Assessment of Gravity Field and Steady State Ocean Circulation Explorer (GOCE) geoid model using GPS levelling over Sabah and Sarawak

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Abstract. The GOCE satellite mission has significantly contributed to various applications such as solid earth physics, oceanography and geodesy. Some substantial applications of geodesy are to improve the gravity field knowledge and the precise geoid modelling towards realising global height unification. This paper aims to evaluate GOCE geoid model based on the recent GOCE Global Geopotential Model (GGM), as well as EGM2008, using GPS levelling data over East Malaysia, i.e. Sabah and Sarawak. The satellite GGMs selected in this study are the GOCE GGM models which include GOCE04S, TIM_R5 and SPW_R4, and the EGM2008 model. To assess these models, the geoid heights from these GGMs are compared to the local geometric geoid height. The GGM geoid heights was derived using EGMLAB1 software and the geometric geoid height was computed by available GPS levelling information obtained from the Department Survey and Mapping Malaysia. Generally, the GOCE models performed better than EGM2008 over East Malaysia and the best fit GOCE model for this region is the TIM_R5 model. The TIM_R5 GOCE model demonstrated the lowest R.M.S. of ±16.5 cm over Sarawak, comparatively. For further improvement, this model should be combined with the local gravity data for optimum geoid modelling over East Malaysia.

1. Background

Geoid is a fundamental surface in geoscience which is defined as an equipotential surface of the earth’s gravity field associated with some average of sea level that is commonly adopted as the height reference datum [1]. The geoid model is strongly dependent on the quality and quantity of the gravity data utilised for the solution [2]. One of the primary data sources in geoid determination is from the Global Geopotential Model (GGM). GGM is one of the cheapest and reliable methods to derive geoid height, and it contributes to the long-wavelength parts of the geoid model. GGM is an important component in developing high resolution geoid models over local regions. For example, Malaysia used the GGM01C model [3]. In addition, GGM provides a reference field for local gravimetric geoid. The GGM model is used to derive parameters such as geoid height, gravity anomaly and deflection of
The importance of the geoid has increased substantially due to the widespread use of Global Navigation Satellite Systems (GNSS) for positioning and navigation. GNSS, unlike traditional surveying instruments, has the ability to provide three-dimensional coordinates (latitude, longitude and height) anywhere in the world, at any time irrespective of the weather. However, the GNSS-determined heights, i.e. ellipsoidal heights, are geometrical heights. These cannot be used in surveying and engineering projects of which orthometric heights are required. Hence, there is a need for geoid determination, since it is the reference surface for orthometric heights. Thus, by combining the geoid and GNSS observations, the ellipsoidal heights can be converted to the physically meaningful orthometric heights [4].

The recent GGM can be accessed via http://icgem.gfz-potsdam.de/icgem. A GGM comprises a set of fully normalized spherical harmonic coefficients to model the long wavelength features of the external earth gravity field. Users of GGM should perform their own accuracy and precision verifications, such as comparing the GGM-derived gravity field quantities with local data [2]. There are a few classes of GGM such as satellite-only GGM, combined GGM, and tailored GGM. For this paper, we focus on satellite-only GGM which is derived from satellite GOCE.

The GOCE satellite gravity mission was launched in 2009 and ended in 2013, whereby the collected data lead to significant improvements on the long-wavelength aspects of the earth’s gravity field. The advantage of satellite gravity missions is that it provides a homogenous and near global coverage of gravity field information [5]. However, usually, the error estimates for such GGMs are not too optimistic and presented as global averages, and thus does not necessarily represent the performance of the GGM over a particular region [2].

Sabah and Sarawak has a rough topography and many rivers that cause conventional levelling difficult to be carried out [6]. Hence, as an alternative, GPS levelling technique is employed for conducting levelling over rough and mountainous areas. GPS levelling requires a precise geoid model in order to transform geometric height to physical height, i.e. orthometric height. GPS leveling technique has been used widely; for example, to monitor dam subsidence due to water or natural gas removal, earth crustal movements, and as height control across water bodies for bridge construction [2]. Since the release of the GOCE GGM model, there has been no specific study conducted over Sabah and Sarawak related to the performance of GOCE GGM model over the region. Therefore, this paper aims to determine the best fit GOCE model over the East Malaysian region.

