Evaluation of GOCE's Global Geopotential Model to The Accuration of Local Geoid (Case Study: Java Island, Indonesia)

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Key words: GOCE GGM, Local Geoid, Java Island-Indonesia

SUMMARY

Precise local geoid determination requires three geoid components, namely short-wavelength, medium-wavelength, and long-wavelength components. The short-wave component is obtained from the digital terrain data (DTM). The medium-wave component is derived from terrestrial gravity data and the long-wave component is obtained from the global geopotential model (GGM) data. The GGM is generated from gravity satellites data, including GOCE (Gravity field and steady-state Ocean Circulation Explorer). Currently, there are several GOCE GGMs with various degree of variation ranging from 210 to 250. However, existing of GOCE GGMs have not been evaluated in a local geoid modelling in Indonesia. Therefore, the objective of this the study is to evaluate the effect of the accuracy level of the GOCE GGM to the local gravimetrics geoid determination in Indonesia with a case study on the Island of Java. The utilized-GOCE GGM included three approaches, namely DIR (direct approach), TIM (time-wise approach) and SPW (space-wise approach). The utilized-GOCE GGMs are DIR-R2, SPW-R1, SPW-R2, TIM-R2, and TIM-R3. The gravimetric geoid modelling used the Remove Compute Restore (RCR) method with 2D Fast Fourier Transformation (2D-FFT) approach. The accuracy of the local geoid model was controlled by 49 co-located GPS/levelling points. The results showed the model that produces the highest accuracy of local geoid is SPW-R1 with a mean differences value of 0,644 meters compared with the GPS/levelling data. Meanwhile the local geoid with the lowest accuracy of the models generated by TIM-R3 had a value of 0,703 meters. These mean difference values mainly could be due to inconsistency of the utilized-height reference system between the local geoid model and the GPS/levelling data.

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1. INTRODUCTION

The development Global Navigation Satellite System (GNSS) technology, particularly Global Positioning System (GPS) causes the positioning system on the earth's surface becomes more accurate, easy, and inexpensive. These characteristics lead to the broad and varied increase in the number of application and use of GPS/GNSS. However, the positioning using the GPS/GNSS can not be optimized. GPS/GNSS generate geometric height that is referenced to the ellipsoid surface of the earth so that it does not show the true physical realization and therefore can not be used for practical purposes. Transformation of geometric height into orthometric height having physical realization requires geoid data. Undulation or geoid height can be modelled by two methods, namely geometric and gravimetric method. Geoid modelling geometrically obtained from measurement of co-site GPS/levelling, while gravimetric geoid modelling needs three components, namely short-wave, medium-wave, and long-wave component. Short-wave component represent the condition of terrain area. Shuttle Radar Topographic Mission (SRTM) data are often used to represent a short-wave component. Medium-wave component is obtained from terrestrial gravity data. Long-wave component is obtained from the global geopotenstial models (GGMs). The GGM are generated from gravity satellites data such as CHAMP (Challeging Mini-satellite Payload), GRACE (Gravity and Climate Experiment recovey), and GOCE (Gravity field and steady-state Ocean Circulation Explorer).

Several studies have been conducted to evaluate the accuracy of local geoid, among others, in Brazil (Guimarães et al., 2012), Donana national park of Spain (Nunez et al., 2008), Dronning Maud Land of East Antartica (Müller et al., 2007), Turkey (Erol and Nurhan, 2004), Australia (Featherstone et al., 2001), and Korean peninsula (Yun, 1999). The studies address several issues related to the accuracy of local geoid, such as modelling approaches, a combination of data, as well as the GGM and the best value of degree that can be used. Local geoid modelling approaches can use the Fast Fourier Transformation (FFT) approach or least-square collocation (LSC). One factor to be considered in the selection of the approaches is the availability of terrestrial gravity data. The study has been done on the Korean Peninsula (Yun, 1999), Poland (Łyszkowicz, 2010), and Egypt (Abd-Elmotaal, 2011) showed that the LSC produce better internal accuracy than the FFT approach. However, for local geoid modelling with a limited amount of terrestrial gravity data, FFT approach produces better external accuracy. For the study area of Poland and Egypt, FFT approach generates standard deviation between 0,027 and 0,035 meters, while using the LSC approach, results in a standard deviation of between 0,022 and 0,032 meters. The combination of terrestrial data with the airborne gravity data was also evaluated to determine its effect on the local geoid accuracy (Müller et al., 2007). Futher, the effect of SRTM data has been examined to determine the level contribution and reliability of local geoid modelling (Liu, 2008, Kiamehr and Sjöberg, 2005). EGM2008 with maximum degree of 2.190 is commonly GGM used in modelling the geoid locally as predicted to produce high accuracy. The use EGM2008 in local geoid modelling in Indonesia showed that the resulting local geoid accuracy of 0,441 meters (Ramdani, 2008). This value is better than the use of EGM1996 which produces accuracy value of 0,955 meters (Ramdani, 2008).

