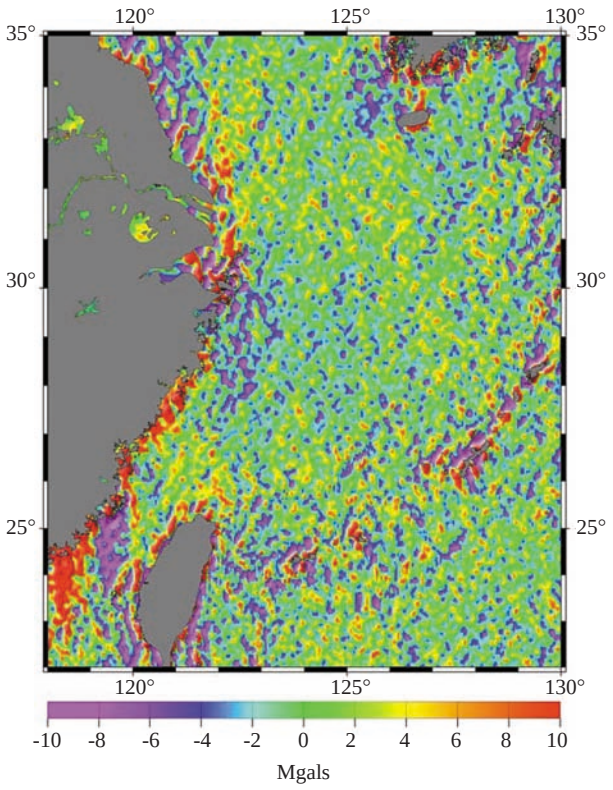


Fig. 2 Differences between the SS02 and KMS02 global gravity anomaly grids

and Hsu, 2004; Deng, 2003). Inferior or erroneous altimeter data will lead to gravity anomalies containing artifacts and in turn false interpretations of the underlying geophysical phenomena.

The East China Sea and the Taiwan Strait are two typical shallow-water areas, defined as waters with a depth < 500 m in this paper. Here the gravity fields are relatively smooth, but large gravity variations occur over regions with thick sediments, structural highs and at the margin of the continental shelf. Fig. 1 shows the bathymetry in the East China Sea and the Taiwan Strait. Over the East China Sea, publicly accessible databases of shipborne gravity data can be found at, e.g., the National Geophysical Data Center (NGDC) (http://www.ngdc.noaa.gov) and International Gravimetric Bureau (http://bgi.cnes.fr:8110/). In most areas of the ocean, shipborne gravity data are sparsely distributed. In the Taiwan Strait, the shipborne gravity data were mostly collected by research vessels studying marine geophysics around Taiwan. Global altimeter-derived gravity anomaly grids have been important sources of gravity anomalies in these areas. Due to the shallow-water nature of these areas, the procedures used in the derivations of global grids may not be optimal. Therefore, it is expected the accuracy of altimeter-derived gravity anomalies can be improved. Also, it is possible to further improve the gravity accuracy by using a different altimeter data type than commonly used ones such as sea surface height (SSH) and deflection of the vertical (DOV). With these problems as the background, the objective of this paper is to (1) investigate selected sources of error in altimeter-derived gravity anomaly and data processing issues in altimetry, and (2) experiment with different altimeter-derived observations in gravity computation to see how the results are compared with shipborne gravity anomalies. Case studies, using data from over the East China Sea and the Taiwan Strait, were also examined.

## II. DIFFERENCE OF TWO GLOBAL GRAVITY ANOMALY GRIDS OVER SHALLOW WATERS

The motivation of this paper is the large differences over shallow waters between two commonly used global gravity anomaly grids given below. One grid is the 2002 version of the global gravity anomaly grid of Sandwell and Smith available at http://topex.ucsd.edu. The method to compute this grid is described in Sandwell and Smith (1997). Another grid is from Andersen *et al.* (2005). The two grids are derived mainly from Geosat/GM and ERS-1/GM altimeter data using different methods, and are hereafter designated as SS02 and KMS02. Fig. 2 shows the differences

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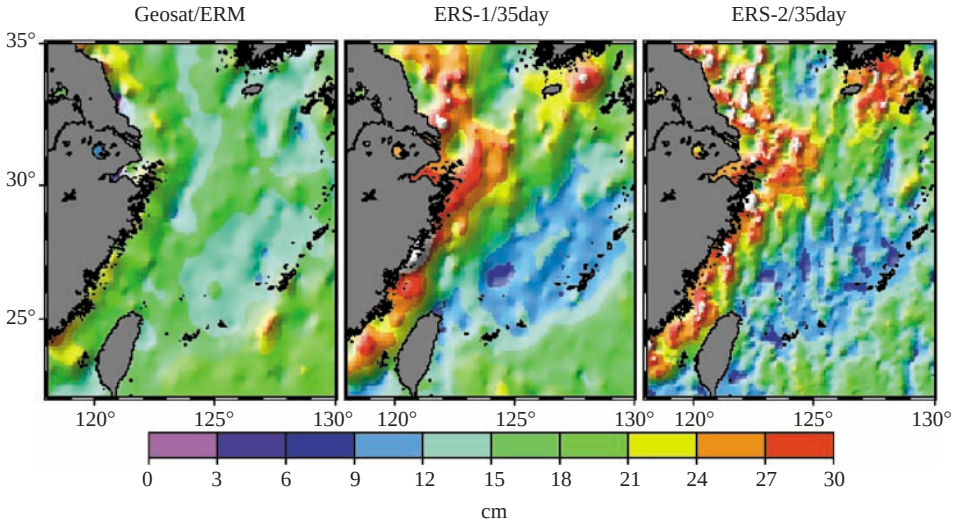


