Estimation of marine gravity anomaly model from satellite altimetry data (Case Study: Kalimantan and Sulawesi Waters-Indonesia)

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Abstract. Nowadays satellite altimetry has become an advanced instrument to observe many natural physical phenomena, such as sea-level rise, ocean circulation, water mass changes, and marine gravity anomaly. The use of satellite altimetry data to compute marine gravity anomaly provides good results and costs relatively low. Those advantages make geodesists utilize this method as an alternative in geoid determination, especially over the seas. Several sets of satellite altimetry data from Cryosat 2, Jason 1 phase C, Geosat and ERS1 were used to compute gravity anomaly over the surrounding waters of Kalimantan and Sulawesi Island in Indonesia. The study area spans between -7⁰-7⁰ N and 108°E-127°E with a spatial resolution of 1’x1’. In the pre-processing step, the altimetry data especially Geosat and ERS1, were retracked to reduce errors due to the land influence. The main computation step was done by using two different methods, least square collocation (LSC) and Inverse Vening-Meinesz (IVM). The computed gravity anomaly models then assessed with the in-situ marine gravity data from the National Geophysical Data Center (NGDC). The best model in term of RMS error is the 10 km Gaussian filtered LSC with an RMS error of 15.042 mgal. The least accurate model is the non-filtered IVM with an RMS of 16.704 mgal.

1. Introduction

The Kalimantan and Sulawesi are two main islands of Indonesian Archipelago. In order to determine the regional geoid, the government of Indonesia in collaboration with Technical University of Denmark (DTU) ran airborne gravity surveys over those two islands in 2008-2009 [1]. However, the surveys did not cover the waters surrounding those two islands [2]. In order to fill those gaps, some geodetic mission altimetry datasets were used to determine the gravity anomalies over an area between 7⁰S - 7⁰ N and 108°E - 127°E. The datasets consist of Sea Surface Height (SSH) measured by Cryosat-2, Jason-1 phase C, Geosat and ERS-1 satellite altimetry missions. By definition, SSH is the difference of altimeter range from the satellite altitude above the reference ellipsoid [3], or in another word SSH is the height of instantaneous sea surface above the reference ellipsoid.

To make the SSH data usable in gravity anomaly determination, some accuracy defects related to land occurrence should be reduced by performing waveform retracking. Waveform retracking was performed to fit a model or functional form to the measured waveforms, and retrieve geophysical...
parameters such as range, echo power, etc [4]. Four retracking methods are available to use; threshold [5], subwaveform threshold [6], improved threshold [7], and beta-5 parameter [8]. The past research by Hsiao et al., shows that the subwaveform retracker gave the best result for SSH and altimeter-derived gravity values [9]. The corrected altimetry range then used in SSH determination. Further explanation of the altimetry data handling will be discussed in Section 2 and 3.

Next, the obtained SSH of those altimetry missions are then combined together to be used as the main input in gravity anomaly determination. Moreover, supplementary data are required, those are tide, reference geoid and sea surface topography (SST) models. This research objective is to make the best altimetry-only gravity model with spatial resolution of 1’ x 1’.

2. Data
2.1. Satellite Altimetry Data
There were four satellite altimetry missions used as the main input for this research, Geosat/GM, ERS-1/GM, Jason-1/GM and Cryosat-2. The “GM” phrase defines that an altimetry mission is a geodetic mission or in other word a non-repeat mission. The Geosat/GM is a sun-synchronous mission which orbited earth in the period of March 31st 1985 to September 30th 1986, with the sampling frequency of 10 Hz. The ERS-1/GM was gathered from the European Space Agency (ESA), which consisted of two 168 days data cycles with a sampling frequency of 20 Hz. The Jason-1/GM data was downloaded from AVISO data center or Jet Propulsion Laboratory (JPL) alternatively. This mission is a drifted orbit of Jason-1 repeat mission, with a repeat period of 406 days and sub cycles of 3.9, 10.9, 47.5, and 179.5 days [10]. The Cryosat-2 data used are the level 1B data with a sampling frequency of 20Hz [11]. Because of the different sampling rates of each satellite mission, the SSH datasets should be resampled into 2Hz. Besides, the datasets also needed to be freed from outlier by applying a Gaussian filter with a 10 km window size.

