pyGABEUR-ITB: A FREE SOFTWARE FOR ADJUSTMENT OF RELATIVE GRAVIMETER DATA

(pyGABEUR-ITB: Perangkat Lunak Gratis Perataan Data Gayaberat Relatif)

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ABSTRACT

pyGABEUR-ITB (Python GayaBEUrat Relatif – Institut Teknologi Bandung) is a free and interactive software for adjustment of relative gravimeter data, developed based on Python programming language. pyGABEUR-ITB can adjust relative gravity measurements and provide reliable estimates for correcting instrument’s systematic errors, such as gravimeter drift. Furthermore, pyGABEUR-ITB can also detect possible outliers in the observations using the τ-criterion method. Since pyGABEUR-ITB is using the weighted constraint adjustment, at least one fixed station is required accordingly. Relative gravimeter data around Palu-Donggala area (Central Sulawesi) observed by Center for Gravity Control Networks and Geodynamics, Geospatial Information Agency, were used to test the performance of pyGABEUR-ITB. The processing results were then compared against those calculated using GRAVNET software. The comparisons show that both pyGABEUR-ITB and GRAVNET softwares statistically provide similar results, with the total RMS value of about 5 μGal. In term of computer’s requirement, pyGABEUR-ITB can be executed under a computer with the following minimal requirements: x64 CPU, 1 GB memory and WINDOWS 7 OS. Finally, it is important to mention that pyGABEUR-ITB is recently suited to process the data from the gravimeter that adopts the principle of vertical spring balance. In the near future, pyGABEUR-ITB will be extended to be able to automatically adapt to various observation principles.

Keywords: free software, python, relative-gravity, constrained adjustment

ABSTRAK

pyGABEUR-ITB (Python GayaBEUrat Relatif – Institut Teknologi Bandung) merupakan perangkat lunak gratis yang interaktif untuk perataan data gayaberat relatif. Perangkat lunak tersebut dibuat menggunakan bahasa pemrograman Python. pyGABEUR-ITB bisa melakukan proses perhitungan data gayaberat relatif dan memberikan nilai koreksi bagi kesalahan sistemik pada alat, seperti koreksi drift. pyGABEUR-ITB juga bisa mendeteksi kesalahan pengukuran menggunakan metode τ-criterion. Karena pyGABEUR-ITB menggunakan metode hitung perataan terkendala-berbobot, maka diperlukan minimal sebuah titik ikat. Data gayaberat relatif di area Palu-Donggala (Sulawesi Tengah), yang diukur oleh Bidang Jaring Kontrol dan Gayaberat, Badan Informasi Geospatial, digunakan untuk menguji performa dari pyGABEUR-ITB. Data yang diolah pyGABEUR-ITB dibandingkan dengan hasil perhitungan perangkat lunak GRAVNET. Hasil perbandingan menunjukkan bahwa kedua perangkat lunak tersebut memberikan hasil yang sama, dengan nilai RMS sebesar 5 μGal. Terkait kebutuhan komputer, untuk menjalankan pyGABEUR-ITB diperlukan komputer dengan kebutuhan minimal sebagai berikut: x86 CPU, 1 GB RAM, WINDOWS 7 OS. Perlu dikemukakan, pyGABEUR-ITB saat ini hanya bisa digunakan untuk mengolah data gayaberat relatif yang diukur oleh alat gravimeter yang menggunakan prinsip keseimbangan pegas vertikal. Dalam waktu dekat, pyGABEUR-ITB akan dikembangkan supaya bisa mengolah data yang diperoleh menggunakan beberapa jenis prinsip pengukuran.