Fig. 3 Standard deviations of sea surface heights from the Geosat/ERM, ERS-1/35 day and ERS-2/35 day repeat missions

between SS02 and KMS02 gravity anomalies. There are large differences near coastlines, but smaller differences throughout the study area. The differences exhibit a bumpy texture with a diamond shaped fabric, most likely due to altimeter track lines. It appears the two grids have different spectral contents at short wavelengths. In particular, large differences occur over almost the entire Taiwan Strait, and some areas distant from the coasts also contain large differences, e.g., a spot off the east coast of China centering at about latitude = 28°N and longitude = 122°E.

In order to see the possible causes of the differences, we investigate the qualities of SSHs and two selected tide models here. An SSH, in this paper, is defined as the vertical distance of the sea surface from a reference ellipsoid. Fig. 3 shows the standard deviations of SSH. from the Geosat/ERM, ERS-1/ 35 day and ERS-2/35 day repeat missions. The SSHs have been corrected for standard geophysical corrections such as ocean tide, solid earth tide, sea state bias, ionospheric and tropospheric effects and inverse barometer effect (the same effects as those given in Hwang *et al.*, 2002). Here a standard deviation of SSH is the result of SSH measurement error and SSH variability. The standard deviations of Geosat/ERM SSHs are relatively small because a large number of repeat cycles (68 cycles) were used, compared to only 26 cycles used in averaging ERS-1 and ERS-2 repeat SSHs. The pattern of ERS-1 standard deviations resembles that of ERS-2 standard deviations. In general, standard deviation of SSH increases with decreasing depth. As seen in Figs. 2 and 3, gravity anomaly difference is highly correlated with standard deviation of SSH. In general, gravity anomaly difference (absolute value) increases with standard deviation of SSH.

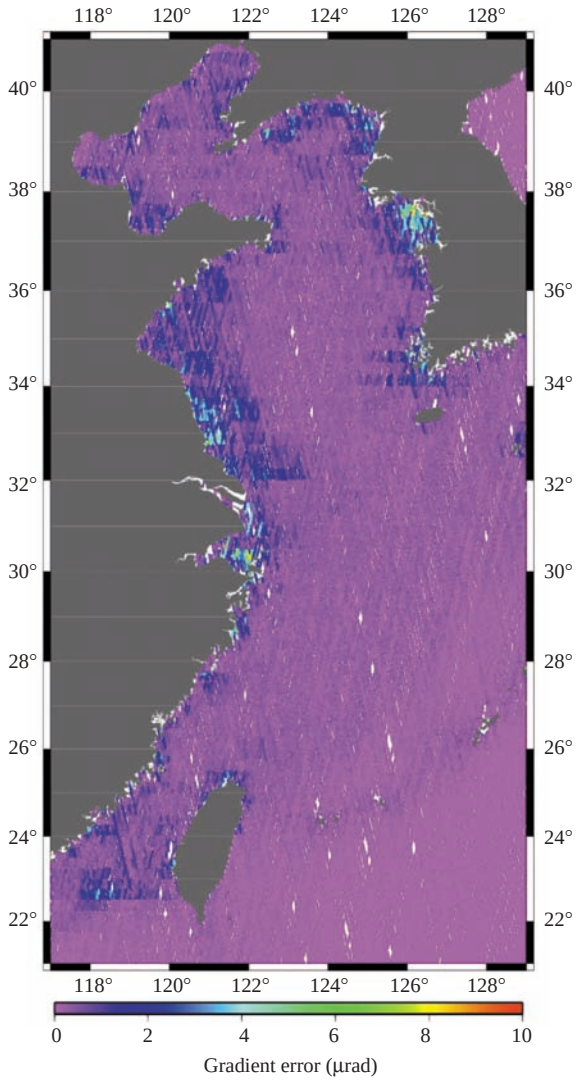


Fig. 4 Geoid gradient errors along ERS-1 tracks, based on the differences between NAO99b and CSR4.0 tide models

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Figure 4 shows geoid gradient errors along ERS-1/GM tracks based on the differences between the NAO tide model (Matsumoto *et al.*, 2000) and the CSR4.0 tide model (Eanes, 1999). A geoid gradient error between consecutive along-track points is computed as $|\Delta h_2 - \Delta h_1|/s$, where $\Delta h_2$ and $\Delta h_1$ are the differences between NAO and CSR4.0 tidal heights at the two points, and $s$ is the distance (see also the height slope in Section III.1). Here we assume that the tide model error in the East China Sea and the Taiwan Strait is about the same magnitude as the difference between NAO and CSR4.0. According to Hwang *et al.* (2002), the NAO tide model outperforms CSR4.0 in the East China Sea and the Taiwan Strait. A one μrad gradient error will translate into a one-mgal error in altimeter-derived gravity. Again, large gradient errors occur in the same places where large standard deviations of SSHs (Fig. 3) and large gravity anomaly differences (Fig. 2) occur, showing these three quantities are geographically correlated. The NAO and CSR4.0 tide models are derived from the TOPEX/Poseidon (T/P) altimeter data. Over areas with bad T/P SSHs, which are largely caused by bad range measurements and bad geophysical corrections, these two tide models will produce inaccurate tidal heights. Also, neglecting shallow-water tidal constituencies in the tide models introduces additional errors. Those areas with large differences in Fig. 4 are just where NAO 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 seen in Fig. 3.