Currently, several GGMs were generated from GOCE which are expected to improve the accuracy of local geoid models. GOCE satellite became the first mission for ESA's Living Planet program (Drinkwater et al., 2006), with the purpose of the mission was to obtain data such as gravity gradient of global and local models of microgravity on earth that can accurately modelling the geoid and has a high degree of spatial resolution. GOCE satellite is expected to obtain an accuracy of 1 mgal for gravity anomaly and 2 cm for geoid on the scale of 100 km. GOCE GGM was developed through three different approaches, namely direct-approach (DIR), time-wise approach (TIM), and space-wise approach (SPW) (Pail et al., 2011). Each approach has a degree value that varies between 210 to 250. Nevertheless, the influence of GOCE GGM to the accuracy of local geoid modelling in Indonesia has not been evaluated. Therefore, the study is aimed to evaluate the effect of the GOCE GGM to the accuracy of local geoid in Indonesia, with case study on the Island of Java. The local geoid modeling was done by a combination of terrestrial gravity data, SRTM30*plus* data, and GOCE GGMs. The method used for geoid modelling is remove compute restore (RCR) with 2D FFT approach. The accuracy of resulted gravimetric geoid was tested using the co-site GPS/levelling data.

2. THE THEORY OF LOCAL GEOID MODELLING

Gravimetric geoid

Gravimetric geoid determination is performed using two basic formulas, namely Brun's formula and Stokes function. Brun's formula expresses the relation between potential anomalies (T) and undulation (N). Equation 1 shows Brun's formula.

$$N = \frac{T}{\gamma} \qquad (1)$$

Here, T is potential anomalies and γ is normal gravity. Stokes determined potential anomalies (T) as a function of gravity anomaly (Δg). Potential anomalies according to Stokes are indicated in Equation 2 (Heiskanen and Moritz, 1967).

$$T = \frac{R}{4\pi} \iint_{\sigma} \Delta g \, S(\psi) d\sigma \qquad (2)$$

Δg is gravity anomaly and R is the radius of the earth (≈ 6.371 km). The value of $S(\psi)$ can be determined using Equation 3.

$$S(\psi) = \frac{1}{\sin\left(\frac{\psi}{2}\right)} - 6 \sin\frac{\psi}{2} + 1 - 5\cos\psi - 3\cos\psi \, \ln\left(\sin\frac{\psi}{2} + \sin^2\frac{\psi}{2}\right) \qquad (3)$$

ψ is spherical distance between elements of $d\sigma$ with the point of potential anomalies.

Substitution of Equation 2 into Equation 1 generates Stokes function as shown in Equation 4.

$$N = \frac{R}{4\pi\gamma} \iint_{\sigma} \Delta g\, S(\psi) d\sigma \tag{4}$$

Remove Compute Restore (RCR)

Geoid determination can be done using the remove compute restore (RCR) method (Serpas and Jekeli, 2005, Ågren and Sjöberg, 2004). The basic principle of this method is divided into two steps, ie. remove and restore. Remove step eliminate the contribution of GGM and terrain contribution, whereas at the restore step both components reused. One reason for subtracting GGM contribution is to represent the gravity field outside the area covered with data (Yildiz et al., 2011). Equation 5 shows the remove step, while Equation 6 shows the restore step (Sjöberg, 2005).

$$\Delta g = \Delta g_{FA} - \Delta g_{GM} - \Delta g_{H} \tag{5}$$

$$N = N_{GM} + \Delta N_{res} + N_{H} \tag{6}$$

Δg_{FA} is a medium-wave component generated from terrestrial gravity data. Δg_{H} is a contribution of short-wave component that was generated from the terrain contribution which is a terrain correction. Δg_{GM} is the contribution of the long-wave component or the GGM.

