Determination of Gravimetric Geoid Model in Sulawesi – Indonesia

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Key words: Reference System, Gravimetric Geoid Model, Geometric Geoid, Airborne Gravity

SUMMARY

In 2013, Indonesia has a new reference system, the Indonesian Geospatial Reference System 2013 (SRGI2013). SRGI2013 uses geoid as its vertical reference. Since a few decades ago, many efforts have been made to determine the Indonesian geoid using terrestrial gravity measurement. Indonesia is a large archipelagic, therefore gravity terrestrial measurement cannot effectively cover the whole area. To solve this problem, in 2008, we started using airborne gravity to obtain gravity data, collaboration between Technical University of Denmark (DTU) and Geospatial Information Agency of Indonesia (*Badan Informasi Geospasial*, BIG). Airborne gravity measurement was conducted in the Sulawesi Island. By combining airborne gravity data, global geopotential model and topography model from Shuttle Radar Topography Model (SRTM), we generate a geoid model of Sulawesi. The accuracy of the new Sulawesi geoid model is better than the global geoid model, EGM2008 by 25 cm. The accuracy was obtained by comparing the gravimetric geoid and geometric geoid from Global Navigation Satellite System, GPS- leveling measurement at vertical benchmarks in Sulawesi Island.

RINGKASAN

*Sejak disahkannya sistem referensi baru di Indonesia yaitu Sistem Referensi Geospasial Indonesia 2013 (SRGI 2013), sistem referensi vertikal nasional yang disepakati adalah model geoid. Usaha penentuan model geoid local Indonesia sudah dilakukan sejak beberapa decade lalu, menggunakan data pengukuran gravity yang dilakukan secara terestris. Namun, karena wilayah Indonesia yang luas dan kepulauan, maka pengukuran gravity ini kurang efektif. Pada tahun 2008 mulai dilakukan pengukuran gayaberat dengan menggunakan teknologi Airborne Gravity, hasil kerjasama antara DTU (*Technical University of Denmark*) dan BIG (Geospatial Information Agency). Airborne Gravity Survey dilakukan di Pulau Sulawesi. Dengan menggunakan hasil pengukuran airborne gravity dan mengombinasikannya dengan model geopotensial global serta model topography dari Shuttle Radar Topography Model (SRTM), dihasilkan model geoid Sulawesi dengan ketelitian yang lebih baik dari model geoid global EGM2008 sebesar 25 cm. Ketelitian geoid yang dihasilkan diperoleh melalui perbandingan antara geoid gravimetric dan geoid geometric hasil pengukuran GPS dan sipat datar di pilar titik tinggi geodesi (TTG) di Pulau Sulawesi.*

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1. INTRODUCTION

Since the legalization of the Indonesian Geospatial Reference System 2013 (SRGI2013), Indonesia has been using the geoid as the national vertical reference (Perka BIG 15/2013, article 10(1)). The geoid model was obtained based on a gravimetric survey which was tied to the Geodetic Control Networks (*Jaring Kontrol Geodesi*, JKG). JKG is tied to the IGSN71, making the geoid model used as the national reference is tied globally (Perka BIG 15/2013, article 10(2-3)).

Geoid is an equipotential surface which coincides with the mean sea level during an ideal condition. Equipotential surface is a surface where every point on the surface has the same potential value. Physically, it can be stated that water will not move on an equipotential surface. Earth has many equipotential surfaces. However the surface which can be used as a height reference is the surface which coincides with the MSL, namely the geoid (Bakosurtanal 1993).

The height measured from the geoid is known as orthometric height. With the development of GPS, the orthometric height can be easily determined as long as a geoid model is provided. The accuracy of the orthometric height depends on the accuracy of the ellipsoid height and the geoid. Presently, the accuracy of the ellipsoid height can reach up to 1-2 cm. To obtain a highly accurate orthometric height in Indonesia, a precise Indonesian geoid model is required.

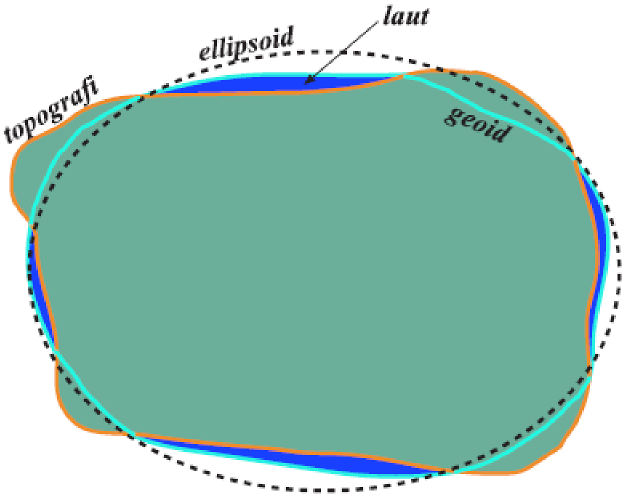


Figure 1. A global description of geoid, ellipsoid, and topography (Prijatna, 2010)

The efforts to determine the Indonesian local geoid model has been done since the 1980s, using terrestrial gravity measurement along the Vertical Benchmark points (*Tanda Tinggi Geodesi*, TTG). The terrestrial gravity measurement was conducted until the 2000s. After two decades of terrestrial measurement, only 5871 gravity measurement points were obtained (BIG, 2012). This number is too few to determine the Indonesian geoid model. The size of Indonesian archipelago with its various terrains causes the terrestrial gravity measurement to be ineffective and inefficient to carry out.

To overcome this, in 2008 the gravity measurement started to be carried out using Airborne Gravity technology, a collaborative work between DTU (Technical University of Denmark) and BIG (Formerly, Bakosurtanal). The implementation of airborne method allows a faster completion of the necessary gravity data for the National Geoid model. The resolution of gravity anomaly as obtained from the airborne gravity survey contributed to the short to medium wavelength gravity data which are required for Geoid computation with the remove-restore computation technique.

This research aims at determining the gravimetric geoid model in Sulawesi Island using data from airborne gravity survey and other supporting data. The Geoid result was validated using geometric geoid from GNSS measurement at vertical benchmarks. It was then compared with EGM08 gravimetric geoid.

2. HEIGHT SYSTEM IN INDONESIA

2.1 Spirit Levelling

Indonesia has been doing spirit leveling at TTGs since the 1980s in almost every island in Indonesia, including Sulawesi Island. The spirit leveling measurement is tied to the Mean Sea Level (MSL) of each island. **Figure 2** shows the distribution of TTGs in Indonesia, which forms the national vertical control network (*Jaring Kontrol Vertikal Nasional*, JKVN). It can be seen in **Figure 2** that JKVN in Sulawesi Island is located in North Sulawesi, Central Sulawesi, South Sulawesi, and Southeast Sulawesi. JKVN in North Sulawesi is tied to MSL at Bitung tide station, JKVN in Central Sulawesi is tied to MSL at Palopo, Mamuju, and Makassar tide stations, while JKVN in Southeast Sulawesi is tied to the MSL at Kendari tide station.