Kata kunci: perangkat lunak gratis, python, gayaberat relatif, perataan terkendala-berbobot

INTRODUCTION

In order to establish a reliable geoid model over the Indonesian region, Center for Gravity Control Networks and Geodynamics, Geospatial information Agency (BIG) has been carrying out terrestrial relative gravity measurements over several places. Such measurements are of important for determining gravity values, which eventually will serve as the main inputs for the geoid determination. On the other hand, such accurate gravity values are not only important for establishing the geoid model, but also for other geodetic and geophysical purposes.
Accurate determination of the gravity values is not an easy task, since one should ensure that possible systematic and gross errors (such as geophysical effects and the instrumental errors) (Tapley, Born, & Parke, 1982; Tscherning, 1991; Van Camp, Williams, & Francis, 2005) in the measurements are optimally handled. Furthermore, one should also correctly define mathematical and weighting (stochastic) models during the adjustments (Lerch, 1991). On the other hand, the availability of the related software is limited. If we can have access to such software, some modifications may be necessary to make them fit into our own purposes.

Fortunately, in geodetic literature, methods for adjusting the gravity measurements and detecting possible outliers have been excessively studied, for example, by Lagios (1984), Zhiheng et al. (1988), Torge (1989), Hwang et al. (2002) and the most recently by Timmen (2010). These literatures are the best sources that can guide us to practical adjustment of the relative gravimeter data and also to develop a dedicated software that really fits our purposes.

Since the existing software, like GRAVNET, cannot really fit with our purposes and is not user-friendly, we have developed pyGABEUR-ITB (Python GayaBEUrat Relatif – Institut Teknologi Bandung), a free and interactive software for accurate adjustment of the relative gravimeter data. The term “GayaBEUrat Relatif” (from mixed Sundanese-Indonesian words) means relative gravity. pyGABEUR-ITB is fully written using Python language and is freely available for public. Detailed descriptions of pyGABEUR-ITB including practical instructions on how to use pyGABEUR-ITB can be found in Wijaya et al. (2018).

In this paper, first, we briefly present the used methods for adjusting the relative gravimeter measurements and for correcting some geophysical effects. Second, we discuss the performance test of pyGABEUR-ITB using the gravimeter data around Palu-Donggala area (Central Sulawesi) and the comparisons with GRAVNET software (Hwang et al., 2002).

METHOD

An Equation for the Single Measurement

For a gravity measurement $\Delta g(\mathbf{r}, t)$, within the measurement loop $k$, at epoch $t$ and station $\mathbf{r}$, the corresponding mathematical equation may be expressed as (Torge, 1989):

$$
\Delta g(\mathbf{r}, t) + \beta(\mathbf{r}, t) = g(\mathbf{r}) + \hat{D}_k(t - t_0) + N_{ok} + \Delta F(\mathbf{r}) + g_{ok}(\mathbf{r}) + \varepsilon(\mathbf{r}, t) \quad \text{................................. (1)}
$$

Whilst $g(\mathbf{r})$ denotes the absolute gravity value at position $\mathbf{r}$, $\hat{D}_k$, $N_{ok}$ and $\Delta F(\mathbf{r})$ represent the gravimeter’s drift, bias, and the calibration function, respectively, for the loop $k$. $t_0$ is the epoch reference when the reference absolute gravity value $g_{ok}(\mathbf{r})$ is inherently determined by the gravimeter instrument. $\beta(\mathbf{r}, t)$ and $\varepsilon(\mathbf{r}, t)$ are corrections for geophysical (or environmental) effects and the measurements noise, respectively.

The term $\Delta F(\mathbf{r})$ in Equation 1 represents the calibration function to correct for the periodic error in reading the gravimetric factor (Krieg, 1982; Torge, 1989). For a gravimeter that adopts the vertical spring balance principle, such a correction is very small and hence it may safely be neglected. Furthermore, in our works, we use the CG-5 and CG-6 gravimeters that are designed to minimize this calibration error. In pyGABEUR-ITB, the term $\Delta F(\mathbf{r})$ is therefore excluded from Equation 1.