According to Jan *et al.* (2004) and Lefevre *et al.* (2000), ocean tides in the East China Sea and the Taiwan Strait are complex with high-frequency spatial variations in tidal amplitude and phase. The strong, fast-changing tidal currents over the Taiwan Strait also increase the roughness of the sea surface and in turn increase the noise level of altimeter ranging (Sandwell and Smith, 2001, pp. 444). This explains why the tide model error over the Taiwan Strait is large throughout almost the entire area (Fig. 4). In addition, the monsoonal winds in winter and summer induce large waves over the East China Sea and the Taiwan Strait (Jacobs *et al.*, 2000; Wang, 2004), resulting in a large sea surface variability lasting more than half of a year. Therefore, one would expect that the noise level of altimeter measurements in these two areas is higher than that over a calm sea. In conclusion, inferior altimeter range measurements and inferior geophysical corrections combine to produce inferior SSHs, which in turn result in degraded gravity anomalies. More discussions on the limitations of gravity recovery from altimetry can be found in Sandwell and Smith (2001).

## III. METHOD AND DATA FOR GRAVITY DERIVATION OVER SHALLOW WATERS

### 1. Deflection of the Vertical, Differenced Height and Height Slope

The basic observation of satellite altimetry for gravity derivation is SSH. SSH-derived observations can also be used for this purpose. For example, DOV has been used by Sandwell and Smith (1997) and Hwang *et al.* (2002), with the advantage of reduction of long wavelength errors in altimeter data without crossover adjustment of SSHs (Sandwell and Smith, 1997; Hwang, 1997). Typical long wavelength errors are orbit error and ocean tide model error. Along-track DOV is defined as

$$\varepsilon = -\frac{\partial h}{\partial s}, \tag{1}$$

where $h$ is geoidal height obtained by subtracting the sea surface topography (SST, defined as the vertical distance of the sea surface from the geoid) from SSH, and $s$ is the along-track distance. Since $h$ is discretely sampled, DOV in Eq. (1) can only be approximately computed. On the other hand, differenced height is free from approximation. A differenced height is defined as

$$d_i = h_{i+1} - h_i, \tag{2}$$

where $i$ is index of an SSH observable. Using differenced height has the same advantage as using DOV in terms of mitigating long wavelength errors. Another SSH-derived observation is height slope, defined as

$$\chi_i = \frac{h_{i+1} - h_i}{s_i}, \tag{3}$$

where $s_i$ is the distance between the points associated with $h_i$ and $h_{i+1}$. The spectral characteristics of height slope are the same as those of DOV and gravity anomaly, because they are all first spatial derivatives of the Earth's disturbing potential. Again, the advantage of using height slope is similar to that of using differenced height in mitigating altimeter data errors.

To derive gravity anomaly from DOV, differenced height or height slope, one can use least-squares collocation (LSC) (Moritz, 1980), which requires modeling of the needed covariance functions. Modeling of covariance functions for the DOV-gravity conversion has been carried out by Hwang and Parsons (1995). Here we shall model the covariance functions for height difference-gravity and height slope-gravity conversions. The covariance function between two differenced heights is

$$\begin{aligned}\mathrm{cov}(d_i, d_j) &= \mathrm{cov}(h_{i+1} - h_i, h_{j+1} - h_j) \\ &= \mathrm{cov}(h_{i+1}, h_{j+1}) - \mathrm{cov}(h_{i+1}, h_j) \\ &\quad - \mathrm{cov}(h_i, h_{j+1}) + \mathrm{cov}(h_i, h_j). \end{aligned} \quad (4)$$

The covariance function between two height slopes is

$$\mathrm{cov}(\chi_i, \chi_j) = \frac{1}{s_i s_j}\mathrm{cov}(d_i, d_j)\,. \quad (5)$$

The covariance function between gravity anomaly and differenced height is

$$\begin{aligned}\mathrm{cov}(\Delta g, d_i) &= \mathrm{cov}(\Delta g, h_{i+1} - h_i) \\ &= \mathrm{cov}(\Delta g, h_{i+1}) - \mathrm{cov}(\Delta g, h_i). \end{aligned} \quad (6)$$

Finally, the covariance function between gravity anomaly and height slope is

$$\mathrm{cov}(\Delta g, \chi_i) = \frac{1}{s_i}\mathrm{cov}(\Delta g, d_i)\,. \quad (7)$$

It is clear that in Eqs. (4) to (7), two basic covariance functions are needed: the covariance function between two heights and the covariance function between gravity anomaly and height. Methods to model these two covariance functions can be found in Tscherning and Rapp (1974) and Moritz (1980). In this paper, we use the Model 4 gravity anomaly variance of Tscherning and Rapp (1974) to compute the needed covariance functions, see also Hwang and Parsons (1995). Furthermore, we used the remove-restore procedure with the EGM96 model (Lemoine *et al*., 1998) as the reference gravity field.