By using several tide stations as tie points or reference points, the orthometric heights at TTGs are not continuous because MSL has local characteristics and is highly dependent on local bathymetry, meteorology, and oceanography. MSL can be used as a height reference if there is no disturbance. However, this condition is never met. MSL is always dynamic and affected by meteorology and oceanography condition. Therefore, in 2013, Indonesia changed its height reference from MSL to geoid.

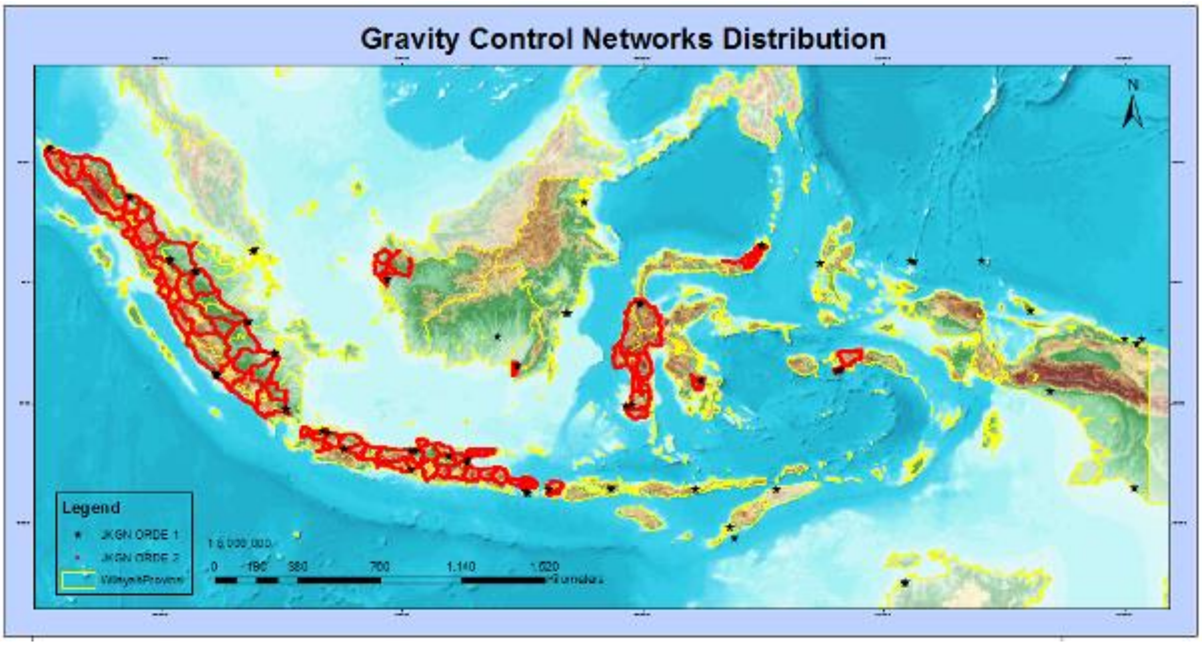


Figure 2. Gravity Control Networks Distribution from 1980 - 2009 (BIG, 2012)

2.2 Airborne Gravity Survey

To model the geoid in Indonesia, a dense gravity data in the area are required. One way to obtain such data in Indonesia in a short time is by using the airborne gravity technology. Indonesia did an airborne gravity measurement between 2008 and 2010 in Sulawesi, Kalimantan, and Papua with the total measuring time of around 750 flight hours. The equipment used in the measurement is S-99 LaCoste-Romberg airborne/marine gravimeter which was set on Cessna Caravan plane with the resolution of 0.01 mgal and accuracy at sea of 1 mgal, dual frequency geodetic GPS receivers, and land gravimeter G-956.

Figure 3 shows the flight path of airborne in Sulawesi, Kalimantan, and Papua, with the distance between each flight path of 10 nautical miles. The average velocity of the plane was 150 nautical miles/hour, or 77 m/s. The airborne gravimeter equipment measures the gravity every second, which means the equipment did the measurement every 77 m in each flight path.

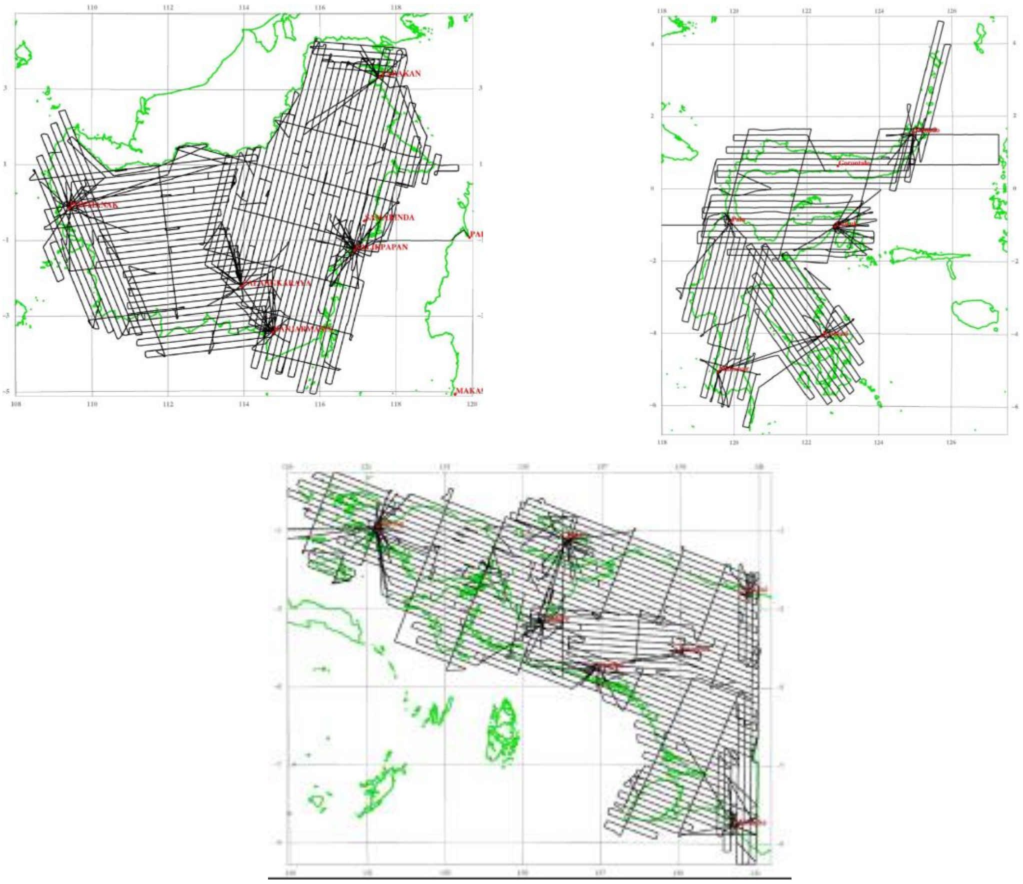


Figure 3. The flight path of airborne gravity measurement in Sulawesi, Kalimantan, and Papua