2D Fast Fourier Transformation (2D-FFT)

In principle, determining undulation by using Stoke's formula applied to gravity field quantities at the geoid. The evaluation of Stokes'formula can be done using Fast Fourier Transformation (FFT), such a 2D spherical FFT (Yildiz et al., 2011). FFT is an algorithm used for converting residual gravity anomalies into residual geoid undulation and calculating the contribution terrain. The FFT offers a very practical way to compute detailed terrain correction on a cintinent-wide scale (Featherstone et al., 2001). Equation 2D-FFT method get the undulation by Stoke's formula can be in the form of a grid or frequency. Equation 7 shows the FFT in the form of a grid, while Equation 8 shows the similarities in frequency.

$$\mathrm{Ngra}\ (\varphi, \lambda) = \frac{R\Delta\varphi\Delta\lambda}{4\pi\gamma} \sum_{i=1}^{M} \sum_{i=1}^{N} S(\psi)\Delta g(\varphi i, \lambda i) \cos \varphi i \tag{7}$$

$$\mathrm{Ngra}\ (\varphi, \lambda) = \frac{R\Delta\varphi\Delta\lambda}{4\pi\gamma} F^{-1}\{F[S(\psi)][F[\Delta g(\varphi i, \lambda i) \cos \varphi i]]\} \tag{8}$$

Here, M express the sum of grid parallel, while N is the sum of grid meridian. φ and λ show the geodetic position of the point and Δφ dan Δλ is the space both of them.

Contribution of global geopotential model (GGM)

Global geopotential model (GGM) can be used as a long-wave component on local geoid modelling. There are two contributions of GGM, i.e. the anomaly and undulation of GGM. Each of them can be determined by Equation 9 and Equation 10 (Wellenhof and Moritz, 2005).

$$\Delta g_{GM} = G \sum_{n=2}^{n_{\max}} (n-1) \sum_{m=0}^{n} [C_{nm} \cos m\lambda + S_{nm} \sin m\lambda]\ P_{nm}(\sin\varphi) \tag{9}$$

$$N_{GM} = R \sum_{n=2}^{n_{\max}} \sum_{m=0}^{n} [C_{nm} \cos m\lambda + S_{nm} \sin m\lambda]\, P_{nm}(\sin\varphi) \qquad (10)$$

Here, G is the earth gravitational constants (6,67 x 10^{-11} Nm^2/kg^2), R is the radius of the earth (≈ 6.371 km), Pnm is constants associated with the full Legendre functions, Cnm and Snm is the spherical harmonic fully normalized, while n and m express the value of degree and orde.

3. THE METHODOLOGY

Case study: Island of Java, Indonesia

The study was conducted in Java Island with boundaries area between 5°30' S up to 9° S and 105° E up to 115° E. The selection of study area was based on the availability of terestrial free-air gravity data as well as the co-located GPS/leveling data which is quite adequate compared to other regions in Indonesia. Figure 1 shows the variation of topography surface in Java Island. The elevation range on the whole area is significant for about 0 meter up to > 2.000 meters. The significant elevation range can be found on the regions that contain several mountains like West Java and East Java regions. There are series of active-volcano in Java Island, such as Merapi, Semeru, Bromo, and Papandayan mountain. Most of them are distributed on the southern area of Java Island. In the others, northern area of Java Island relatively flat which means there are no significant topographic objects.

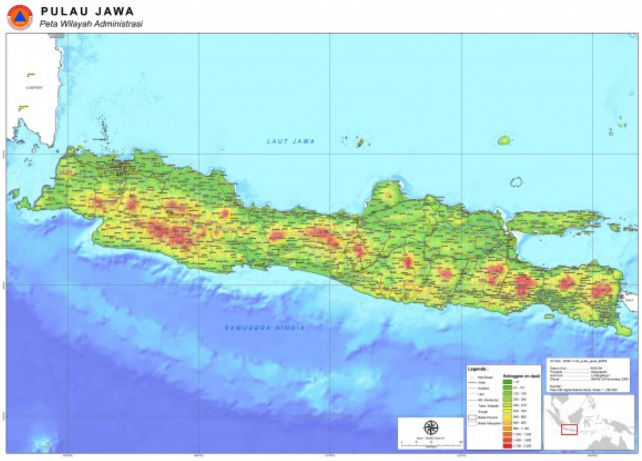

Figure 1. Case study: Island of Java, Indonesia
Source: www.geospasial.bnpb.go.id