2. Data and method

2.1 Global Geopotential Model

GGM is the most essential component in modern geoid determination which significantly contributes to its long wavelength information. Currently, various GGMs have been derived and made available freely for the scientific community which can be downloaded from the official website of the International Centre for Global Earth Models (http://icgem.gfz-potsdam.de/icgem). From this website, three GOCE GGM models were selected: JYY_GOCE04S, GO_CONS_GCF_2_TIM_R5, and GO_CONS_GCF_2_SPW_R4 model, which were released in 2014. The other GGM model selected is EGM2008 which is a known high resolution global geoid model. These GOCE GGM models and the EGM2008 model were chosen to test how accurate the GOCE models are compared to the EGM2008 over East Malaysia, with the use of local GPS levelling data as the benchmark. The list of GGM data used is summarised in Table 1.
Table 1. List of selected Global Geopotential Models in this study and their descriptions.

| Model                        | Year | Data                        | Reference          |
|------------------------------|------|-----------------------------|--------------------|
| EGM2008                      | 2008 | Satellite(Grace), Gravity data, Altimetry data | Palvis et al., 2008 |
| JYY_GOCE04S                  | 2014 | Satellite(GOCE)             | Yi et al., 2013    |
| GO_CONS_GCF_2_TIM_R5         | 2014 | Satellite(GOCE)             | Brockman et al., 2014 |
| GO_CONS_GCF_2_SPW_R4         | 2014 | Satellite(GOCE)             | Gatti et al., 2014  |

Based on Table 1, the models, year, data and reference are listed, whereby further information can be acquired via the ICGEM website (http://icgem.gfz-postdam.de/ICGEM).

GGMs were then evaluated by comparing geoid heights from GPS levelling with the GGM geoid heights computed using EGMlab through MATLAB. For EGM2008, 360 maximum degree order were used to minimise the time required in computing the geoid heights. The descriptive statistics of the differences between GGM-derived and GPS levelling geoid heights are reported section 3 of this paper.

2.2 GPS levelling data

![GPS on BENCHMARK PROJECT Sabah & Sarawak](image)

**Figure 1.** GPS levelling data on collocated benchmarks in 2004/2005 over East Malaysia.

The GPS levelling data was collected by the Department Survey and Mapping Malaysia in 2004/2005 and made available for this study (see Figure 1). The GPS levelling data on collocated benchmarks used in this study are basically on the Standard benchmarks and 2nd class benchmarks of the
Department of Survey and Mapping Malaysia. For this study, 26 collocated GPS levelling benchmarks in Sabah and 30 collocated GPS levelling benchmarks were selected.

2.3 Methodology
GPS levelling data has become one of the standard tools for validating and evaluating global and local gravimetric geoid models. Nowadays, the ellipsoidal height precision is about 1-2 cm; hence, GPS levelling is used as an external measure of the accuracy of geoid model. This quality evaluation of GGM became a routine procedure before computing any high resolution local gravimetric geoid model. Therefore, the statistical summary of the comparison between the GGMs and the GPS levelling data will be the result that will indicate which GGM model best fits over East Malaysia.

Based on Figure 2, the geoid height derived from GGM is computed using EGMLab [1]. The geometric geoid is determined from GPS levelling data on collocated benchmarks over Sabah and Sarawak from the Department of Survey and Mapping Malaysia. The geometric geoid is assumed as the most probable value. The comparison between GGM geoid height and geometric geoid height is obtained by the following formula;

\[
\Delta N = N_{GGM} - N_{\text{geometric}}
\]

Where:
- \(N_{GGM}\): Geoid height derived from GGM
- \(N_{\text{geometric}}\): Geoid height derived from GPS levelling

\(N_{\text{geometric}}\) is obtained from ellipsoidal height, \(h_{GPS}\), and orthometric height of benchmarks, \(H_{MSL}\). The Root Mean Square (R.M.S.) of the differences, \(\Delta N\), will be obtained and the lowest R.M.S. will indicate the most suitable GGM over East Malaysia.

![Diagram](image_url)

**Figure 2.** Flowchart of the geoid height assessment.
3. Results and analysis
The evaluation of GGM is important because the global geoid model will contribute to the quality of the high resolution local geoid model. The findings will be useful for users of GPS levelling. In this paper, the results are divided into two assessments, one for each state: Sabah and Sarawak.