2.2. NAO99 Ocean Tide Model
Before taken into further process, the altimetry SSH data had to be corrected from the tidal effect. This effect was removed by using a global ocean tide model. In this research we used the NAO99b ocean tide model. This model has a spatial resolution of 0.5° (global version) and 5’ (Japan regional version) and predicts the 16 major tide constituents [12].

2.3. RIO05 Mean Dynamic Topography Model
The RIO05 MDT model was generated from the combination of altimetry data (T/P and ERS1), in-situ measurements (buoys velocities, XBT, CTD) from 1993-2002, and refers to EIGEN-GRACE03S geoid model on a 30’ x 30’ regular grid [13]. The standard deviation of this model is 0.713 m according to Marchenko et. al [14].

3. Method
3.1. Waveform Retracking
After preparing all the data needed (see sub-section 2.1), some corrections would be performed. The altimetry range measurement had to be corrected from the coastal and shallow water effects or well known as the waveform retracking.

Waveform retracking is an improvement method of altimetry range measurement by determining the location of epoch on the leading edge. This epoch, commonly called as tracking gate, is a pre-defined value which computed by the satellite data provider. However, in some cases, especially in near coastal and shallow waters, the given value is not representing the actual state of water surface. Several retracking methods, either statistic or deterministic have been developed. In this research, the applied retracker is subwaveform threshold. This retracker first identifies the leading edge based on subwaveform correlation analysis, and then computes the retracking gate by using a threshold method [6]. All altimetry data but the Cryosat-2 had been retracked by those aforementioned retrackers. The
Cryosat-2 altimeter uses the latest technique of delay/Doppler [15] which improves the determination of altimeter range near coastal area [9].

3.2. Gravity Anomaly Determination

The remove-compute-restore (RCR) technique was applied to determine the gravity anomalies. This technique is based on the separation of gravity anomaly signal into three different spectral components, the long wavelength, the short wavelength and the residual part (see figure 1 and eq. 1). Figure 1 shows that the addition of three different undulation (N) wavelengths gives the most realistic geoid model. Each component of N is computed from corresponding gravity anomaly (Δg) by the Stokes integration formula [16]. The geoid determination by using gravity data is called the gravimetric geoid modelling.

The first step in RCR technique is computing the along-track gradient. The second is removing the reference gradient from the global gravity model and followed by removing outliers. The outlier removal was done by applying τ test as mentioned in the theory of Pope [17]. The next step is computing the residual gravity anomalies. There were two different methods in this computation step, Least-Square Collocation (LSC) and Inverse Vening-Meinesz (IVM). The last step is restoring gravity anomalies from the global gravity model. Eight different models were made and would be assessed with the in-situ data. Those models were 7 LSCs and an IVM. The LSC models were differed from each other by the type and size of the filter applied. Filters were applied to overcome the remains of high frequency noise. In addition, we also assessed Sandwell v23.1 altimeter-only global gravity model. This model has RMS error of 2.6 mgal when compared to National Geospatial Intelligence Agency (NGA) shipborne data [18]. The list of models are shown in table 1. Furthermore, the defined grid-size of the models is 1’ x 1’ due to the cross-track spacing of the altimetry missions are about 1-2 km.

![Figure 1. Illustration of geoid above the ellipsoid](image)

\[
\begin{align*}
N &= N_{\text{long}} + N_{\text{res}} + N_{\text{short}} \\
\Delta g &= \Delta g_{\text{long}} + \Delta g_{\text{res}} + \Delta g_{\text{short}}
\end{align*}
\]  

(1)

with:

- \(N\) = geoid undulation
- \(N_{\text{long}}\) = long wavelength component of N
- \(N_{\text{res}}\) = short component of N
- \(N_{\text{short}}\) = short wavelength component of N
- \(\Delta g\) = gravity anomaly
- \(\Delta g_{\text{long}}\) = long wavelength component of \(\Delta g\)
- \(\Delta g_{\text{res}}\) = residual component of \(\Delta g\)
- \(\Delta g_{\text{short}}\) = short wavelength component of \(\Delta g\)
Table 1. List of gravity anomaly models

| Model | Method | Filter       |
|-------|--------|--------------|
| Kalsul 1 | LSC    | Non filtered |
| Kalsul 2 | LSC    | Gaussian 5km |
| Kalsul 3 | LSC    | Gaussian 10km |
| Kalsul 4 | LSC    | Gaussian 15km |
| Kalsul 5 | LSC    | Median 5km   |
| Kalsul 6 | LSC    | Median 10km  |
| Kalsul 7 | LSC    | Median 15km  |
| Kalsul 8 | IVM    | Non filtered |
| Sandwell v23.1 | - | - |

3.3. Least-square collocation (LSC)
The LSC method computes final gravity anomaly by summing the residual gravity anomalies ($\Delta g_{\text{res}}$) and those computed from a reference gravity field ($\Delta g_{\text{ref}}$) [9]. Beside SSHs from altimetry, a global geopotential model was needed as the reference gravity field. The selected reference was the EGM08 to degree and order 2190. Along with the SSHs, EGM08 gave the value of residual geoid gradient ($\varepsilon_{\text{res}}$).

The computed residual geoid gradients were used to calculate the residual gravity anomalies by equation 2 [19]:

$$\Delta g_{\text{res}} = C_{\Delta g}^\xi C_{\Delta g}^\eta \left( C_{\xi}^\xi + D_{\xi} \right)^{-1} \left( \xi_{\Delta g} \right) + \Delta g_{\text{ref}}$$

with:
- $\Delta g_{\text{res}}$ = vectors of residual gravity anomalies
- $\varepsilon_{\text{res}}$ = residual geoid gradients
- $C_{\Delta g}^\xi$ = gravity anomaly-residual geoid gradients covariance matrices
- $C_{\xi}$ = residual geoid gradient-residual geoid gradient covariance matrices
- $C_{\Delta g}^\eta$ = gravity anomaly- gravity anomaly covariance matrices for
- $D_{\xi}$ = noise of residual geoid gradient
- $\Delta g_{\text{ref}}$ = reference gravity anomaly

The final gravity anomaly was obtained by adding the residual gravity anomalies into those computed from EGM08 [9]. A brief explanation of this LSC method can be found in [9] and [20].

3.4. Inverse Vening-Meinesz (IVM)
This method computes gravity anomaly from deflections of the vertical [21]. The deflections of the vertical (DOV) is defined as the spatial angle between the normal gravity vector on the reference ellipsoid and the actual gravity vector on the geoid [22]. The first three steps in this technique are similar as in LSC: get along-track gradient, remove reference gradient of global gravity model, and remove outliers. However, an intermediate step is needed in this technique, which is the gridding of north and east gradient components as written in equation 3.

$$\left( \begin{array}{c} \xi \\ \eta \end{array} \right) = \hat{S} = C_{\xi\xi}^{-1} \left( C_{\xi\eta} + C_{\eta} \right)^{-1} l$$

with:
- $\hat{S}$ = prediction vector (with $\xi$, $\eta$)
- $\xi$ = north component of DOV
- $\eta$ = east component of DOV
- $l$ = observation vector, the geoid gradient from altimetry
- $C_{\xi\xi}$ = covariance matrices for $l$ and $l$
\( C_n \) = covariance matrices for the noise of \( l \)
\( C_{st} \) = covariance matrices for \( s \) and \( l \)

Vector \( l \) is an observation vector contains the geoid gradient derived from altimetry SSHs and EGM08 as the reference gravity field (\( \delta g_{res} \), see sub-section 3.3).