3. GRAVIMETRIC GEOID MODEL COMPUTATION METHOD

3.1 Gravimetric Geoid

Gravimetric geoid determination can be done using gravity data, either absolute or relative. Absolute method is done by determining the gravity potential value at each point on earth, while relative method is done by determining the height deviation and the geoid direction from the reference ellipsoid. Absolute method requires a solution of the complex Geodetic Boundary Value problem. Therefore, the relative method is more widely used. The relative geoid determination is shown in **Figure 4**. One arbitrary point A on the geoid is projected to point B on the reference ellipsoid. The distance AB is the undulation or geoid height (N), while the angle between the normal geoid (n) and normal ellipsoid (n') line is called the deflection of vertical (ε).

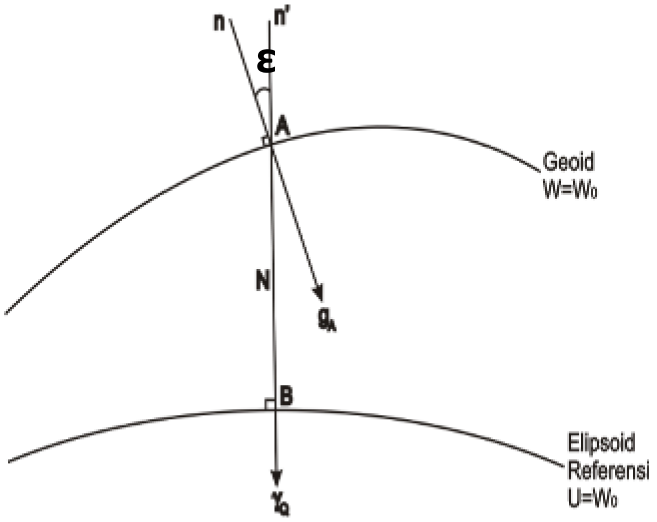


Figure 4. The relationship between the geoid and reference ellipsoid. (Heiskanen dan Moritz, 1967)

Geoid determination using gravity anomaly is defined by the Stokes formula, as follows:

$$N = \frac{R}{4\pi G} \iint_{\sigma} \Delta g . S(\Psi) d\sigma \tag{1}$$

The Stokes formula requires a well distributed gravity data and cover the whole earth to model an accurate geoid model. In reality, it is difficult to provide such data. To solve this problem, the geoid is defined by dividing the geoid signals into three components (**Figure 5**), namely (1) the long wavelength component, which contains the global information which can be derived from satellite gravimetry, (2) the medium wavelength which consists of regional information, whose data are obtained from terrestrial gravity data, and (3) the short wavelength which consists of local information which can be derived from topography model.

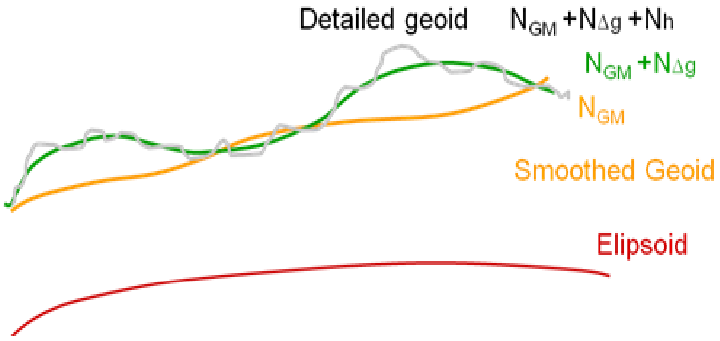


Figure 5. The three components of geoid: long wavelength (orange), medium wavelength (green), and short wavelength (grey) components.

The computation steps of the geoid model using remove-restore method are shown as follows:

1. Remove step: gravity data are subtracted with the global gravity anomaly value and surface correction to obtain the residuals of gravity anomaly.
2. Computing the residuals of geoid from the residuals of gravity anomaly can be done using several methods. This research utilized the Fast Fourier Transform (FFT).

3. Restore step: the residuals of geoid as obtained from step (2) are added with the global geoid model value and indirect effects to obtain the geoid undulation value.

The remove-restore steps are shown in equations (2) and (3):

$$Ngeoid = \Delta Nres + \Delta NGM + \Delta Nh \quad (2)$$

$$\Delta gres = \Delta gFA - \Delta gGM - \Delta gh \quad (3)$$

3.2 Geometric Geoid

To determine the geometric geoid, the geoid undulation (N) is obtained from the height difference between ellipsoid or geometric height (h) and orthometric height (H). The geometric geoid undulation can be calculated if both geometric and orthometric height at a certain point are known. The geometric geoid undulation can be computed using two methods, namely the absolute and relative methods. The absolute method is done by determining the undulation at one point using equation (6). While the relative method is done by calculating the difference of the undulations at two points (ΔN) as shown in equations (7) and (8) (Basciftci et al., 2006), and illustrated in **Figure 6**.

$$N = h - H \quad (6)$$

$$NQ = NP + (hQ - hP) - (HQ - HP) \quad (7)$$

This can be reduced to:

$$\Delta NPQ = \Delta hPQ - \Delta HPQ \quad (8)$$

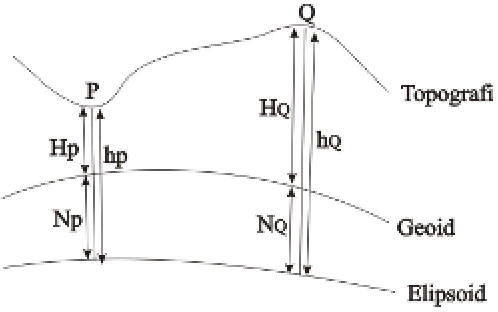


Figure 6. Geometric undulation using absolute and relative methods (modified from Basciftci et al., 2006)

In this research, the geometric geoid is used as the validator of gravimetric geoid.