Tools and data

Data processing has be done using Gravsoft packages software (Tscherning, 2014, Srinivas et al., 2012). The data used in the study consisted of four data, including free-air gravity anomaly data, 49 co-located GPS/levelling points, five GOCE GGMs, and SRTM30*plus*. The Gravity data obtained from The National Gravity Committee and research funded by The Ministry of Research and Technology, Directorate General of Higher Education, and also cooperation between Gadjah Mada University and Pertamina Corporation. Figure 2 shows the distribution of the gravity data which consists of 11.343 data. The co-located GPS/levelling are the secondary data that was published by the Geospatial Information Agency. The distribution of the most reliable co-located GPS/levelling stations with known geometric undulation is shown in Figure 3. Five GOCE GGMs are available to be downloaded at http://icgem.gfz-postdam.de/ICGEM/. Table 1 describes all of GOCE GGM that used in this study. SRTM30*plus* data was downloaded at http://topex.ucsd.edu/WWW_html/srtm30_plus.html/. The number of SRTM data for case study area consists of 532.800 data includes water area.

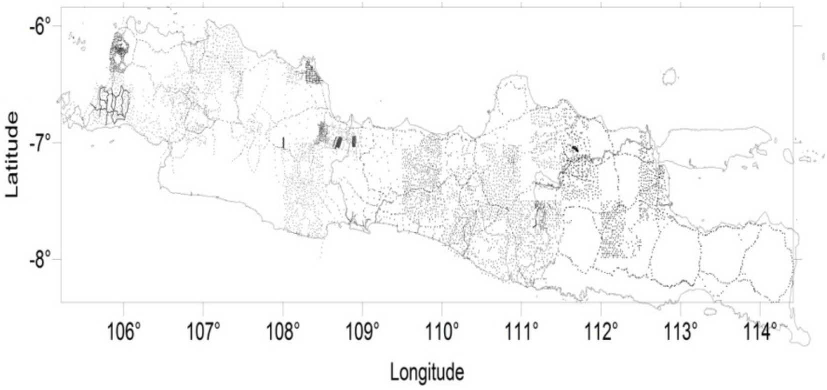

Figure 2. The distribution of free-air gravity anomaly in Java Island

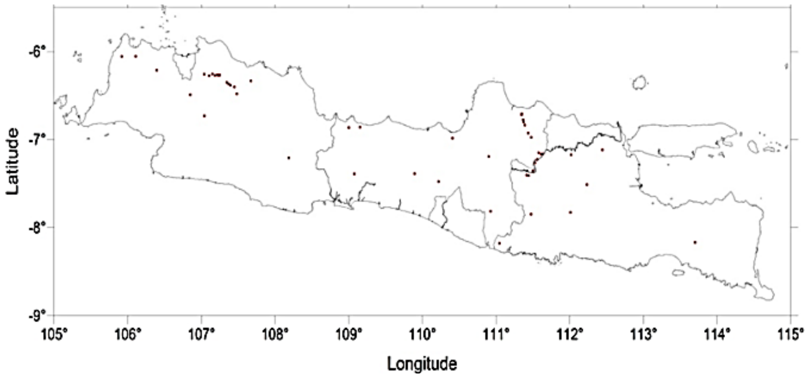

Figure 3. The distribution of 49 co-located GPS/levelling points in Java Island

Table 1. Description of GOCE GGMs used in the study
Source: http://icgem.gfz-potsdam.de/ICGEM/

Model	**Year**	**Degree**	**Data**	**References**
DIR-R2	2011	240	S(GOCE)	Bruinsma et al.,2011
TIM-R3	2011	250	S(GOCE)	Pail et al.,2011
SPW-R2	2011	240	S(GOCE)	Migliaccio et al.,2011
TIM-R2	2011	250	S(GOCE)	Pail et al.,2010a
SPW-R1	2010	210	S(GOCE)	Migliaccio et al.,2010