The term $\beta(\mathbf{r}, t)$ in Equation 1 may consists of several geophysical effects, which may significantly change the gravity values around the measurement site. These effects must be corrected before the gravimeter data are processed. According to Timmen (2010), these geophysical effects can be categorized according to their possible sources, namely (1) Man-made effects: mineral exploration, ground water extraction, (2) Tectonic effects: earthquake, volcano eruption, post-glacial rebound and (3) Non-tectonic effects: Earth and ocean tides and load, redistribution of the atmosphere mass and its loading effects, polar motion and hydrological cycle. Due to their complexity and lack of knowledge, the first and second sources are difficult to model. The third source, non-tectonic effects, is relatively easy to model using physical or empirical method. Therefore, the geophysical corrections applied to the relative gravimeter data are usually due to the third source.

pyGABEUR-ITB estimates the gravity changes due to the following geophysical effects namely (1) The solid Earth tides ($\Delta g_{SET}$) is calculated using the model developed by Longman (1959), (2) The Ocean loading ($\Delta g_{OL}$) is determined using the GOTIC2 model (Matsumoto, Sato, Takanezawa, & Ooe, 2001), (3) The polar motion ($\Delta g_{PM}$) is calculated using the model proposed by Wahr (1985), and (4) The redistribution of atmospheric mass ($\Delta g_{ATM}$) is determined using a simple model recommended by the 2010 International Association of Geodesy (IAG) convention.

In pyGABEUR-ITB, the geophysical corrections $\beta$ is therefore expressed as the sum of the above models:

$$
\beta = \Delta g_{SET} + \Delta g_{OL} + \Delta g_{PM} + \Delta g_{ATM} \quad \text{.................. (2)}
$$

Equations for the Relative Measurements

Assuming that the geophysical effects have been corrected using Equation 2 and then
according to Equation 1, the relative gravity measurements between stations \( \vec{r}_A \) and \( \vec{r}_B \) (within the loop \( k \)) may be derived as:

\[
\nabla g_{AB} = \Delta g(\vec{r}_B, t_B) - \Delta g(\vec{r}_A, t_A) \\
= g(\vec{r}_B) - g(\vec{r}_A) + \dot{D}_A(t_B - t_A) + \epsilon_{AB} \quad \text{(3)}
\]

\( g(\vec{r}_A) \) and \( g(\vec{r}_B) \) represent the absolute gravity values at the two stations. \( \epsilon_{AB} \) denotes the measurement residuals. In the adjustment, the terms \( g(\vec{r}_A) \), \( g(\vec{r}_B) \) and \( \dot{D}_A \) will be determined along with the other parameters.

The relative gravity measurements usually involve more than two stations and one loop. To solve all the possible parameters, one should be able to derive the corresponding mathematical equations for all measurements. We here briefly provide a practical example to illustrate how the equations are derived (and adjusted) in pyGABEUR-ITB. Consider the relative gravity network (see Figure 1) that consists of loops A and B. The relative measurements for loop A follow the trajectory/route 1-2-3-1, while those for loop B is 3-4-5-3. If station 1 is held fixed, one may estimate the following values: four gravity terms \( g(\vec{r}_3), g(\vec{r}_4), g(\vec{r}_5) \) and \( g(\vec{r}_2) \) and two graviometer drifts for each loop \( \dot{D}_A \) and \( \dot{D}_B \).

\[
\nabla g_{23} = g(\vec{r}_3) - g(\vec{r}_2) + \dot{D}_A(t_3 - t_2) + \epsilon_{23}
\]

\[
\nabla g_{31} = g(\vec{r}_1) - g(\vec{r}_3) + \dot{D}_A(t_3^2 - t_3) + \epsilon_{31} \quad \text{(4)}
\]

Similarly, station 3 is also measured twice with two different epochs \( t_3^1 \) and \( t_3^2 \). Mathematical equations for the measurements in loop B are:

\[
\nabla g_{34} = g(\vec{r}_4) - g(\vec{r}_3) + \dot{D}_B(t_4 - t_3) + \epsilon_{34}
\]

\[
\nabla g_{45} = g(\vec{r}_5) - g(\vec{r}_4) + \dot{D}_B(t_5 - t_4) + \epsilon_{45}
\]

\[
\nabla g_{53} = g(\vec{r}_3) - g(\vec{r}_5) + \dot{D}_B(t_3^2 - t_3) + \epsilon_{53} \quad \text{(5)}
\]