3.3 Data Computation Methodology

3.3.1 <u>Case Study</u>

The case study of this research is Sulawesi Island which is located at -6.5° S until 4.5°U and 118° until 126° E. This area was chosen because the short-medium wavelength data as obtained from airborne gravity survey and the TTG are more evenly distributed that the other two islands (see **Figure 2**). The case study area can be seen in **Figure 7**.

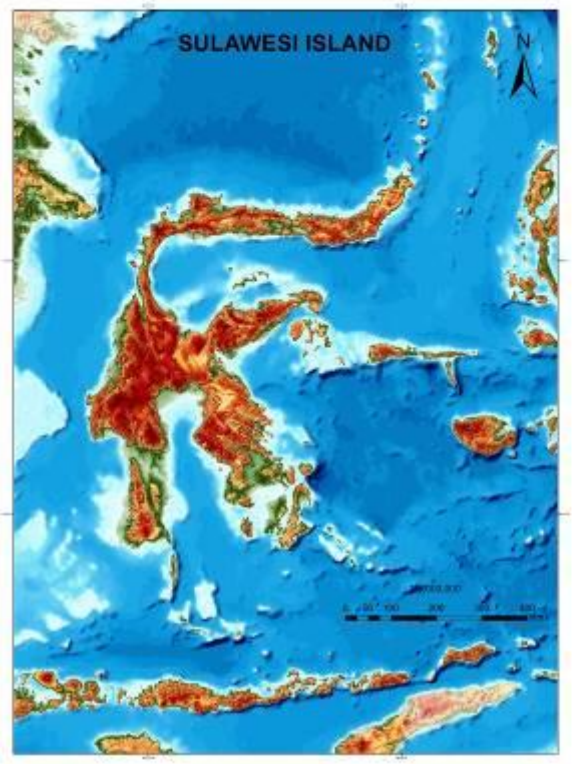


Figure 7. Case study, Sulawesi Island

3.3.2 Data and Tools

The data used in this research are Global Geopotential Model (GGM), i.e. EGM2008, which is combined with GOCE data as the long wavelength component, and the free air anomaly from the airborne gravimetric in Sulawesi Island as the short-medium wavelength component. The terrain data are corrected using SRTM30, which can be downloaded from http://topex.ucsd.edu/WWW_html/srtm30_plus.html/. SRTM is used as the short wavelength component. Those data are then processed in Gravsoft Package Software (Tscherning, 2014; Srinivas et al., 2012).

3.3.3 Geoid Modelling

The determination of gravimetric geoid model is done using the remove-restore. This consists of two computing steps, namely: processing the gravity data and geoid modelling. The first step is the processing of raw data from the airborne gravity survey (gravity and position data) to obtain the free air anomaly. The geoid modelling is computed from the free air anomaly combined with other data, i.e. the Global Geopotential Model and SRTM. This research only consists of the geoid modelling. The research scheme can be seen in **Figure 8.**

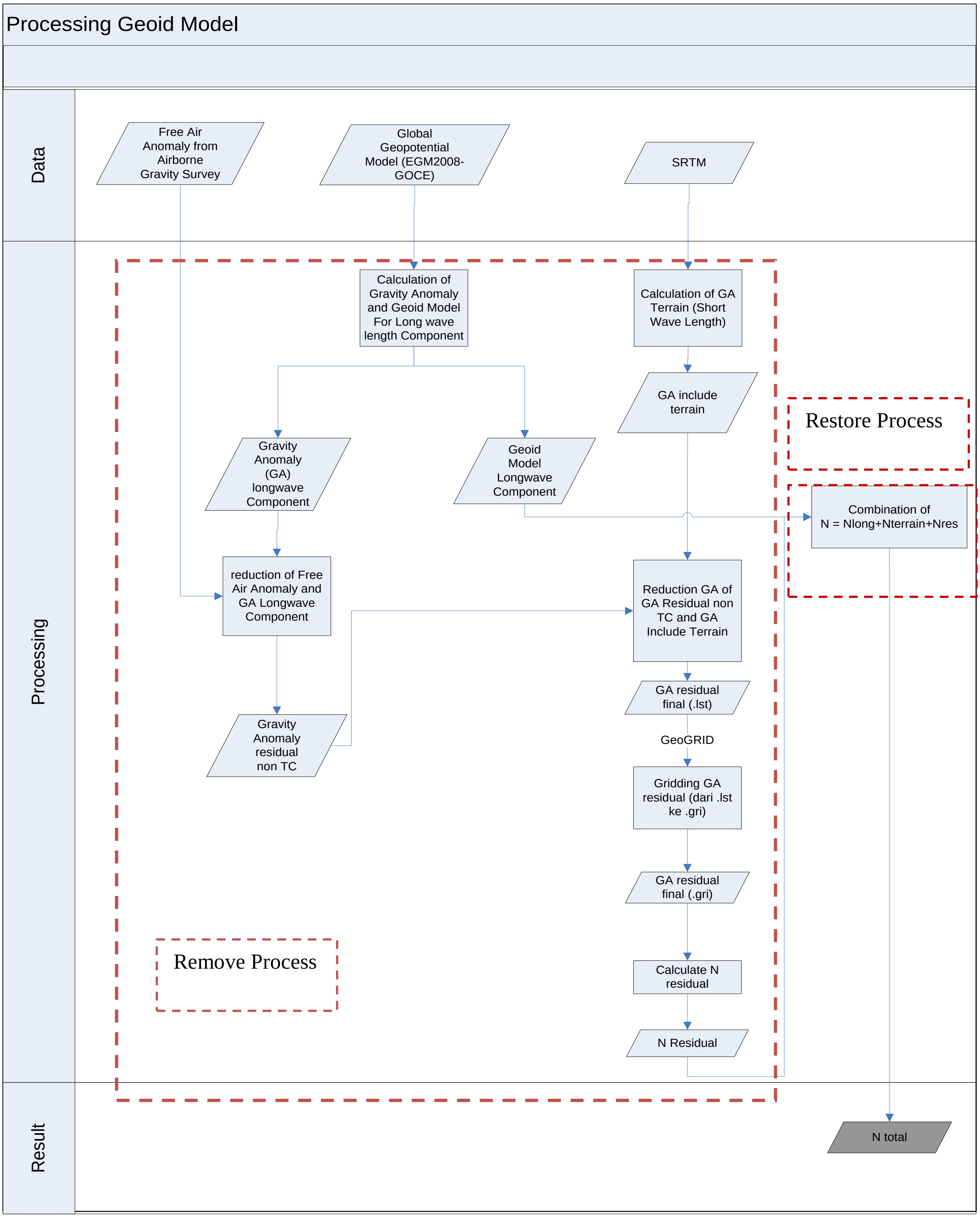


Figure 8. Processing cheme of the geoid modelling

Based on the scheme in **Figure 8**, the data processing step utilized remove-restore method.