Note: S is Satellite

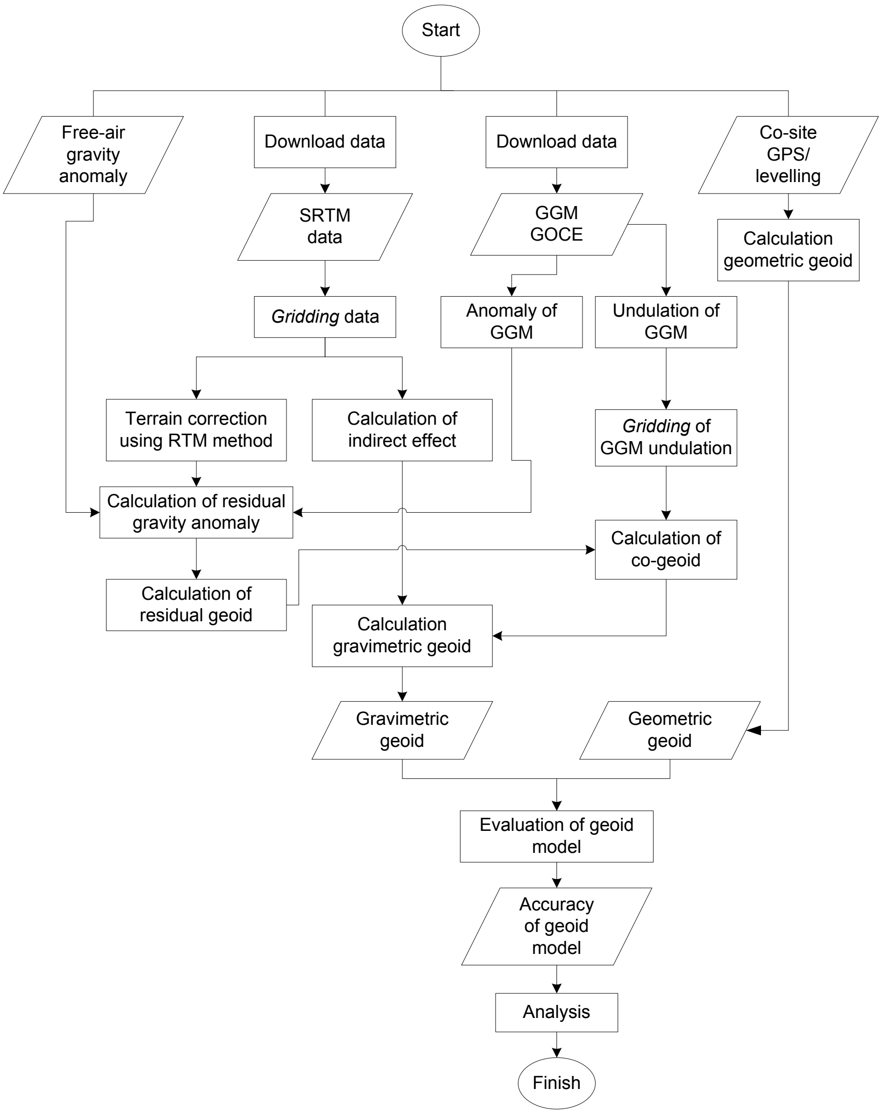

Figure 4. Flow chart of the study

Local geoid modelling

Local geoid modelling involves three steps, that are calculation of the contribution of GGM, calculation of the contribution of terrain, and modelling of the gravimetric geoid. Figure 4 shows the flow chart of the study. The GGM contributions, anomaly and undulation of GGM are calculated in gridding system with an interval of 1’30”. Calculation of the terrain contribution using the SRTM data, consists of terrain correction and the indirect effect. Terrain correction was computed using Residual Terrain Model (RTM) method that requires three surfaces, those are: detailed surface, coarse surface, and reference surface, with the grid interval of 1’30”, 3’, and 15’, respectively. Remove step substracts the value of gravity anomalies with GGM’s anomaly and terrain correction. This step gives the residual gravity that was for calculation of residual geoid using 2D-FFT approach. Due to the limitation of data, interpolation of residual geoid data to cover whole area is needed. Interpolation method that used in the study is kriging interpolation. However, others interpolation can be used such an inverse distance weighting (IDM) interpolation (Erol and Çelik, 2004). Restore step adds the residual geoid with GGM's undulation resulting co-geoid model. To obtain a gravimetric geoid, the co-geoid must be added with the indirect effect value. Evaluation of the best GOCE model for local geoid modelling in Java Island was done by comparing the value of the geoid model with the co-located GPS/levelling. The mean difference between gravimetric and GPS/levelling data shows the accuracy of the local geoid models. The smaller mean difference value of the local geoid model derived with different GOCE GGM shown the rigorous geoid model increase.

4. RESULTS

There are three main results will be presented which include the contribution of GOCE GGMs, local geoid of Java Island, and the results of the evaluation of Java local geoid.