The next step is converting DOV to gravity anomaly by using the IVM formula, as written in equation 4.

\[
\begin{bmatrix} N_p \\ \Delta g_p \end{bmatrix} = \frac{1}{4\pi} \left( R \int_0^1 (\xi_q \cos \alpha_{qp} + \eta_q \sin \alpha_{qp}) {C'} \, d\sigma_q \right)
\]

where

- \( N_p \) = geoidal height at \( p \)
- \( \Delta g_p \) = gravity anomaly at \( p \)
- \( R \) = mean Earth radius
- \( \gamma \) = normal gravity
- \( C' \) = Kernel function
- \( \xi_q \eta_q \) = north and east component of DOV at \( q \)
- \( \alpha_{qp} \) = azimuth from \( q \) to \( p \)
- \( d\sigma_q \) = surface element = \( \cos \varphi_q \, d\varphi_q \, d\lambda \)
- \( \phi_q, \lambda_q \) = latitude and longitude of \( q \)

Because of the singularity of the Kernel function \( C' \) and \( H' \) at zero spherical distance, the innermost zone effects on geoid and gravity anomaly must be taken into account and were computed by equation 5:

\[
\begin{bmatrix} N_p \\ \Delta g_p \end{bmatrix} = \frac{1}{4} \left( \xi_y + \eta_x \right) \left( s_0^2 \right) \left( \frac{s_0}{\pi} \right)
\]

where

- \( \xi_y = \frac{\delta \xi}{\delta y} \)
- \( \eta_x = \frac{\delta \eta}{\delta x} \)
- \( s_0 = \sqrt{\frac{\Delta x \Delta y}{\pi}} = the \ size \ of \ the \ innermost \ zone \)

When using the RCR procedure, the error in using spherical approximations should be very small compared to data noise. Consider the formula of error-free LSC in the case of using ellipsoidal correction [23] as written in equation 6:

\[
S = C_{st} C_{ll}^{-1} \left( l - e^2 l \right) + e^2 s l
\]

\( e^2 \) is the squared eccentricity of a reference ellipsoid, which is about 0.006694 for the GRS80 ellipsoid. If the largest element of DOV in \( l \) was assumed as 100 \( \mu rad \), then the largest element in \( e^2 l \) would be 0.66 \( \mu rad \). This value was far smaller than the noise of DOV from the multi-mission satellite altimetry. In conclusion, the value of ellipsoidal correction could be neglected.

3.5. NGDC Marine Gravity Data

The NGDC datasets were used as the assessment values for the modelled gravity anomalies. The datasets consist of several data types such as gravity, magnetics and bathymetry, but in this research we only utilized the gravity data. Over the research area, the gravity data was observed by many shipborne survey missions dated back from 1963 to 1991. The data were available in MGD77T format [24].

As the models were in the grid format, an interpolation should be made to the NGDC data. We used a two dimensional polynomial interpolation to define an NGDC gravity value on the desired cell grid. This value then subtracted from the models corresponding value to calculate the difference. Figures 5, 6 and 7 below show the map of the differences while table 2 presents the statistics.
4. Results and Analysis
In figure 2, Kalsul 1 model, it can be seen that the spatial distribution of gravity anomalies over the area is similar as in figure 3 (Kalsul 8) and figure 4 (Sandwell). All figures show gravity anomalies ranged from about -300 to 300 mgal with a pattern of negative anomalies on the waters east-side of Sulawesi Island (-2° - 0° N and 122° – 127° E). This pattern represents an area of deep waters.

Figure 2. Gravity anomaly as computed by LSC technique (Kalsul 1)

Figure 3. Gravity anomaly as computed by IVM Technique (Kalsul 8)
Figure 4. Gravity Anomaly from Sandwell v 23.1

To get a better understanding of the models quality, the gravity anomaly differences were plotted on the NGDC shipborne tracks (figure 5, 6 and 7). Figure 5 shows the differences of the non-filtered LSC model (Kalsul 1), while figure 6 and 7 display the differences of IVM (Kalsul 8) and Sandwell models respectively. Kalsul 1 and Kalsul 8 show a similar pattern with the biggest difference occurs in around latitude 6$^\circ$ N. Furthermore, the Kalsul 1 model give a better accuracy than Kalsul 8 by 1.62 mgal. The application of Gaussian filter with a 10 km window size (Kalsul 3) had improved the accuracy of LSC model by 0.2% (Table 2). On the other side, the application of median filter with the same window size only gave 0.17% improvement. Overall, the LSC models outperformed the IVM one.