Remove step: in this step, the gravity measurement data are subtracted with the global gravity anomaly and surface correction, resulting in the residuals of gravity anomaly. The formula used in this step is as follows:

$\Delta g_{res} = \Delta g_{FAA} - \Delta g_{GGM} - \Delta g_{Terrain}$

1. Extract the global geoid model to produce the longwave component of gravity anomaly (Δg_{GGM}).
2. Extract the SRTM data to produce short-medium wavelength component of gravity anomaly ($\Delta g_{Terrain}$).
3. Subtract the gravity anomaly from the measurement with the longwave and short-medium wavelength.
4. The result is the residuals of gravity anomaly (Δg_{res}).
5. Apply the FFT approach to the residuals of gravity anomaly to obtain the geoid residuals (ΔN_{res}).

Restore step: in this step, Geoid residuals summed with global geoid undulation and indirect effect, resulting geoid height (Undulation).

The equation is:

$N_{geoid} = \Delta N_{res} + \Delta N_{GGM} + \Delta N_{terrain}$

1. Global geoid undulation from extraction of global geoid model (ΔN_{GGM}).
2. Indirect effect from the extraction of SRTM data, resulting geoid terrain ($\Delta N_{terrain}$).
3. Sum three components, namely geoid residuals, global geoid undulation and geoid terrain (indirect effect).
4. Resulting the total of geoid height (N_{geoid}).

3.3.4 Geoid Validation

The purpose of geoid validation is to test the accuracy of the resulting geoid model. This was done by subtracting the total value of geoid (gravimetric geoid), as obtained from the previous step, with the geometric geoid from GNSS-Leveling measurements. The difference between the geoid value of EGM2008, as the comparator, and the geometric geoid from GNSS-Leveling measurement was calculated. The scheme for the gravimetric geoid validation can be seen in **Figure 9**.

The vertical benchmarks used in the validation were measured in 2010 and 2013 by the Geospatial Information Agency. As many as 54 points were used to validate the geoid, which consists of TTGs and tide station benchmarks, which were distributed in South Sulawesi, Cental Sulawesi, and a few in North Sulawesi, as seen in **Figure 10**.

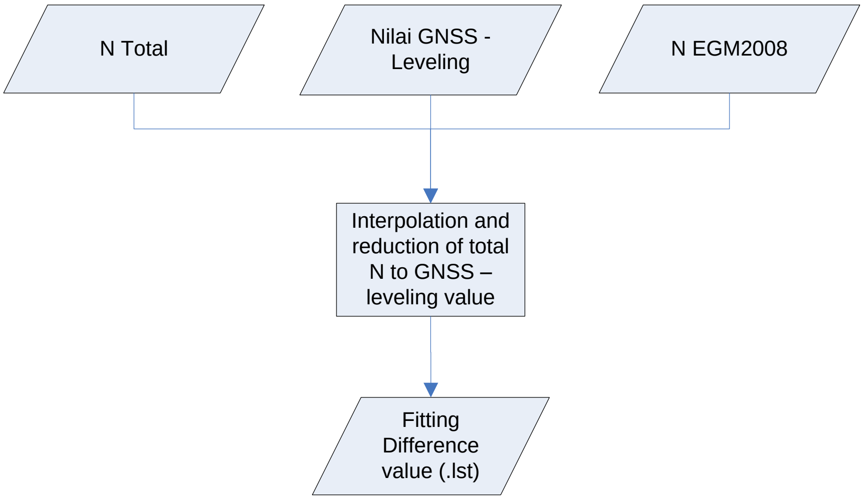


Figure 9. The scheme of gravimetric geoid validation

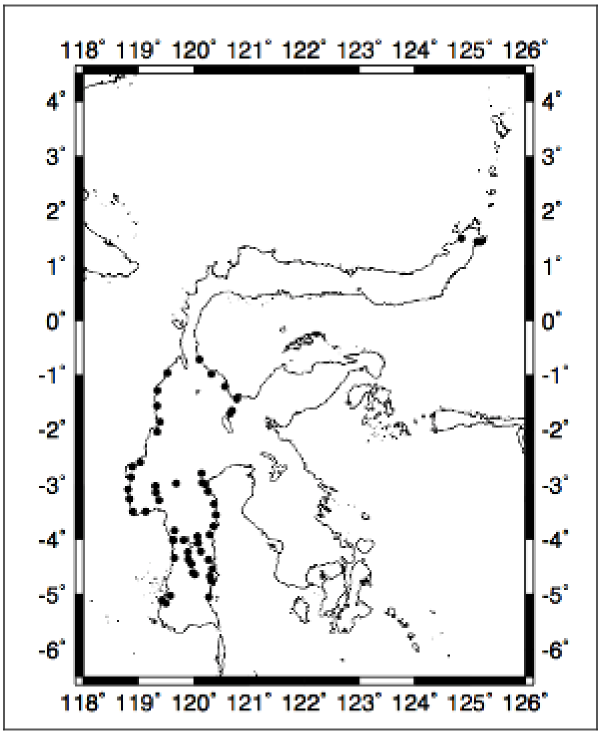


Figure 10. The distribution of geoid validation points in Sulawesi

4. RESULT AND ANALYSIS

The gravity anomaly residuals, in this case Free Air Anomaly (FAA) residuals, can be seen in **Figure 11**.

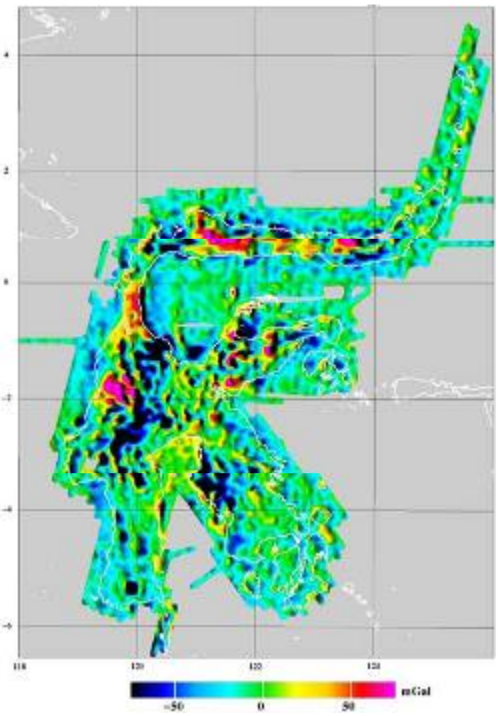


Figure 11. FAA Residuals

Figure 11 shows the FAA deficiency against the global model EGM08 by -60 mgal to 60 mgal. This means that the FAA signals in that range cannot be detected if using only the global model. Therefore, the global model is not capable to detect the small variations in the geoid as seen in **Figure 12**, where the geoid deficiency against the global model EGM08 by -1 meter to 1 meter in Sulawesi.