Gravity Anomaly of GOCE GGMs

The statistical summary of the gravity anomaly GOCE GGMs can be seen in Table 2. The value of GOCE GGMs gravity anomaly over the Java island range from minimal -126,25 mgal obtain from the SPW-R2 model and maximal value of 205,97 mgal from the DIR-R2 model. The range between the minimum and maximum values start from 307,18 mgal until 344,46 mgal. While the mean value of the model start between 40,043 mgal to 41,449 mgal. There are no any increase of range and mean values in accordance with increasing in degree and orde. However, the two SPM models have lower range and higher mean values compare with the TIM and DIR models. The DIR-R2, the model with highest range anomaly, has detailer patterns of the anomaly countur compare to the others models.

Table 2. The results of GOCE GGMs anomaly

Model	Degree	Min. (mgal)	Max. (mgal)	Mean (mgal)	Range (mgal)
DIR-R2	240	-138,49	205,97	40,043	344,46
SPW-R1	250	-130,65	185,90	41,449	316,55
SPW-R2	240	-126,25	180,93	40,847	307,18
TIM-R2	224	-139,04	198,51	40,233	337,55
TIM-R3	210	-137,48	202,35	40,347	339,83

To be able to indicate the effect of GGMs degree to the anomaly value over the Java island, the difference value of the highest (TIM-R3) and the lowest (SPW-R1) degree GGM has been calculated and shown in Figure 5. as can be seen in figure 3 that the pattern of differences have distributed randomly. The difference values ranged from -28 to 30 mgal, with a maximum positive difference values occurs in the mountainous region in the southern part of Java island. It is also indicated that the anomaly countur patterns generated by GOCE GGM is correlated with the patterns of surface topographic (Figure 1).

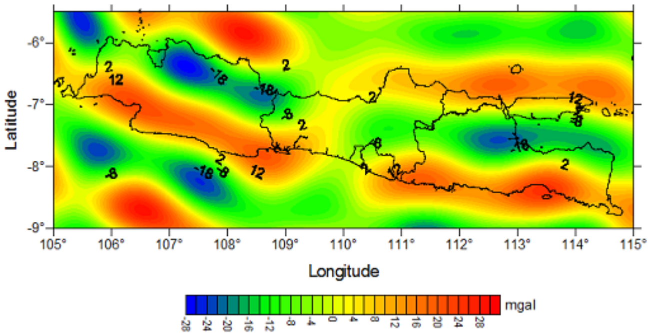

Figure 5. Trends resulted from substraction between TIM-R3 and SPW-R1

Undulation of GOCE GGMS

The geoid undulation values of the GOCE GGMs over the Java island is range from minimal -12,48 m to maximal 40,82 m, as shown in Table 3. Same as the anomaly value, there is no correlation of the increasing of degree with increasing of the undulation range, also the same patterns of undulation values difference between the SPW-R1 and TIM-R3 (Figure 6). These conditions could be due to the different of degree and order among the utilized-GOCE GGMs is not big.

Table 3. The statistics of GOCE GGMs undulation

Model	Degree	Min. (m)	Max. (m)	Mean (m)	Range (m)
DIR-R2	240	-12,48	40,80	20,64	53,28
SPW-R1	250	-12,82	40,61	20,62	53,43
SPW-R2	240	-12,62	40,75	20,65	53,38
TIM-R2	224	-12,64	40,82	20,66	53,46
TIM-R3	210	-12,58	40,82	20,65	53,40

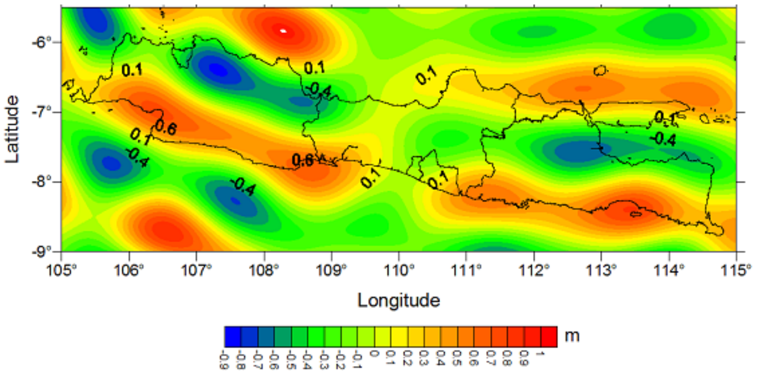

Figure 6. Contour pattern resulted from substraction of TIM-R3 and SPW-R1

Local geoid of Java Island

The local geoid of Java, using different GOCE GGMs for its longwavelength component, have been obtained with the value range from -12 to 42 m, and the value increase from the west to the east part of Java Island (Figure 7). The statistics of the Java Island geoid (table 4) shows that the range between the minimum and maximum values start from 53,35 m until