The general expression of LSC for altimeter-gravity conversion is

$$\Delta \boldsymbol{g} = \boldsymbol{C}_{sl}(\boldsymbol{C}_t + \boldsymbol{C}_n)^{-1}\boldsymbol{l}, \quad (8)$$

where vector $\boldsymbol{l}$ contains any data related to the Earth's disturbing potential, $\boldsymbol{C}_t$ and $\boldsymbol{C}_n$ are the signal and noise parts of the covariance matrices of $\boldsymbol{l}$, and $\boldsymbol{C}_{sl}$ is the covariance matrix of gravity anomaly and the signal of $\boldsymbol{l}$. Altimeter data can also be used to compute geoidal undulation: one simply replaces $\boldsymbol{C}_{sl}$ with the covariance matrix of geoid- signal of $\boldsymbol{l}$ in Eq. (8). Assuming that the errors in the undifferenced height data are uncorrelated, the correlation between two successive DOVs, differenced heights or height slopes along the same satellite pass is -0.5, which must be included in $\boldsymbol{C}_n$. The FFT-based method of gravity derivation using DOV can be found in, e.g., Sandwell and Smith (1997), and Haxby *et al*. (1983).

### 2. Coastal Land and Sea Data for Accuracy Enhancement

Altimeter-gravity conversion at the land-sea boundary is an extrapolation process since land altimeter data cannot be used for gravity derivation. In the immediate waters off the coast, there can be no reliable altimeter data due to waveform contamination (Deng *et al*., 2003). Also, because of depth limitation a large research ship cannot closely approach the coasts, so there are always void zones of shipborne gravity. This deficiency can be reduced by using data near the coasts, including gravity anomalies from relative and airborne gravity surveys (Torge, 1989), DOVs from astro-geodetic surveys and geoidal heights from Global Positioning System (GPS) and leveling surveys (Wolf and Ghilani, 2002). A GPS-leveling-derived geoidal height, $N$, is defined as

$$N = h - H, \quad (9)$$

where $h$ and $H$ are ellipsoidal height and orthometric height, respectively. Due to the need for these figures in engineering and mapping applications, geoidal heights from GPS and leveling in coastal areas may be abundant. In the case of combining altimeter readings and other data for gravity derivation, it would be difficult to use an FFT-based method even if it is possible (e.g., the input-output system method (Li and Sideris, 1997)). The LSC method outlined in Section III.1 is an efficient method for data combination, only requiring related models of covariance functions. To merge altimeter data and land/sea data for gravity anomaly determination, one needs to include such data in the $\boldsymbol{l}$ vector in Eq. (8), and the needed covariance matrices are constructed using the rule of LSC (Moritz, 1980). A good weighting scheme for different types of data is essential for obtaining a good result. The usefulness of land gravity data in enhancing the accuracy of altimeter-derived gravity anomaly will be demonstrated in Section V.2.

## IV. OUTLIER DETECTION

Outliers in altimeter data will create a damaging effect on the resulting gravity fields and must be removed before filtering. Methods for removing outliers in one-dimensional time series are abundant in the literature, e.g., Koch (1987) and Pearson (2002). In this paper, we will use an iterative method to detect outliers in along-track altimeter data. This method follows closely the principle of normal point reduction for satellite laser ranging (Seeber, 2003). Consider a time series of along-track altimeter readings observable with the along-track distance as the independent variable. First, a filtered time series is obtained by convolving the original time series with the Gaussian function

$$f(x) = e^{-\frac{x^2}{2\sigma^2}}, \quad (10)$$

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where $x$ is the distance between two data points and $\sigma$ is 1/6 of the given filter width of convolution. A filter width is the size of a window within which all data points are convolved with the Gaussian function. The definition of the Gaussian function in Eq. (10) is the same as that defined in module "filter1d" of GMT (Wessel and Smith, 1995). For all data points the differences between the original and the filtered values are computed, and the standard deviation of such differences is determined. The largest difference that also exceeds three times the standard deviation is considered an outlier and the corresponding data value is removed from the time series. The initially cleaned time series is filtered again and the new differences are examined against the new standard deviation to remove remaining outliers. This process is repeated and terminated when no outlier is found. It turns out differenced height is more sensitive to outliers than SSH, especially when along-track SSHs experience an abrupt change. A spike of SSH will create two distinct height differences. We experimented with several filter widths. It was concluded that different filter widths should be used for different sets of altimeter data for best results. Based on testing results, we adopt 28 km and 18 km as the optimal filter widths for the repeat and non-repeat missions, respectively.

