Airborne gravity survey, towards a precise Indonesian geoid model (case study: Sumatera Island)

A M Pahlevi¹, B Bramanto², B Triarahmadhana¹, S Huda¹, D Pangastuti¹, A Nur¹, D D Wijaya², K Prijatna², M Julianto¹ and A B Wijanarto¹

¹ Geospatial Information Agency, Jl. Raya Jakarta-Bogor KM. 46 Cibinong 16911, Indonesia
² Bandung Institut of Technology, Jl. Ganesha 10 Bandung 40132, Indonesia

Abstract. Airborne gravity method for high-resolution geoid model in Indonesia held in Sumatera Island using Lacoste & Romberg Air-Sea Gravity Meter S-130 and Trimble R9S GNSS installed in the cessna grand caravan type C208B. Flight altitude ranging from 3000 to 4000 meters and the aircraft speed is 277 km/h. Processing GNSS are using differential processing which is tied to SRGI2013 with a standard deviation tolerance <7 cm in high position and 90% data fix. The gravity raw data (LCR file) is filtered using the lowpass filtering filter mode with the weight function blackman window, the filter window used is 150-seconds. From crossover analysis, some cross over misfit relatively large difference with more than ±20 mGal difference, the average and standard deviation of crossover misfit were -0.0023 mGal and 9.0214 mGal respectively. The result of spectral analysis, airborne gravity signal has minimum 10 km of wavelength while the EGM2008 degree 2190 has minimum 18 km of wavelength.

1. Introduction

Based on Head of BIG Regulations Number 15 of 2013, the implementation of national Geospatial Information in Indonesia must be tied to a national geospatial reference system called Indonesian Geospatial Reference System 2013 or SRGI2013 (Sistem Referensi Geospasial Indonesia 2013). SRGI2013 consists of a horizontal and vertical geospatial reference system. Indonesia uses geoid as vertical geospatial reference system. Geoid is generated from gravity data taken in all regions. As archipelago country, the terrestrial gravity method held since the 1980s has not been able to produce a precise geoid model. The implementation of gravity data with the airborne method was carried out from 2008 to 2011 as a result of the collaboration of the Technical University of Denmark (DTU) and the Geospatial Information Agency (BIG), producing gravity data of Sulawesi, Kalimantan and Papua. In 2018, BIG continued of airborne gravity survey on the Sumatera Island, using Lacoste & Romberg Air-Sea Gravity Meter S-130 and Trimble R9S GNSS installed in the cessna grand caravan type C208B. Performed for 400 flight hours with flight altitudes ranging from 3000 to 4000 meters, the aircraft speed is 277 km/h or 150 knots. The main path has north-south direction with azimuth 315 or 135, and the crossing path has an east-west direction with azimuth 45 or 225. The spacing of the main lines is 15 km and the spacing of the cross lines is 100 km. This paper aims to study the method of
airborne gravity as a basis for realizing a precise Indonesian geoid model while focusing on cross over analysis and spectral analysis of free air anomaly.

2. Airborne gravity
The locations of the airborne gravity survey at 2018 are on the Sumatera mainland including the Bangka and Belitong Island. The survey area is divided into 9 areas based on the provinces on Sumatra, where each area has one gravity reference point (GBU [Gayaberat Utama]). The GBU is a 0-order gravity pillar measured using portable absolute gravity (A-10) at the beginning of 2018. The location of GBU is located in the Meteorological, Climatology, and Geophysical Agency (BMKG) tool park in each major airports in each province. The airborne gravity survey is carried out for 66 active days, from September-22 to December-29, 2018, during the rainy season. The airborne gravity survey is very dependent on the weather and turbulence, so there is 20% flight repetition during survey.

Processing GNSS are using differential processing which is tied to SRGI2013 with a standard deviation tolerance <7 cm in high position and 90% data fix. GNSS products are processed together with airborne gravity raw data to produce gravity anomalies ([FAA] free air anomalies). Time synchronization in position and gravity is needed in this process, tolerating the time difference is <0.5 seconds. Airborne gravity data is LCR file. The LCR file is filtered using the lowpass filtering filter mode with the weight function blackman window, the filter window used is 150-seconds. The results of filtering data are compared with the EGM2008 degree 2190 data at the same height. Both of these data are compared with a tolerance of <10 mGal. If in 1 flight line there are more than 30% of data lost or not fulfilling tolerance <10 mGal, then the line must be re-flight. Figure 1 show the surveyed line of airborne gravity survey at 2018, some areas cannot be surveyed due to flight licensing problems.