Equation 4 and Equation 5 can be combined and represented into the matrix form as:

\[
L_o = A_pX + e_o \quad \text{.......................... (6)}
\]

The measurements matrix \( L_o \), the design matrix \( A_p \), the parameter matrix \( X \) and the residual matrix \( e_o \) are, respectively, expressed in Equation 7, Equation 8, Equation 9, and Equation 10:

\[
L_o = [\nabla g_{12} \ \nabla g_{23} \ \nabla g_{31} \ \nabla g_{34} \ \nabla g_{45} \ \nabla g_{53} ]^T \quad \text{................. (7)}
\]

\[
A_p = [\begin{bmatrix}
-1 & 1 & 0 & 0 & 0 & t_2 - t_1^1 \\
0 & -1 & 1 & 0 & 0 & t_3 - t_2 \\
1 & 0 & -1 & 0 & 0 & t_4 - t_3 \\
0 & 0 & -1 & 1 & 0 & t_5 - t_4 \\
0 & 0 & 0 & -1 & 1 & t_3 - t_4 \\
0 & 0 & 0 & 0 & -1 & t_2 - t_1^1
\end{bmatrix}] \quad \text{................. (8)}
\]

\[
X = [\begin{bmatrix}
g(\vec{r}_1) \\
g(\vec{r}_2) \\
g(\vec{r}_3) \\
g(\vec{r}_4) \\
g(\vec{r}_5) \\
\dot{D}_A \ \dot{D}_B
\end{bmatrix}]^T \quad \text{................. (9)}
\]

\[
e_o = [\epsilon_{12} \ \epsilon_{23} \ \epsilon_{31} \ \epsilon_{34} \ \epsilon_{45} \ \epsilon_{51}]^T \quad \text{.......................... (10)}
\]

**Weighted Constraint Adjustment**

One may easily verify that the design matrix \( A_p \) in Equation 8 has a rank defect of 1. Therefore, the least-squares solutions of Equation 6 will be impossible without applying a minimum constraint. Here, we apply a constraint to the gravity value observed at (minimum) one station during the adjustment to get the solutions of \( X \).

According to Figure 1, suppose that the gravity value measured at station 1 is held fixed. One can then introduce an equation as a minimum constrain:

\[
\bar{g}(\vec{r}_1) = g(\vec{r}_1) + \epsilon_1 \quad \text{............................................. (11)}
\]

\( \bar{g}(\vec{r}_1) \) and \( \epsilon_1 \) represent the measurement value at station 1 and its measurement error, respectively. More gravity values observed at other stations may also be introduced as additional constrains.

In a matrix form, Equation 11 can be expressed as (Koch, 1999):

\[
L_c = A_cX + e_c \quad \text{.......................... (12)}
\]
where
\[ L_c = \hat{g}(\hat{\mathbf{f}}) \] ................................. (13)
\[ A_c = [1 \ 0 \ 0 \ 0 \ 0 \ 0] \] ................................. (14)
\[ \mathbf{e}_c = \varepsilon_1 \] ................................. (15)

**Equation 13** consists of the observations, **Equation 14** is the coefficient matrix, and **Equation 15** denotes the measurement residuals.