Compared to Sandwell, our models are better in term of RMS error by almost 6 times. This result is not only consistent with the previous research by Hsiao et al [9], but also indicate that the Sandwell model is not accurate enough in the research area. However, the Sandwell model has a better mean deviation (0.411 mgal) than the Kalsul 8 (0.581 mgal). In term of mean deviation, the best computed model is Kalsul 7, with mean deviation of -0.019 mgal, while Kalsul 3 is the best model in term of RMS error (15.042 mgal) and STD of error (15.041 mgal). The complete results shown in table 2 below.

| Model     | Max (mgal) | Min (mgal) | Mean (mgal) | RMS (mgal) | STD (mgal) |
|-----------|------------|------------|-------------|------------|------------|
| Kalsul 1  | 277.636    | -227.900   | 0.084       | 15.077     | 15.077     |
| Kalsul 2  | 277.712    | -227.072   | 0.085       | 15.064     | 15.064     |
| Kalsul 3  | 277.889    | -223.814   | 0.094       | 15.042     | 15.042     |
| Kalsul 4  | 277.866    | -221.080   | 0.115       | 15.072     | 15.071     |
| Kalsul 5  | 277.534    | -227.403   | 0.076       | 15.064     | 15.064     |
| Kalsul 6  | 277.707    | -224.629   | 0.031       | 15.051     | 15.051     |
| Kalsul 7  | 278.113    | -221.516   | -0.019      | 15.140     | 15.140     |
| Kalsul 8  | 284.513    | -230.813   | 0.581       | 16.704     | 16.694     |
| Sandwell  | 588.134    | -451.830   | 0.411       | 93.923     | 93.923     |
Figure 5. a) Differences between LSC (Kalsul 1) and NGDC and b) its latitudinal profile

Figure 5a and 6a show green lines all over the research area. The green lines indicate near zero difference to the NGDC marine gravity data. However, in the northern part of Sulawesi waters, a pattern with blue color appeared, this is an indication of negative differences with magnitude -50 to -75 mgal. The latitudinal profiles of the anomaly differences show the existence of major errors (figure 5b and 6b), especially in latitude 2° - 1° S, 0° - 1° N, and 1.5° - 6° N. Those phenomena appear because of some gross errors in at least three NGDC datasets.

On the other hand, figure 7 does not show a similar pattern. Figure 7a shows that the difference between Sandwell 23.1 and in-situ data vary all over the area, indicated by multi-colored lines. However, there is a small region in the middle of research area which gives errors ±250 mgal, shown in blue/purple lines. Those errors possibly caused by high frequency noises affected by the land influence on that narrow waters region. Figure 7b shows major errors in almost all latitude. This is an indication that Sandwell v 23.1 model still has some systematical errors in the research area. The most probable systematical errors source is aliasing which occurred when cutting the global model into smaller regional parts.

Figure 6. a) Differences between IVM (Kalsul 8) and NGDC and b) its latitudinal profile
5. Conclusion

This research has produced eight gravity anomaly models with mean deviation range from -0.019 to 0.581 mgal, and RMS error ranged from 15.042 to 16.704 mgal. Those values were obtained by using NGDC marine gravity data as the assessment values. The best model in term of RMS error is Kalsul 3, an LSC gravity anomaly model with 10 km Gaussian filter applied, while the least accurate one is Kalsul 8, an IVM gravity anomaly model with no filter applied. Kalsul 3 might not be the most optimum model, yet it is suitable enough to determine the regional geoid model of Indonesia, especially on waters area. To improve the models quality, a list of supplementary data could substitute the data used, such as Indonesian tide gauges assimilated tidal model as an alternative to NAO99, CNES-CLS09 as an alternative to RIO05 MDT model, and the incoming EGM as the substitution to EGM08 geoid reference. The use of most recent altimetry missions, such as ICESat and Saral-Altika, could also enhance the quality of the model, as it densifies the altimetry footprints over the research area.

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