Figure 5 shows the result of outlier detection along Tracks d019 and a034 of Geosat/ERM. Track d019 passes through the East China Sea and is far away from the coasts. In this case, outliers occur only at the two ends of this arc, near South Korea and Taiwan. As expected, the differenced heights in the open sea are relatively smooth. Track a034 is a short arc passing through the Korean Strait between S. Korea and Kyushu of Japan. This track contains no outliers over the Korean Strait, but many along the coasts of Kyushu. Along Track a034, most of the differenced heights near the coasts are highly oscillatory, making it difficult to derive useful gravity anomalies from such values. Furthermore, Fig. 6 shows the result of outlier detection along Tracks d0222 and a3083 of Geosat/GM. Both tracks pass through Peng-Hu Island in the Taiwan Strait, where most of the outliers occur and the differenced heights contain large variation. These examples from the Geosat altimeter show that differenced height is very sensitive to sudden changes in height, and is particularly useful for outlier detection utilizing the above iterative method. Since Geosat does not carry a radiometer, the outliers in Figs. 5 and 6 are not due to land interference in the radiometer's footprint.

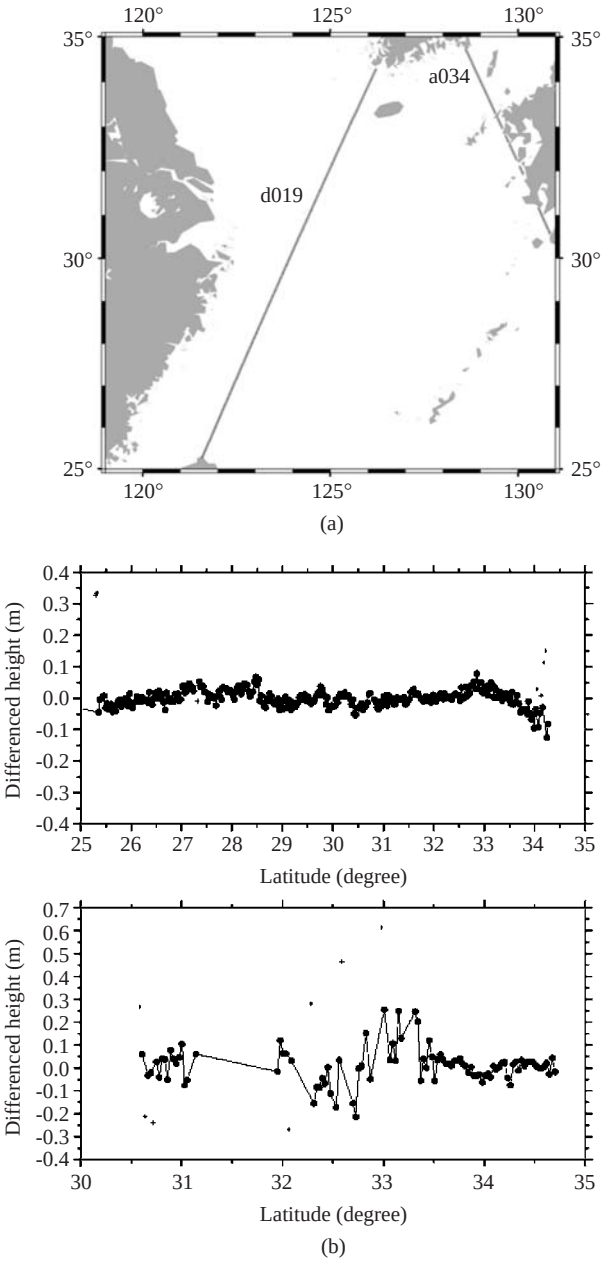


Fig. 5 (a) Ground tracks of Geosat/ERM d019 and a034, (b) differenced heights, crosses represent outliers

## V. CASE STUDIES

### 1. The East China Sea

The first case study to assess the accuracies of gravity anomaly from the three altimeter-derived observations was carried out in the East China Sea. The altimeter data we used are from the non-repeat missions ERS-1/GM and Geosat/GM (the sampling rate is 2 HZ), and the repeat missions Geosat/ERM, ERS-1/35-day, ERS-2/35-day and TOPEX/Poseidon 10-day repeats (the sampling rate is 1 HZ; see Section II for the numbers of repeat cycles). Since no reliable estimate of SST is available here, it was set to zero. Neglecting SST here will introduce error at the submgal level (Hwang, 1997). For LSC computations, standard errors of the altimeter data are needed. For

**Table 1 Statistics of differences (in mgals) between altimeter-derived and shipborne gravity anomalies in the East China Sea**

| Method and alt. data | Mean | RMS | Min | Max |
|---|---|---|---|---|
| LSC (differenced height) | -5.33 | 13.02 | -49.24 | 43.96 |
| LSC (height slope) | -5.45 | 13.19 | -50.77 | 44.38 |
| LSC ( DOV) | -4.61 | 16.99 | -85.59 | 74.65 |
| Inverse Vening Meinesz (DOV) | -4.11 | 15.53 | -52.23 | 80.53 |