3.1 Assessment of GGM in Sabah
Figure 3 shows the geoid heights for the selected GGMs and geometric geoid height at 26 GPS levelling benchmarks over Sabah. TIMR5 follows closely to the geometric geoid values. The EGM2008 is closer to the geometric geoid height values based on the average difference of 1.937 m. However, based on the R.M.S., EGM2008 has the highest R.M.S. of 0.378 m which indicates that the model does not best fit the region. The models from GOCE show better fitting, whereby TIMR5 has a R.M.S. of ±0.271 m. The difference in R.M.S. of TIMR5 and EGM2008 is about 10 cm which demonstrates that TIMR5 has a significant improvement compared to the other GGMs over Sabah.

![Geoid height variation of GGM models at GPS levelling benchmarks over Sabah](image)

**Figure 3.** Geoid height variation of GGM models at GPS levelling benchmarks over Sabah.

Table 2 shows the numerical statistics for the geoid height evaluation of the GOCE GGM models and EGM2008 using 26 Sabah GPS levelling data. Based on the R.M.S. values, the best model is GO_CONS_GCF_2_TIM_R5. Therefore, GGMs from the GOCE satellite are better when compared to EGM2008. The lowest R.M.S. is ± 27.1 cm from the TIM_R5 GOCE model.

**Table 2.** Statistic of geoid heights from GGM compared to geometric geoid height over Sabah.

| GGM     | Min (m) | Max (m) | Average Difference (m) | R.M.S. (m) |
|---------|---------|---------|------------------------|------------|
| EGM2008 | 1.269   | 2.729   | 1.937                  | 0.378      |
| JJY04S  | 1.874   | 3.089   | 2.534                  | 0.318      |
| SPWR4   | 1.820   | 3.022   | 2.514                  | 0.311      |
| TIMR5   | 1.787   | 3.079   | 2.517                  | 0.271      |
3.2 Assessment of GGM in Sarawak

Based on Table 3, the best fit GGM for the Sarawak region is TIMR5 (GO_CONS_GCF_2_TIM_R5) as well. All GOCE GGM models show a good performance based on the R.M.S. values compared to EGM2008. Hence, GOCE GGM models significantly contribute to the improvement of geoid height. The difference of R.M.S. between EGM2008 and TIMR5 is about ±10 cm which proves that the GOCE GGM models have impact in GNSS heighting and height unification. It could be sufficient for engineering and most scientific applications, but for precise applications, a high resolution geoid model is needed. For further research, an investigation on the impact of GOCE GGM models in various scientific applications, such as in oceanography, i.e. in ocean circulation and sea level rise, needs to be carried out. We suggest that, for future geoid computations, further GGM evaluations need to be carried out and the contribution of GOCE models should be addressed.

Table 3. Statistic of geoid heights from GGM compared to geometric geoid height over Sarawak.

| GGM         | Min (m) | Max (m) | Average Difference (m) | R.M.S. (m) |
|-------------|---------|---------|------------------------|------------|
| EGM2008     | 1.878   | 2.792   | 2.179                  | 0.254      |
| JJY04S      | 2.131   | 3.169   | 2.776                  | 0.244      |
| SPWR4       | 2.569   | 3.208   | 2.793                  | 0.213      |
| TIMR5       | 2.377   | 3.230   | 2.762                  | 0.165      |

4. Conclusion

The assessment of the GOCE geoid models based on recent GOCE Global Geopotential Model (GGM) and EGM2008 has been performed using GPS levelling data over Sabah and Sarawak. Three GOCE GGM 2014 models, which are GOCE04S, TIM_R5, and SPW_R4, and EGM2008 are evaluated using local GPS levelling data as the benchmark. Based on the results, the best fitting GOCE GGM model is the GO_CONS_GCF_2_TIM_R5 and the lowest is the JYY_GOCE04S. The R.M.S for the best fit TIMR5 model over Sabah and Sarawak is ±27.1 cm and ±16.5 cm, respectively. In general, the GOCE model is better than EGM2008 over this study area. The R.M.S. difference between the best fit GOCE model, i.e. TIMR5 model, and EGM2008 is about ±10 cm. In conclusion, the GOCE satellite improves the longwave of gravity field and geoid height. As a suggestion, for better results in future, the GOCE model should be combined with the local gravity data in order to develop a high resolution geoid model over an area.

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