![Surveyed line of airborne gravity 2018.](image)

3. Airborne gravity data processing
The fundamental of the observed gravity derived from airborne gravity measurement on the aircraft trajectory at the flight level of the airborne gravity survey can be derived as follows [1]:

\[ g_{\text{obs}} = (f_z - f_b) - a_z + \delta g_{\text{tilt}} + g_0 + \delta g_{\text{Eötvös}} \] (1)
Where $f_z$ and $f_b$ are related with the gravity observation at $z$ and at the airport (base reading) respectively, $a_z$ is the vertical acceleration of aircraft with positive value to the zenith direction, $\delta g_{\text{tilt}}$ is the platform off-level correction, $g_o$ is the gravity value at the base and $\delta g_{\text{Eötvös}}$ is the Eötvös correction.

Eötvös effect is the change of the reading gravitational force caused by the change in centrifugal acceleration which is resulting from eastbound and westbound acceleration. Eötvös correction can be defined as follows:

$$\delta g_{\text{Eötvös}} = 2w_e v_h \cos \varphi \sin \alpha + \frac{v_h^2}{R_e + z}$$  \hspace{1cm} (2)

Where $w_e$ is the mean rotational velocity of the Earth $7.292115 \times 10^{-5}$ rad s$^{-1}$, $\varphi$ and $\alpha$ are the geodetic latitude of the Earth and the direction of the flight, $v_h$ is the horizontal velocity component, and $z$ are the mean radius of the Earth and the flight height above the sea level.

Unlike the terrestrial gravity measurement which the gravity sensor axis is well aligned to the vertical direction of the gravity field, airborne gravity measurement needs an additional gyro to minimize the error. If there is still a misalignment between the axes, the tilt gravity signal needs to be corrected with an Inertial Measurement Unit (IMU) which can be expressed as follows [2]:

$$\delta g_{\text{tilt}} = \frac{L_{\text{acc}}^2 + X_{\text{acc}}^2 - (acce^2 + acn^2)}{2g}$$  \hspace{1cm} (3)

with acceleration in long axis ($L_{\text{acc}}$), cross axis ($X_{\text{acc}}$), east direction ($acce$) and north direction ($acn$).

The free-air gravity anomaly is widely used in the most cases of the geoid determination based on the geodetic boundary value problem. Thus, the gravity reduction from the observed gravity to free-air gravity anomaly at $z$ can be computed by [3]:

$$\Delta g_z = g_{\text{obs}} - \left[ g_0 + \delta \gamma \frac{h}{h^2} + \frac{1}{2} \left( \delta^2 \gamma \frac{h^2}{h} \right) \right]$$  \hspace{1cm} (4)

where $g_0$ is the normal gravity on the referenced ellipsoid, $h$ is the orthometric height, $\delta \gamma$ is the vertical gradient (-0.3087) and $\frac{\delta^2 \gamma}{\delta h^2}$ is the gravity gradient $(2.8906 \times 10^{-7})$.

Figure 2 show the free-air anomaly over the researched area. The anomaly varies from -100 to 210 mGal. The high anomaly was occurred along the mountainous area with the Northwest-Southeast direction on the West coast of Sumatra Island.
Crossover analysis is a method to evaluate the consistency of the observed gravity from two survey lines which introduced by its misfit of its intersection point. However, the exact crossover point between two survey lines does not available, therefore an interpolation should be used to identify the gravity value for each line survey in the crossover point ([4] and [5]). Misfit of the crossover analysis can be derived by:

$$\Delta \bar{g} = \Delta \bar{g}^1 - \Delta \bar{g}^2$$  \hspace{1cm} (5)

where $\Delta \bar{g}^1$ and $\Delta \bar{g}^2$ are the interpolated free-air gravity anomaly from line 1 and line 2 at the crossover point.

Crossover misfit (total 220 points) shown on Figure 3. Some crossover misfit suffers a relatively large difference with more than ±20 mGal difference. These phenomena mostly occurred due to heavy turbulences which mostly occurred on the mountainous area as the large difference mostly occurred on that area. The other possibility is the positioning error which lead into incorrect Eötvös correction. As seen on Eq. (2), Eötvös correction is dependent with the direction of the flight trajectory. Assumed that the height and the velocity is a constant, then the absolute minimum value of the Eötvös correction will be given on the North-South direction as shown on Figure 4. Figure 5 simulates the correlation between Eötvös correction and the positioning accuracy. With the typical accuracy of GNSS kinematic within 10 cm [6], the expected error accuracy of velocity determination is within 20 cm/s. The simulated Eötvös correction error for the North-South and West-East direction were less than 0.001 mGal and 3 mGal respectively.
Figure 3. Crossover misfit over the researched area.