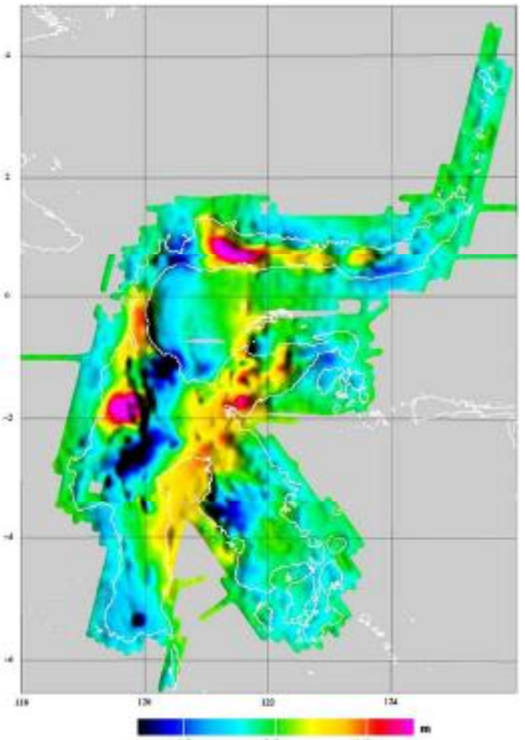


Figure 12. The geoid residuals in Sulawesi

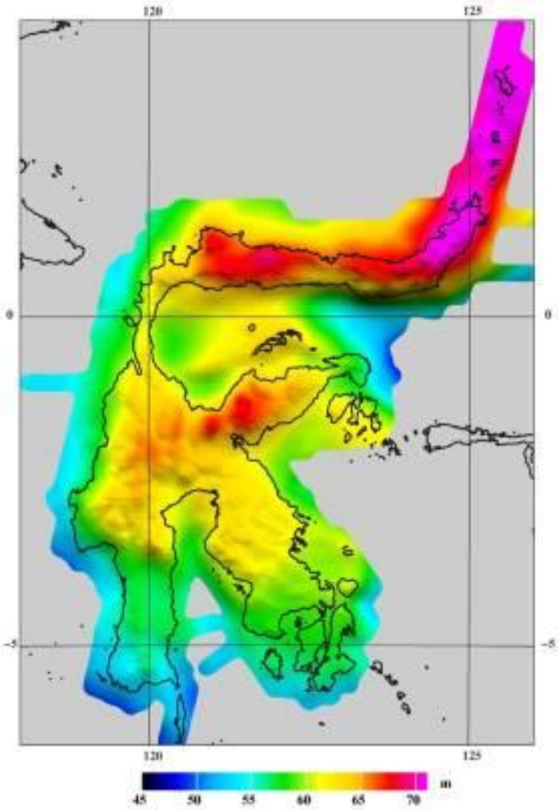
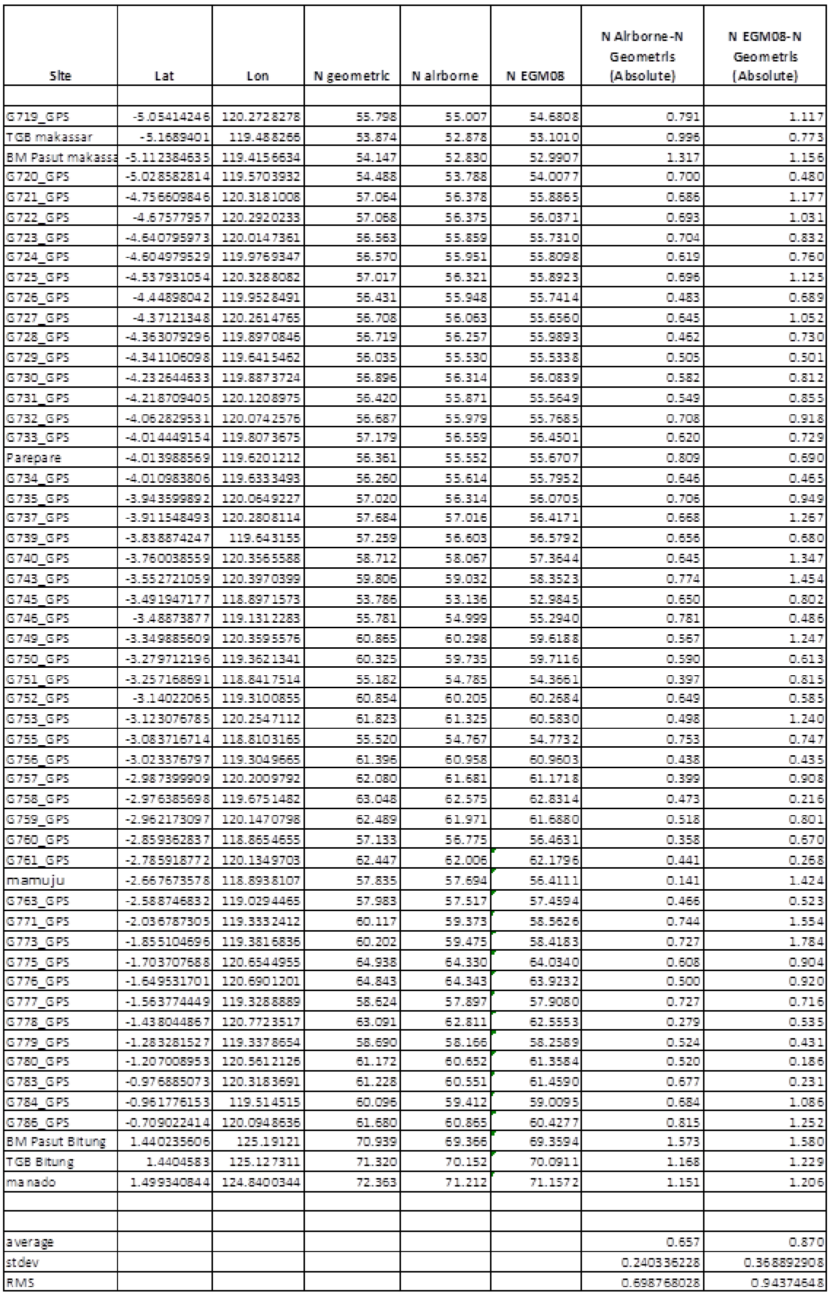


Figure 13. Gravimetric geoid model of Sulawesi

Figure 13 shows the gravimetric geoid model of Sulawesi. The pattern of geoid in Sulawesi is that the value of the geoid increases from sothwest to northeast, with the geoid height range between 45-80 meter.