By combining **Equation 6** and **Equation 12**, an augmented measurement equation can be derived from:
\[
\mathbf{V} = \begin{bmatrix} \mathbf{e}_o \\ \mathbf{e}_c \end{bmatrix} = \begin{bmatrix} A_o & A_c \end{bmatrix} \mathbf{X} - \begin{bmatrix} L_o \\ L_c \end{bmatrix} \] ................................. (16)

Since matrix \([A_o, A_c]^T\) has the full rank, the least-squares solutions of **Equation 16** are now possible. The solution can be derived by minimizing **Equation 17**, as follow:
\[ \theta = \mathbf{V}^T \mathbf{P} \mathbf{V} = e_o^T \mathbf{P} e_o + e_c^T \mathbf{P} e_c \rightarrow \min \] ................................. (17)
where \( \mathbf{P} \) is the weight matrix defined as:
\[ \mathbf{P} = \begin{bmatrix} P_o & 0 \\ 0 & P_c \end{bmatrix} \] ................................. (18)

The terms \( P_o \) and \( P_c \) in **Equation 18** are diagonal matrices, representing the weights for the measurements and constraints, respectively. While the diagonal elements of \( P_o \) are inversely proportional with the variance of observations, those of \( P_c \) can be set to the following different options: (1) infinite, meaning that the corresponding a priori gravity value will not be changed after the adjustment, (2) zero, meaning that the corresponding a priori gravity value will be adjusted, and (3) the inverse of variance of the a priori gravity value. pyGABEUR-ITB provides all these options.

Finally, the least-squares adjustments with weighted-constraint for \( \mathbf{X} \) and its standard deviations may be determined using **Equation 19**, **Equation 20**, and **Equation 21**, as follow:
\[ \mathbf{Q}_{xx} = A_o^T \mathbf{P} A_o + A_c^T \mathbf{P} A_c \] ................................. (19)
\[ \sigma^2 = \frac{\mathbf{v}^T \mathbf{P} \mathbf{v}}{m_o + m_c - n} \] ................................. (20)
\[ \mathbf{X} = Q_{xx}^{-1} [A_o^T \mathbf{P}_o L_o + A_c^T \mathbf{P}_c L_c] \] ................................. (21)

**Goodness-of-Fit Test and Outliers Detection**

The least-squares solutions may still be affected by several errors such as: outliers in the measurements, incorrect mathematical equations (**Equation 4** and **Equation 5**) and inappropriate stochastic models. In the adjustment theory, the goodness-of-fit test must be performed to justify whether or not the solutions are still affected by such errors. The solutions are accepted if the following condition is fulfilled (Baarda, 1968; Caspary, 1987):
\[ \chi^2 \equiv \frac{\mathbf{n}^2}{\sigma^2} < \chi^2_{\nu} \] ................................. (22)

\( \sigma^2 \) is the a priori variance before the adjustments, \( \chi^2_{\nu} \) is the chi-square distribution when the confidence level is \( 1 - \alpha \) and the degree of freedom is \( m \), as shown in **Equation 26**. \( \alpha \) is the significant level.

If the condition in **Equation 22** is not fulfilled, the mathematical equations and weighted matrices needs to be checked whether the equations are inadequate or the outliers exist in the measurements. pyGABEUR-ITB adopts the \( \tau \)-criterion method proposed by (Pope, 1976) that employs the t-student distribution to check the possible outliers. According to this method, the \( i^{th} \) measurement is indicated as outlier if the following condition is met:
\[ \frac{|\mathbf{v}_i|}{\sigma^2} > \tau_{a/2} \] ................................. (23)
where
\[ \bar{v}_i = \frac{v_i}{\sqrt{q_{ii}}} \] ................................. (24)
\[ \tau_{a/2} = \frac{t_{a/2, m - 1} \sqrt{m}}{\sqrt{m + m - a/2, m}} \] ................................. (25)
\[ m = m_o + m_c - n \] ................................. (26)

**Equation 23**, **Equation 24**, and **Equation 25** are mathematical representations for the \( \tau \)-criterion test. \( v_i \) and \( \bar{v}_i \) are the residual and the standardized residual for the \( i^{th} \) measurement, \( \tau_{a/2} \) is the critical values deduced from the t-student distribution \( t_{a/2, m} \). \( q_{ii} \) is the diagonal element of the cofactor of the residuals \( Q_{vv} \), which can be calculated using the following relation:
\[ Q_{vv} = \mathbf{P} - \mathbf{A} Q_{xx} \mathbf{A}^T \] ................................. (27)
\[ \mathbf{A} = \begin{bmatrix} A_o \\ A_c \end{bmatrix} \] ................................. (28)