Figure 4. Simulation of Eötvös correction with difference direction of flight trajectory.
Figure 5. Simulation of Eötvös correction on the difference direction and its correlation with the positioning error.

Figure 6 shows the histogram of crossover misfit. A normal distribution was on the histogram which suggesting that these crossover misfits are due to a random error. The average and standard deviation of crossover misfit were -0.0023 mGal and 9.0214 mGal respectively.

The differences of the flight height were also evaluated in this research to assess the possibilities of the systematic error. With the modification of the eq. 5, the elevation differences on the crossover point is defined as follows:

$$\Delta h = \Delta h^1 - \Delta h^2$$  \hspace{1cm} (6)

where $\Delta h^1$ and $\Delta h^2$ are the interpolated height from line 1 and line 2 at the crossover point. The height and the free-air gravity anomaly difference the compared as shown on Figure 7. The height
differences vary from -700 to 700 meter with an approximate 150-meter height steps. It could be interferes that there was no systematic error as indicated by the error distribution were around 0 mGal.

![Figure 7](image)

**Figure 7.** The correlation between height and free-air anomaly differences.

5. **Spectral Analysis**
Spectral analysis is done by using fourier transform method to estimate the resolveable wavelength which might consist in the data observation. The spectral then compared with the full degree of Geopotential model such as Earth Geopotential Model 2008 (EGM2008) with degree up to 2190. By using fourier transform, the signal decomposes into several components. A mathematical way to represents fourier transform is defined by [7]:

\[
F(u) = \int_{-\infty}^{\infty} f(x)e^{-imux}dx
\]

where \(i = \sqrt{-1}\) and \(u\) is the frequency variable and \(f(x)\) is the function of the observed data. Three lines of survey were evaluated in this research (Figure 8). The chosen lines were expected to have various wavelength components as observed from mountainous area and across the Island.
Figure 8 shows the spatial and frequency domain for each line of survey. It could be interfering that the airborne gravity survey gives large amplitude differences in spatial domain. As in the North region of Sumatra, the large amplitude differences given by the gravity variation along the mountainous area. With a degree up to 2190, EGM2008 expected to have minimum 18 km of wavelength signal which is approved by the frequency domain analysis in Figure 9 while the observed gravity signal has minimum 10 km of wavelength signal in the South region of the Island.
Figure 9. Spatial and frequency domain for each line survey from North to South.

6. Conclusion
Airborne gravity data in Sumatera, 2018 was contaminated with heavy noises due to weather conditions. The preliminary processing was considered for data preparation prior to precise geoid modeling. Cross over analysis shows there was no systematic error. The average and standard deviation of crossover misfit were -0.0023 mGal and 9.0214 mGal respectively. Spectral analysis
shows medium wavelength from airborne gravity data provide more information than EGM2008
degree 2190.

7. References
[1] Olesen A V 2003 Improved airborne scalar gravimetry for regional gravity filed mapping and
geoid determination Tech. Rep. No. 24 National Survey and Cadastre-Denmark,
Copenhagen, Denmark
[2] Vallian H 1992 The Lacoste & Romberg air/sea gravimeter: an overview i CRC Handbook of
Geophysical Exploration at Sea Boca Raton Press
[3] Torge W 1989 Gravimetry (New York: Walter de Gruyter)
[4] Amos M J, Brett W E and Featherstone W E 2005 Crossover adjustment of New Zealand
marine gravity data and comparisons with satellite altimetry and global geopotential models
Gravity Geoid and Space Missions pp. 266-271
[5] Shih H, Hwang C, Barriot J P, Mouyen M P, Correia D, Lequex D and Sichooix L 2015 High-
resolution gravity and geoid models in Tahiti obtained from new airborne and land gravity
observations: data fusion by spectral combination Earth, Planets and Space 67:124
[6] Lee H, Ham G, Yun S and Choi 2017 Experimental assessment of achievable accuracy of
GNSS-derived height from carrier phase-based positioning techniques for ellipsodially
reference hydrographic surveys FIG Working Week
[7] Hansen E W 2014 Fourier Transforms: Principles and Applications Wiley

Acknowledgments
Thanks to Hsuan Chang Shih and Sin Da Tsai from StrongCo-Taiwan who assist Airborne Gravity
Survey in Sumatera. And also thanks to Prof. Cheinway Hwang for airborne gravity software.