Pseudo height anomaly over Indonesia in respect of GRACE gravity

Dina Anggreni Sarsito¹, Brian Bramanto¹, Heri Andreas¹, Dhota Pradipta¹, Muhammad Syahrullah¹

¹Geodesy Research Group – Faculty of Earth Sciences and Engineering – Institut Teknologi Bandung Jl. Ganesa 10 Bandung 40132, Indonesia

e-mail: dsarsito@gd.itb.ac.id

Abstract. This paper presents an overview of the recent height anomaly over Indonesia region in respect of Global Geopotential Model 2008 (EGM2008) which known as the most advance Global Geopotential Model. Recent height anomaly over Indonesia computed from Gravity Recovery and Climate Experiment (GRACE) satellite mission long term static solution using Bruns’ formula with degree and order up to 180. The results indicate that the deviation between geoid undulation with pseudo height anomaly deviation vary up to 12 meters with the largest deviations occur in several zones. Further investigation still needed to deduce the causes of the high height anomaly deviation that occur in several places in Borneo, Celebes and Papua, whether it is caused by a large compression forces or any other.

1. Introduction

The gravity field is widely known as one of the important information for geodesy and geophysics applications, as gravity signal responded from the mass distribution beneath and Earth’s. Several issues in geodesy and geophysics application are expected to be solved if the gravity field could be precisely determined. Recently, geoid determination data acquisition which represents the equipotential gravity field has been developed rapidly, it started with a terrestrial gravimeter that uses a pendulum principle and becomes a spring-based gravimeter which takes a lot effort to observed gravity in global region. Then, an airborne and satellite-based gravimeter found to cover a world-wide data acquisition. A satellite to observe the geometry of the Earth’s (ocean and tides), known as altimetry satellite, is also used to support the gravity data acquisition.

Figure 1. Gravity anomaly (top) and geoid (bottom) over Indonesia region

Due to the different type of data acquisition, the data processing aspect is significantly improved. In present, various ways to assimilate these data can be applied, for example using least-square collocation. Furthermore, the geoid is no longer recognize as a static geoid, it could be inferred as a dynamic geoid due to satellite-based gravimeter temporal resolution. As a result, geoid can be powerful tool to describe the Earth’s dynamic.
The gravity field could be also represented as a set of global geopotential model coefficients which can be expanded using a spherical or ellipsoidal harmonic equation. EGM2008 is known as the reference global geopotential model at present. Further, EGM2008 along with ITU_GRACE16 which derived from long term observation of a satellite-based gravimeter are used in this research for the realization of Molodensky’s Geodetic Boundary Value that applied the gravity field data. One of the important parameters that could be derived is the height anomalies, which are used later in this research to find the relation between the anomalies and the Earth’s geophysical phenomena.

2. Data and Method

2.1. EGM2008
National Geospatial-Intelligence Agency (NGA) first launched the EGM2008 with degree up to 2159 and accompanied with additional degree up to 2190 and order up to 2159 since 2012 [1]. EGM2008 is computed using 5’ gridded sampling gravity anomaly from terrestrial, airborne gravimeter and altimetry satellite, thus, assimilated with the other global geopotential model, ITG-GRACE03S with degree up to 180 for the long wavelength gravity field component. For an area where insufficient gravity anomaly data available, an inverse gravity anomaly computed from the orography variation are then used. Gravity data over Indonesia region which are used for EGM2008 computation are mainly from altimetry satellite and gravity inversion from orography with some marine gravity data as shown in Figure 2. In general, EGM2008 cover short to long wavelength gravity field component.

![Figure 2. EGM2008 data source over Indonesia region [2]](image)

2.2. Gravity Recovery and Climate Experiment (GRACE)
GRACE launched in March 2002 as a joint mission from NASA (US), CSR (France), GFZ and DLR (German). GRACE consists of a twin identical satellite orbiting at an altitude of ±500 km with a distance of 200 km between satellites. Gravity variation could be observed by analysing the distance variation between satellite by using radar and GNSS. ITU_GRACE model that is used in this research consists of a set of gravity coefficients with degree up to 180. This model is computed by two approaches: First, the in-situ geopotential differences between twin satellites are estimated using SST and precise orbit using improved integral method, second, the geopotential differences were then used as observable data to estimate the set of gravity coefficients in spherical harmonic approximation [3, 4].

2.3. Height anomaly
In geodesy approach, there are two main references that can be used as a reference for the determination of Earth’s gravity potential, which are geoid, represents the true physical potential surface and ellipsoid as a mathematical surface. Assumed there is a point \( A(\lambda, \varphi) \) located in an arbitrary position on the Earth’s surface with gravity potential \( W_T \), then the projection along the plumb line in normal direction \( n \) gravity line \( g \) over arbitrary geoid equipotential surface \( W_g \) refers as orthometric height \( H^0 \) (unit in meter). The \( A \) projection perpendicular with the ellipsoid will through the ellipsoid equipotential surface \( U_E \) with vertical distance between them refers as geodetic height \( h \). The height differences between orthometric and geodetic height introduce as geoid undulation \( N \).