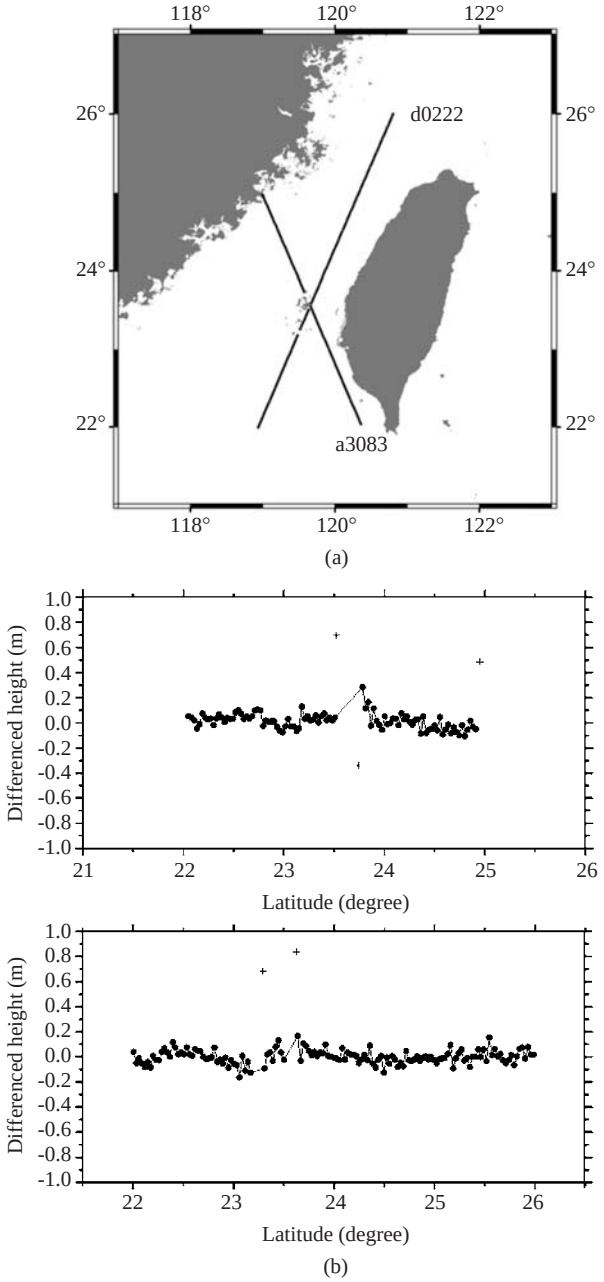


Fig. 6 (a) Ground tracks of Geosat/GM d0222 and a3083, (b) differenced heights, crosses represent outliers

repeat missions, the standard errors of the altimeter data are derived from repeat observations, while for non-repeat missions, the standard errors are based on empirical values (Hwang *et al*., 2002). All altimeter data were screened against outliers using differenced heights. Due to data editing in extracting SSHs from the geophysical data records (GDRs), most of the bad altimeter data in the immediate vicinity of coasts have already been removed before outlier detection. In general, there is a higher concentration of outliers near the coasts and islands than other areas. In particular, clusters of outliers were found at the southern Korean coast, the estuary of the Yangtze River and Peng-Hu Island in the Taiwan Strait.

We experimented with four cases of altimeter-gravity conversion. In these four cases, we used two methods of conversion: LSC and the inverse Vening Meinesz method (Hwang, 1998), and three altimeter-derived observations: DOV, differenced height and height slope. To identify the best case, we compared the altimeter-derived gravity anomalies with shipborne gravity anomalies. Fig. 1 shows the tracks of two selected ship cruises in the East China Sea (Tracks dmm07 and c1217) and two cruises in the Taiwan Strait (Tracks 1 and 2). The shipborne gravity data in the East China Sea are from the Lamont-Doherty Earth Observatory database and the accuracies of gravity anomalies on Tracks dmm07 and c1217 were discussed in Wessel and Watts (1988). Before comparison, for each track we removed a bias and a trend in the shipborne gravity relative to the altimeter-derived gravity anomalies (Hwang and Parsons, 1995; Wessel and Watts, 1988). Table 1 shows the statistics of the differences between the altimeter-derived and shipborne gravity anomalies. The best result is from the case of using LSC with differenced height, followed by the case of using LSC with height slope. The case of using LSC with DOV yields the least accurate gravity anomalies. Fig. 7 shows the shipborne and altimeter-derived gravity anomalies along c1217 and dmm07. In general, the altimeter-derived gravity anomalies are smoother than the shipborne gravity anomalies. This is due to the filtering of the altimeter observations before the gravity derivations. At large spatial scales, the shipborne and altimeter-derived gravity anomalies agree very well, but at small spatial scales the differences become random and are not correlated with the standard deviation of SSH, tidal model error or depth (see Figs. 1, 3 and 4).