53,52 m. Meanwhile the mean value of the model start between 53,35 m until 53,52 m with standar deviation start from 12,85 m to 12,91 m. There are no any increase of range and mean values in accordance with increasing in degree and orde. The range, the mean and the standar deviation of the local geoid models using the five GOCE GGMs are almost similar each others.

Table 4. The statistics of local geoid of Java Island

Model	Degree and order	Min. (m)	Max. (m)	Range (m)	Mean (m)	Std. Deviation (m)
DIR-R2	240	-12,34	41,01	53,35	20,88	12,91
SPW-R1	250	-12,65	40,87	53,52	20,89	12,85
SPW-R2	240	-12,36	41,05	53,41	20,89	12,85
TIM-R2	224	-12,44	41,06	53,50	20,90	12,90
TIM-R3	210	-12,39	41,07	53,46	20,90	12,90

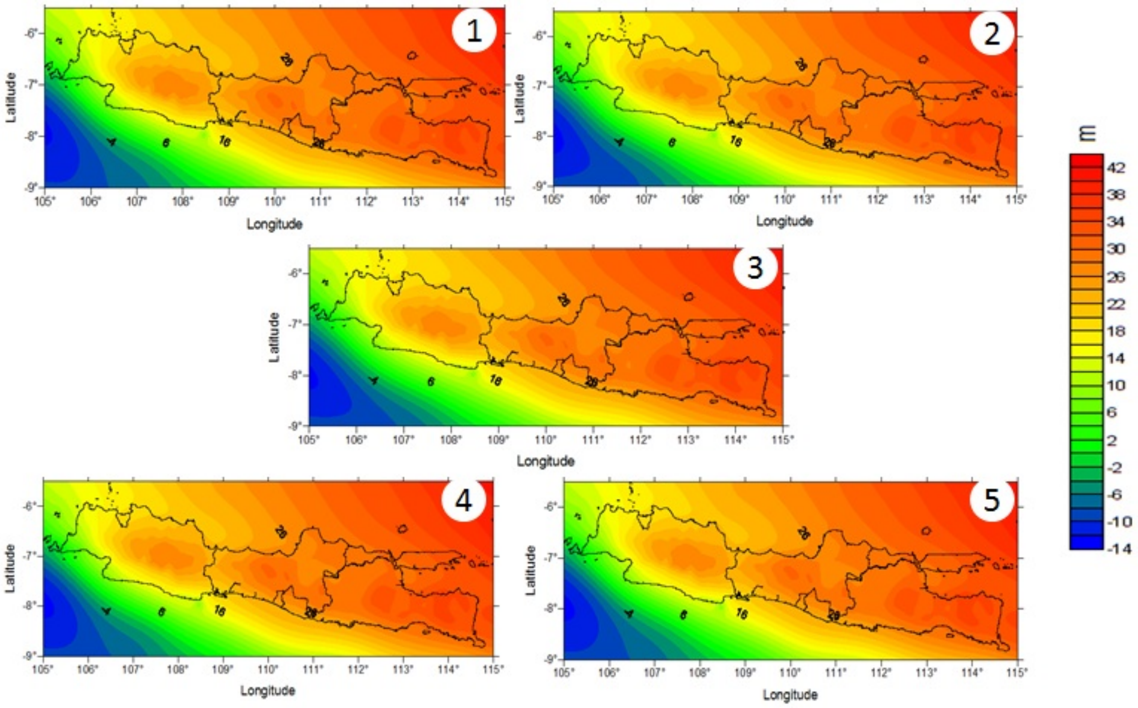

Figure 7. Contour pattern of local geoid of Java island
(1) DIR-R2, (2) SPW-R1, (3) SPW-R2, (4) TIM-R2, (5) TIM-R3