The absence or lack information about the heterogeneous and anisotropic distribution of the Earth’s density causes the determination of the true surface potential becomes unclear and complex as classical Stokes theorem implies that all gravity observation must be referred to the geoid surface. One of the solutions to avoid this issue is by applying the Moledensky Geodetic Boundary Value Problems which applying an additional reference surface namely telluroid. Then, the vertical distance along the plumb lines between the orography and the telluroid is referred as height anomaly \( \zeta \) while the differences between ellipsoid and telluroid is called normal height \( H^* \).

Using the disturbance potential \( T_S \) which refers as a potential difference between the potential in orography \( W_S \) and its normal potential in orography \( U_S \)

\[
T_S(\lambda, \varphi) = W_S(\lambda, \varphi) - U_S(\lambda, \varphi) \tag{1}
\]

Geoid undulation defined by Bruns theorem can be formulated as:

\[
N(\lambda, \varphi) = \frac{T_S(\lambda, \varphi, H^0)}{\gamma_E(\varphi, h)} = \frac{T_S(\lambda, \varphi, 0)}{\gamma_E(\varphi, h)} \tag{2}
\]

with \( \gamma \) is the normal gravity. Let’s say that \( W_S = U_E \) than \( N \equiv \zeta \), so that the height anomaly \( \zeta \) and pseudo height anomaly \( \zeta_E \) can be computed as:

\[
\zeta(\lambda, \varphi) = \frac{T_S(\lambda, \varphi, h)}{\gamma_E(\varphi, h)} \tag{3}
\]

\[
\zeta_E(\lambda, \varphi) = \frac{T_S(\lambda, \varphi, 0)}{\gamma_E(\varphi, 0)} \tag{4}
\]

The obtained height anomaly can be used to determine the gravity disturbance \( \delta g \) by using Earth’s surface as the reference.

\[
\delta g(\lambda, \varphi, h) = \frac{\partial T_S(\lambda, \varphi, h)}{\partial h} = g_S(\lambda, \varphi, h) - \gamma(\lambda, \varphi, h) \tag{5}
\]

If \( \delta g \) is computed in the ellipsoid surface \( h_E = 0 \), then \( \delta g(\lambda, \varphi, 0) \).

Gravity anomaly \( \Delta g \) can be also derived from height anomaly. Classical determination of \( \Delta g \) uses Stoke theorem which requires downward continuation of surface gravity data to geoid surface by using gravity reduction, where \( \Delta g(\lambda, \varphi, H^0) = g_\gamma(\lambda, \varphi, H^0) - \gamma_E(\lambda, \varphi, h = 0) \). Molodensky’s modern approach generalize \( \Delta g \) using gravity observation in Earth’s surface \( g_S \) and the normal gravity in telluroid surface \( \gamma_T \).

\[
\Delta g(\lambda, \varphi, h) = g_S(\lambda, \varphi, h) - \gamma_T(\lambda, \varphi, H^N) \tag{6}
\]

Height anomaly can be also expressed using spherical harmonic expansion:
\[
\zeta(\lambda, \theta) = \frac{GM}{r \gamma(r, \theta)} \sum_{n=0}^{n_{\text{max}}} \left( \frac{R}{r} \right)^n \sum_{m=0}^{n} P_{nm}(\sin \theta)(C_{nm} \cos m \lambda + S_{nm} \sin m \lambda)
\]

with \( (r, \lambda, \theta) \) are the spherical coordinates of the computation point, \( G \) is the Gravitation constant and \( M \) is the Earth’s mass with radius of \( R \). \( C \) and \( M \) are the harmonic coefficients with \( n \) degree and \( m \) order.

3. Result and Discussion

Both of EGM2008 and ITU_GRACE16 degree used in this data are limited to 180 to reduce the high frequency gravity component in the EGMS2008. As described in the previous section, most of the gravity data in Indonesia region are derived from the global topography data and Earth’s density assumption, which could lead into a relatively poor gravity accuracy compared with the low frequency gravity signal derived from satellite-based observation. A linear trend is found in the height anomaly over Indonesia region that varies from -70 to 80 meter with more complex variation over Sulawesi to Papua areas (Figure 3).

The differences between low and high frequency anomaly components in gravity field could be used to infer the large geology structure beneath the surface, thus, a height anomaly deviation map derived from the subtraction between all frequency components and low frequency component was created (Figure 4). Strong negative anomalies (up to -10 meters) were found mostly along the subduction region in West of Sumatra and South of Java, while in the East of Indonesia, strong anomalies were also found between the micro blocks. On the other hand, positive anomaly mostly occurred over the high terrain orography.
Figure 4. Height anomaly deviation between EGM2008 n = 2190 and n = 180

Figure 5 shows the height anomaly for EGM2008 with n = 2190 and n = 180 at longitude 125 and latitude -5. In general, it can be seen that n = 180 shows the low frequency of physical phenomena which is dominated by the depth physical phenomena of the Earth, whereas for n = 2190 it is dominated by high frequency phenomena which show a shallow physical phenomenon of the Earth. As a comparison, the height anomaly between ITU GRACE16 and EGM2008 with degree n = 180 in the same cross section are shown, in Figure 6, the EGM2008 is smoother compared to the ITU GRACE16. This indicates that satellite ITU GRACE16 results are more sensitive to low frequency phenomena / deep earth phenomena compared to EGM2008, however, in the longitudinal cross section, the wiggle effects are likely due to the unresolved de-striping error [5, 6].