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**Table 2 Statistics of differences (in mgals) between altimeter-derived and shipborne gravity anomalies in the Taiwan Strait**

| Method and alt. data | Mean | RMS | Minimum | Maximum |
|---|---|---|---|---|
| LSC (differenced height) | 7.09 | 9.06 | -8.92 | 23.56 |
| LSC (height slope) | 7.94 | 10.26 | -9.39 | 28.96 |
| LSC (DOV) | 7.70 | 10.44 | -10.97 | 29.38 |
| Inverse Vening Meinesz (DOV) | 7.59 | 10.73 | -14.88 | 29.37 |

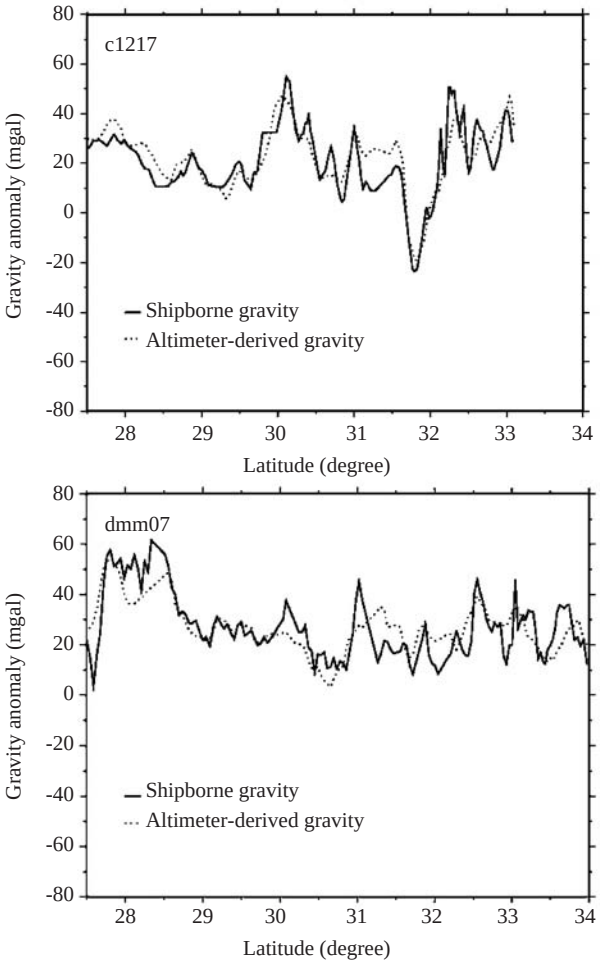


Fig. 7 Gravity anomalies along Cruises c1217 and dmm07 in the East China Sea

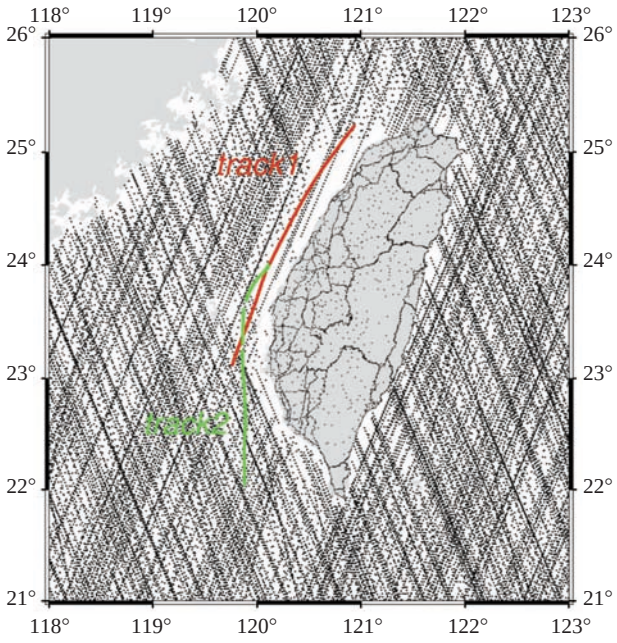


Fig. 8 Distribution of land gravity and Geosat data around Taiwan

## 2. The Taiwan Strait

Next we carried out experiments in the Taiwan Strait using the same four cases as in the East China Sea. We used shipborne gravity data along Tracks 1 and 2 (Fig. 1) to evaluate the altimeter-derived gravity anomalies. These shipborne gravity data were compiled by Hsu *et al*. (1998), who has crossover adjusted the shipborne gravity data and removed bad values. Table 2 shows the results of the comparisons between altimeter-derived and shipborne gravity anomalies in the four cases. The conclusion from Table 2 is similar to what has been drawn from Table 1 and the only difference is that the inverse Vening Meinesz method with DOV produces the worst result. Again, use of differenced heights produces the best results provided that the same altimeter-gravity conversion method is used.

Since land gravity data are available along the coast of the Taiwan Strait, we also assessed the impact of land gravity data on the accuracy of altimeter-derived gravity anomaly. Fig. 8 shows the distribution of land gravity and Geosat/GM altimeter data around Taiwan. (Around Tracks 1 and 2, other altimeter data are quite sparse and are not shown in Fig. 8). Note that there is no altimeter reading for the immediate coastal waters off the west coast of Taiwan. We experimented with the method of LSC using differenced heights, and with and without land gravity data (two cases). Table 3 shows the statistics of the differences between shipborne and altimeter-derived gravity anomalies. Fig. 9 shows the shipborne and altimeter-derived gravity anomalies along Tracks 1 and 2. The patterns of the difference along Tracks 1 and 2 are similar to those for Tracks c1217 and dmm07

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**Table 3 Statistics of difference (in mgals) between altimeter-derived (with and without land data) and shipborne gravity anomalies in the Taiwan Strait**

| Method and data for gravity derivation | Mean | RMS | Minimum | Maximum |
|---|---|---|---|---|
| LSC with differenced heights only | 8.01 | 9.96 | -12.21 | 24.84 |
| LSC with differenced heights and land gravity anomalies | 6.22 | 8.22 | -11.85 | 22.73 |