Evaluation of local geoid of Java Island

The absolute accuracy of the derived local geoid have been obtained base on mean difference value between the local geoid and 49 co-site GPS/levelling data, as shown in Tabel 5. The highest accuracy of about 0,644 m, is obtained for local geoid models using the SPM-R2 model and the lowest of 0,698 is for local geoid model using the DIR-R2 model. Increasing in degree of the models not always follow by increasing in accuracy of the local model or vise versa. Same as mentioned above, this condition could be due to the different of degree and order of the GGMs are not big. Whereas, their small different in resolution was not significantly influence to the resolution of the obtained-local geoid. Along with, uneven distribution of the utilized teresrial gravity data (Figure 2), causing difficulty to see the correlation between degree and order of the GGMs with the accuracy of obtained-local geoid model. In order to understand more about the effect of degree and order to the accuracy of the local geoid model, the EGM2008 with full degree and order of 2.190 has been used also in this study as a comparison model. In Table 5 shown that the local geoid using the EGM2008 also has the mean difference and standar deviation values of 0,683 m and of 0,585 m, respectively, which are not different with values of the local geoid model using much lower degree and order of the GOCE GGMs.

Table 5. The results of difference undulation in the 49 points of co-located GPS/levelling

Model	Min. (m)	Max. (m)	Mean (m)	Std. Deviation (m)
DIR-R2	0,001	2,594	0,698	0,579
SPW-R1	0,005	2,487	0,644	0,564
SPW-R2	0,035	2,524	0,652	0,550
TIM-R2	0,042	2,599	0,697	0,575
TIM-R3	0,033	2,624	0,703	0,575
EGM2008	0,012	2,043	0,683	0,585

Figure 8 shows the distibution of the difference value between the local geoid and co-located GPS-levelling data. Looking in detail on the value and dirrection of difference of each point, there is clearly shown a systimatic pattern with mostly negative values occurring at the nortern part of midle and east Java. Whereas, the positive value mosly occur at the midle and souther part of Java Island. Therefore, the mean difference values shown in Tabel 5, depict also the possibility of difference in reference between the obtained-local geoid which refers to global reference system WGS84 and the co-located GPS/levelling data which refers to local mean sea level.

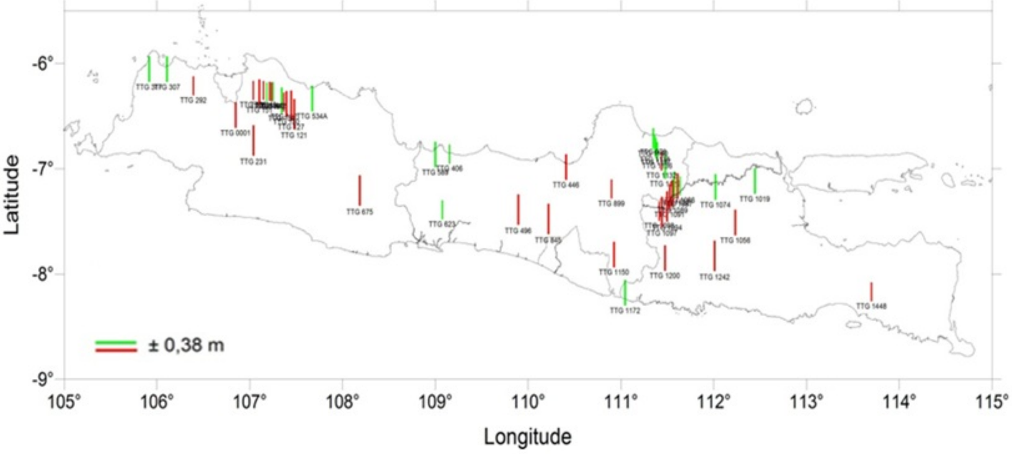

Figure 8. Distribution of errors of local geoid generated by SPW-R1 model
(Green: positive; Red: negative)

5. CONCLUSIONS

Five GOCE GGMs have been evaluated for application on local geoid modelling of Java Island, especially effect of their development methods and their degree and order on the accuracy of local geoid model. The accuracy of the local-geoid models have been evaluated using the 49 co-located GPS/levelling data. The results shows that the accuracy of the local geoid range from 0,703 m to 0,644 m, with the highest accuracy obtained using the SPM-R1 model and the lowest accuracy derived using the TIM-R3 model. There are no correlation between degree and order of the GOCE GGMs with the accuracy of the local geoid in case of Java Island. The two SPM models generate more accurate local local geoid than the DIR and TIM models. Finally, the mean difference values depicts also the possibility of difference on utilized reference height between the local geoid model and the control points of GPS-levelling data, as there are the systimatic pattern shown by the values and dirrections of differenceis.

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