To test the accuracy of the resulting geoid model, the geoid validation was done by comparing the difference between geometric geoid and gravimetric geoid against the airborne gravity measurements and EGM08. The validation result can be seen in **Table 1**.

Table 1. Comparison of the difference of geometric N and gravimetric N between the airborne gravity result and EGM08



Site	Lat	Lon	N geometric	N airborne	N EGM08	N Airborne-N Geometris (Absolute)	N EGM08-N Geometris (Absolute)
G719_GPS	-5.05414246	120.2728278	55.798	55.007	54.6808	0.791	1.117
TGB makassar	-5.1689401	119.488266	53.874	52.878	53.1010	0.996	0.773
BM Pasut makassa	-5.112384635	119.4156634	54.147	52.830	52.9907	1.317	1.156
G720_GPS	-5.028582814	119.5703932	54.488	53.788	54.0077	0.700	0.480
G721_GPS	-4.756609846	120.3181008	57.064	56.378	55.8865	0.686	1.177
G722_GPS	-4.67577957	120.2920233	57.068	56.375	56.0371	0.693	1.031
G723_GPS	-4.640795973	120.0147361	56.563	55.859	55.7310	0.704	0.832
G724_GPS	-4.604979529	119.9769347	56.570	55.951	55.8098	0.619	0.760
G725_GPS	-4.537931054	120.3288082	57.017	56.321	55.8923	0.696	1.125
G726_GPS	-4.44898042	119.9528491	56.431	55.948	55.7414	0.483	0.689
G727_GPS	-4.37121348	120.2614765	56.708	56.063	55.6560	0.645	1.052
G728_GPS	-4.363079296	119.8970846	56.719	56.257	55.9893	0.462	0.730
G729_GPS	-4.341106098	119.6415462	56.035	55.530	55.5338	0.505	0.501
G730_GPS	-4.232644633	119.8873724	56.896	56.314	56.0839	0.582	0.812
G731_GPS	-4.218709405	120.1208975	56.420	55.871	55.5649	0.549	0.855
G732_GPS	-4.062829531	120.0742576	56.687	55.979	55.7685	0.708	0.918
G733_GPS	-4.014449154	119.8073675	57.179	56.559	56.4501	0.620	0.729
Parepare	-4.013988569	119.6201212	56.361	55.552	55.6707	0.809	0.690
G734_GPS	-4.010983806	119.6333493	56.260	55.614	55.7952	0.646	0.465
G735_GPS	-3.943599892	120.0649227	57.020	56.314	56.0705	0.706	0.949
G737_GPS	-3.911548493	120.2808114	57.684	57.016	56.4171	0.668	1.267
G739_GPS	-3.838874247	119.643155	57.259	56.603	56.5792	0.656	0.680
G740_GPS	-3.760038559	120.3565588	58.712	58.067	57.3644	0.645	1.347
G743_GPS	-3.552721059	120.3970399	59.806	59.032	58.3523	0.774	1.454
G745_GPS	-3.491947177	118.8971573	53.786	53.136	52.9845	0.650	0.802
G746_GPS	-3.48873877	119.1312283	55.781	54.999	55.2940	0.781	0.486
G749_GPS	-3.349885609	120.3595576	60.865	60.298	59.6188	0.567	1.247
G750_GPS	-3.279712196	119.3621341	60.325	59.735	59.7116	0.590	0.613
G751_GPS	-3.257168691	118.8417514	55.182	54.785	54.3661	0.397	0.815
G752_GPS	-3.14022065	119.3100855	60.854	60.205	60.2684	0.649	0.585
G753_GPS	-3.123076785	120.2547112	61.823	61.325	60.5830	0.498	1.240
G755_GPS	-3.083716714	118.8103165	55.520	54.767	54.7732	0.753	0.747
G756_GPS	-3.023376797	119.3049665	61.396	60.958	60.9603	0.438	0.435
G757_GPS	-2.987399909	120.2009792	62.080	61.681	61.1718	0.399	0.908
G758_GPS	-2.976385698	119.6751482	63.048	62.575	62.8314	0.473	0.216
G759_GPS	-2.962173097	120.1470798	62.489	61.971	61.6880	0.518	0.801
G760_GPS	-2.859362837	118.8654655	57.133	56.775	56.4631	0.358	0.670
G761_GPS	-2.785918772	120.1349703	62.447	62.006	62.1796	0.441	0.268
mamuju	-2.667673578	118.8938107	57.835	57.694	56.4111	0.141	1.424
G763_GPS	-2.588746832	119.0294465	57.983	57.517	57.4594	0.466	0.523
G771_GPS	-2.036787305	119.3332412	60.117	59.373	58.5626	0.744	1.554
G773_GPS	-1.855104696	119.3816836	60.202	59.475	58.4183	0.727	1.784
G775_GPS	-1.703707688	120.6544955	64.938	64.330	64.0340	0.608	0.904
G776_GPS	-1.649531701	120.6901201	64.843	64.343	63.9232	0.500	0.920
G777_GPS	-1.563774449	119.3288889	58.624	57.897	57.9080	0.727	0.716
G778_GPS	-1.438044867	120.7723517	63.091	62.811	62.5553	0.279	0.535
G779_GPS	-1.283281527	119.3378654	58.690	58.166	58.2589	0.524	0.431
G780_GPS	-1.207008953	120.5612126	61.172	60.652	61.3584	0.520	0.186
G783_GPS	-0.976885073	120.3183691	61.228	60.551	61.4590	0.677	0.231
G784_GPS	-0.961776153	119.514515	60.096	59.412	59.0095	0.684	1.086
G786_GPS	-0.709022414	120.0948636	61.680	60.865	60.4277	0.815	1.252
BM Pasut Bitung	1.440235606	125.19121	70.939	69.366	69.3594	1.573	1.580
TGB Bitung	1.4404583	125.127311	71.320	70.152	70.0911	1.168	1.229
manado	1.499340844	124.8400344	72.363	71.212	71.1572	1.151	1.206
average						0.657	0.870
stdev						0.240336228	0.368892908
RMS						0.698768028	0.94374648

Table 1 shows that the geoid model from airborne gravity measurement has better quality

than the EGM08 model. This can be seen from the value of standard deviation of both models. The value of geoid standard deviation from airborne gravity result is smaller than that from EGM08. The accuracy of the geoid model from airborne gravity measurement is 69 cm, while the EGM08 geoid model has the accuracy of 94 cm.