Figure 5. Height anomaly for EGM2008 with n = 2190 and n = 180 at longitude = 125 (left) and at latitude -5 (right)
Figure 6. Height anomaly for EGM2008 with n = 180 and ITU_GRACE16 n = 180 at longitude = 125 (left) and at latitude -5 (right)

Figure 7. Deviation between geoid undulation and pseudo height anomaly of EGM2008 (n=180)

Figure 8. Deviation between geoid undulation and pseudo height anomaly of ITU_GRACE16 (n=180)

Detailed information can be inferred from figure 7 and figure 8, the sensitivity of both global can be seen. The deviation between geoid undulations which referred to geoid-ellipsoid surface is then
compared with the pseudo high anomaly, which refers as a height anomaly from telluroid to co geoid-ellipsoid. The deviation between the geoid undulation and the pseudo height anomaly from EGM2008 (n = 180) is shown in Figure 7. On the island of Sumatra, the deviation shows a range between 0 to 2 meters, which is worth close to zero for the majority of Sumatra eastern and southern part. For western Sumatra, the biggest deviation is seen in the northern hemisphere and shrinks to the south with a slight gap in latitude 0. This zone besides having high terrain conditions, is also known to be an active fault zone of the Semangko Fault System. For the Java region from the western part extending eastward to East Nusa Tenggara, deviations show zero values (deviations up to 1 m only visible in the northern part of the western part of Java), although it is known that along this zone it has a zone of active subduction structures in Java at the western part up to subduction of the Banda Sea in the east. For Kalimantan region, the deviation in the south looks close to zero, but there is a significant deviation change in gradations reaching 6 meters, namely in the northeastern region. The region has a higher terrain compared to other regions in Kalimantan. The same thing also happened in the Sulawesi region with the highest deviation in the central part of Sulawesi, besides the terrain in that region is relatively higher compared to its surroundings, this region also has a complex geological structure. A much higher deviation occurs in the central Papua region which reaches more than 12 meters. Terrain conditions and geological structures for this region have criteria similar to the deviation conditions in Sulawesi, which are high terrain and active geological structures zone also. Figure 8 shows the deviation to ITU_GRACE 16 (n = 180), showing a pattern that is almost similar to Figure 7 but with more detailed variations. For the Sumatra region, the deviation is seen to reach 4 meters higher for the northernmost zone, and this deviation extends to the southernmost tip of Sumatra. For Java, the deviation is clearly visible with a height of up to 2 meters along the middle of the island of Java from the westernmost to the easternmost tip which has a relatively high terrain for the Java region. For the Bali to East Nusa Tenggara regions, deviations tend to be small to zero with a slight deviation seen between Sumba and Sumbawa in East Nusa Tenggara. For the Kalimantan region, deviations are again seen in the northeast with a narrower zone than in Figure 7 but have a greater deviation value reaching 6 meters. For the Sulawesi region, the same phenomenon is seen again that there is a deviation in the middle, and there is an additional deviation for the southeast arm reaching 6 meters and the south arm and the north arm (west) range up to 2 meters. These zones are known to be zones of active geological structures. A much higher deviation is seen again in the central Papua region reaching more than 12 meters and the addition in the western part of Papua (on the head) with a deviation reaching 6 meters. Majority, the deviation of both derived anomaly maps shows similar pattern, that is a deviation with magnitude up to 12 meter over the western part of Sumatra, central Java, northern Kalimantan, central Sulawesi and Papua area. These deviations are likely due to the terrain effect, however, for some areas in central Sulawesi, Sumatra and Papua are dominated by an active tectonic area.

4. Conclusion
Both of EGM2008, which determined from various types of gravity data acquisition, and ITU_GRACE16, established from satellite-based gravimeter only, show interesting deviation patterns between geoid and pseudo height anomaly. These deviations are likely due to the terrain and tectonic activity beneath the Earth’s surface. Further research by applying a better terrain reduction and de-striping filter should be done to have a better interpretation.

5. References
[1] Pavlis, N.K., et al., The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). Journal of geophysical research: solid earth, 2012. 117(B4).
[2] S.K., Earth Gravitational Model 2008 (EGM2008). 2009.
[3] Guo, J., et al., On the energy integral formulation of gravitational potential differences from satellite-to-satellite tracking. Celestial Mechanics and Dynamical Astronomy, 2015. 121(4): p. 415-429.
[4] Shang, K., et al., GRACE time-variable gravity field recovery using an improved energy balance approach. Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, 2015. 203(3): p. 1773-1786.
[5] Chen, J., et al., *Patagonia icefield melting observed by gravity recovery and climate experiment (GRACE).* Geophysical Research Letters, 2007. 34(22).

[6] Chen, J., et al., *GRACE detects coseismic and postseismic deformation from the Sumatra-Andaman earthquake.* Geophysical Research Letters, 2007. 34(13).