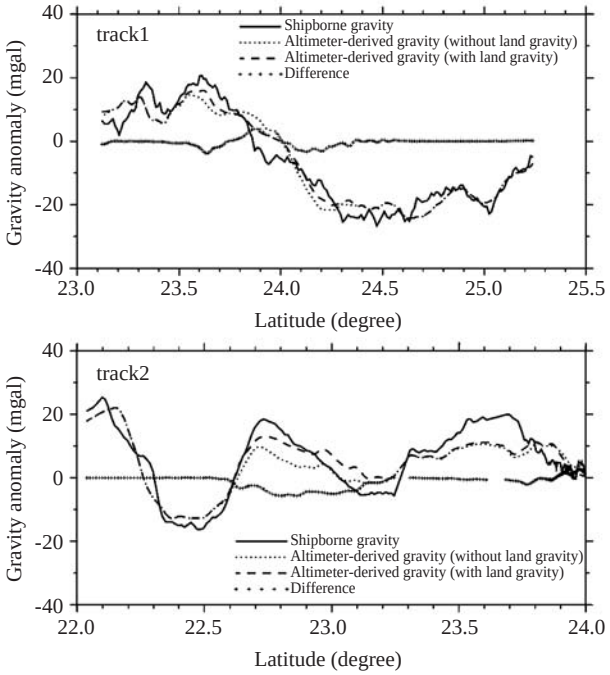


Fig. 9 Gravity anomalies along Tracks 1 and 2 in the Taiwan Strait

(Fig. 7). That is, the agreement between shipborne and altimeter-derived gravity anomalies at large spatial scales is better than that at small spatial scales. Furthermore, Tracks 1 and 2 are only tens of km off the west coast of Taiwan and the density of altimeter data is low along theses two tracks (Fig. 8). In general, difference of gravity anomaly increases with density of altimeter data. The density of land gravity data is relatively high over a zone from 22.5°N to 24.5°N, and here the agreement between altimeter-derived (with land gravity) and shipborne gravity anomalies is better than that in other parts of the ship tracks. In the areas south of 22.5° N and north of 24.5° N, only a few land gravity data are used, so there is virtually no difference between the altimeter-only gravity anomalies and the altimeter-land gravity anomalies.

As discussed in Section II, the major source of large standard derivation of SSH and large error of altimeter-derived gravity anomaly is tide model error. From the case study in the Taiwan Strait, it is clear that a low density of altimeter data also contributes to errors in altimeter-derived gravity anomalies. Such a low density of altimeter data arises mainly from data editing and is common in the vicinity of coasts. Even if the editing criteria near coasts are relaxed to retain more altimeter data, the surviving data may not be of good quality for gravity derivation. One way to improve altimeter data quality near coasts is to retrack waveforms of altimeter ranging. For example, Deng *et al.* (2003) have obtained improved T/P SSHs by waveform retracking over the Australian coasts. Currently, globally retracked ERS-1 and Geosat waveforms are available (Lillibridge *et al.*, 2004; Smith *et al.*, 2004), and have been shown to produce improved marine gravity fields.

## VI. CONCLUSIONS AND SUGGESTIONS

This paper studies the sources of the differences among two global gravity anomaly grids over the East China Sea and the Taiwan Strait. We conclude that tide model error is the biggest contributor to the differences. It is found that tide model error, standard deviation of SSH and ocean depth are highly correlated. Also, the complicated sea states over these two areas increase the roughness of the sea surface and hence the noise level of altimeter ranging. As case studies, we experimented with three SSH-derived observations: DOV, differenced height and height slope. The comparisons between altimeter-derived and shipborne gravity anomalies show that, with the same altimeter-gravity conversion method, differenced height delivers the best result. Also, including land gravity data in the vicinity of coasts enhances the accuracy of altimeter-derived gravity anomalies.

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 models, (3) use improved tide models to correct for the ocean tide effects in SSH. Finally, the improved tide-corrected and waveform-corrected altimeter data will lead to an improved gravity field over shallow waters.

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## NOMENCLATURE

| | |
|---|---|
| $\boldsymbol{C_t}$ | signal part of the covariance matrix of $\boldsymbol{l}$ |
| $\boldsymbol{C_n}$ | noise part of the covariance matrix of $\boldsymbol{l}$ |
| $\boldsymbol{C_{sl}}$ | covariance matrix of gravity anomaly and the signal of $\boldsymbol{l}$ |
| $d_i$ | differenced height (m) |
| $\varepsilon$ | along-track deflection of the vertical (arc-second) |
| $\Delta g$ | gravity anomaly (mgal) |
| $h_i$ | ellipsoidal height from altimetry (m) |
| $H$ | orthometric height (m) |
| $\boldsymbol{l}$ | vector containing data related to the Earth's disturbing potential |
| $s_i$ | distance between two satellite points (m) |
| $\sigma$ | 1/6 of the given filter width of convolution (m) |
| $x$ | the distance between two data points for the Gaussian filter (m) |
| $\chi_i$ | height slope (arc-second) |

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