The individual accuracy of the geoid from the measurement in Sulawesi dan be seen in **Table 2**.

Table 2. Comparison of airborne gravity N and EGM08 N partially

Statistic	N Airborne-N Geometric	N EGM08-N Geometric
	South Sulawesi	**South Sulawesi**
Average	0.66606367	0.865454579
Stdev	0.16821467	0.279395187
RMS	0.686352336	0.908134238
	Central Sulawesi	**Central Sulawesi**
Average	0.49514	0.764666667
Stdev	0.166689312	0.524247735
RMS	0.520669369	0.917185052
	North Sulawesi	**North Sulawesi**
Average	1.011360835	1.020377502
Stdev	0.351501671	0.634774851
RMS	1.061042849	1.173436338

The geoid model from airborne gravity measurement in Central Sulawesi has better accuracy than North and South Sulawesi. This can be seen from the the variation of the difference between geometric geoid and gravimetric geoid. The difference is smaller for Central Sulawesi than North and South Sulawesi, with the RMS value of 52 cm. The gravimetric geoid from airborne gravity measurement can improve the accuracy of global geoid model EGM 2008 by 22 cm in South Sulawesi, 39 cm in Central Sulawesi, and 11 cm in North Sulawesi. While for the island as a whole, the gravimetric geoid from airborne gravity measurement can improve the accuracy of EGM 2008 by 25 cm.

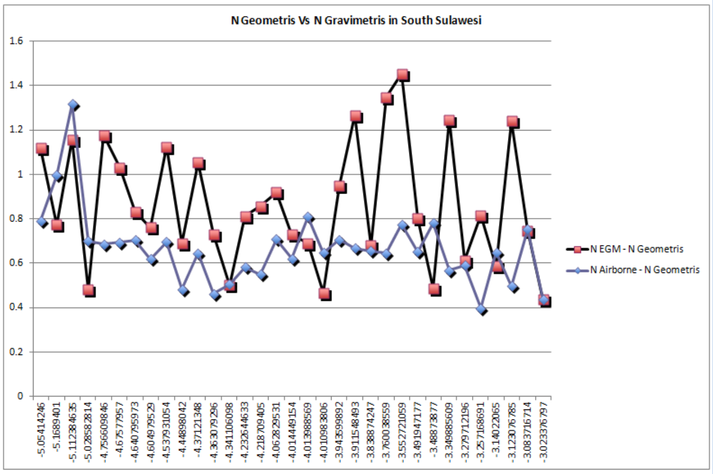


Figure 14. The difference between geometric N and gravimetric N in South Sulawesi

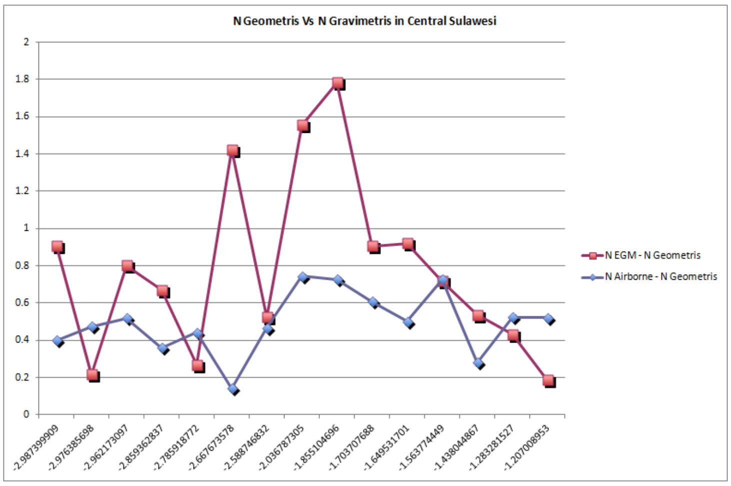


Figure 15. The difference between geometric N and gravimetric N in Central Sulawesi

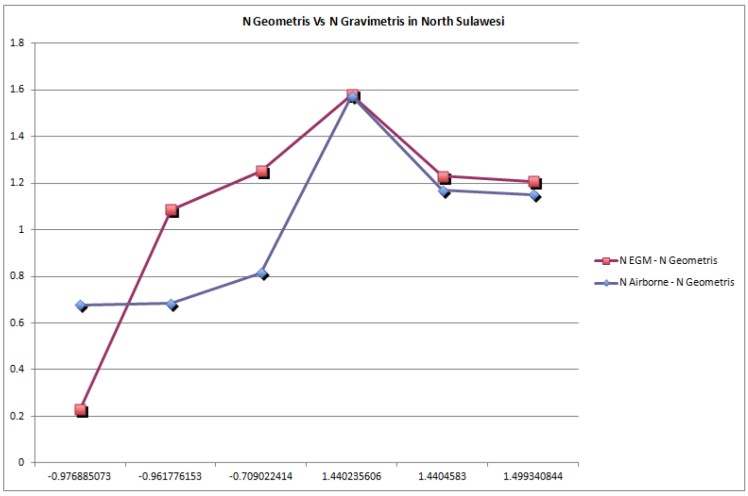


Figure 16. The difference between geometric N and gravimetric N in North Sulawesi

Based on **Figures 14**, **15**, and **16**, the geoid model from airborne gravity measurement has better consistency, as can be seen from the undulation difference. The variation in undulation difference between gravimetric geoid from airborne gravity measurement and geometric geoid in South Sulawesi is around 0.397 until 1.317 meter, while the difference between the EGM2008 geoid model and geometric geoid is around 0.435 until 1.454 meter. The result is better in Central Sulawesi, where the undulation difference between gravimetric geoid from airborne gravity measurement and geometric geoid is around 0.141 until 0.744 meter, while the difference between EGM2008 geoid model with geometric geoid is around 0.186 and 1.784 meter. In North Sulawesi, the undulation difference between gravimetric geoid from airborne gravity measurement and geometric geoid is around 0.677 until 1.573 meter, while the difference between EGM2008 geoid model and geometric geoid is around 0.231 until 1.580 meter.

5. CONCLUSIONS

This reseach aims at developing the gravimetric geoid model of Sulawesi Island based on airborne gravity survey. The remove-restore model was used to determine the gravimetric geoid model. The standard deviation of the resulting model from airborne gravity data is better than the global geoid model (EGM2008). Therefore, the utilization of airborne gravity for the determination of gravimetric geoid model in Indonesia is very beneficial, because this survey allows a faster determination of Indonesian geoid model with a high accuracy, improving the precision of global geoid model, namely the EGM2008, by 25 cm in Sulawesi Island.

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