**RESULTS AND DISCUSSIONS**

**Architecture of pyGABEUR-ITB**

Architecture of pyGABEUR-ITB is very simple that consists of three GUI-based modules: INPUT, PROCESS, and OUTPUT (see **Figure 2**). The module INPUT records all necessary files such as data files, coordinate lists, output files and geophysical files. Selection of such files can be accomplished interactively via the GUI-based main window of pyGABEUR-ITB (see **Figure 4**). It is
important to mention that pyGABEUR-ITB (in its current shape) can only read the gravimeter data file from the Scintrex CG-5 and CG-6 gravimeters.

After selecting all necessary input files, the module PROCESS is then activated to execute the following successive tasks: calculating the geophysical corrections, adjustments of the gravimeter data, and outlier tests. In this module, users may select some options related to selection of constrained site, definition of weighted constraint, and the selection of geophysical effects.

Once the gravimeter data have been completely adjusted, the results then go to the module OUTPUT. By this module, brief statistical information is shown in the main window and all the estimated results including their statistical analysis are written to output files.

**Adjustments of Gravimeter Data**

Center for Gravity Control Networks and Geodynamics, Geospatial information Agency (BIG), carried out the relative gravimeter measurements in Palu and Donggala areas, Central Sulawesi, from October 31st to November 11th 2016. Ninetysix (96) gravity stations were occupied using the CG-5 Scintrex gravimeter. All stations are grouped into 11 measurements loops (see Figure 3). To reduce the drift error, every single loop is measured within one day.

Station 9923 (located at the Palu airport) is chosen as a reference site. A priori gravity value at this station is 978027.7500 mGal. Since the value was derived from the first order of Indonesian Gravity Control Network, we assign relatively high constraint in the element of matrix \( P_c \), namely: \( 10^9 \) (presumed the tie point to be highly accurate). The estimated gravity values and their standard deviations for all stations are summarized in Table 1a and Table 1b, while the measurements residuals calculated using Equation 16 is depicted in Figure 5. The results from global test are presented in Table 2.

From Table 1, it can be seen that the estimated values of the gravity are quite accurate with the standard deviations are less than 0.01 mGal. Furthermore, a symmetric pattern of the residuals plot in Figure 5 indicates that pyGABEUR-ITB can reduce any possible systematic errors (i.e. geophysical effects and instrumental drifts). Results of goodness-of-fit test as summarized in Table 2 show that the test is not success. This is due to the computed reference variance is much smaller than the a priori variance. However, if the goodness-of-fit test fails because of the computed reference variance is too small, the test result could be ignored since correcting it does not change the adjusted result significantly (Ghilani, 2010).
Figure 4. Main window of pyGABEUR-ITB.

Table 1. The estimated gravity values relative to the a priori gravity value at station 9923 and their standard deviations.

| Station | Estimated Gravity (mGal) | Station | Estimated Gravity (mGal) |
|---------|--------------------------|---------|--------------------------|
| 11      | 76.8271±0.0028           | 252     | -27.0819±0.0116          |
| 12      | 81.2661±0.0021           | 253     | -23.5768±0.0110          |
| 31      | 52.0721±0.0146           | 261     | -113.0174±0.0102         |
| 32      | 46.5740±0.0154           | 262     | -194.4188±0.0104         |
| 33      | 44.7810±0.0135           | 271     | 26.6141±0.0099           |
| 41      | 36.5416±0.0152           | 272     | 12.2676±0.0099           |
| 42      | 46.5279±0.0140           | 273     | -12.3881±0.0062          |
| 43      | 47.7254±0.0137           | 281     | 12.7288±0.0105           |
| 51      | 13.9579±0.0049           | 282     | 4.1945±0.0103            |
| 52      | -12.4972±0.0146          | 283     | 2.4358±0.0113            |
| 53      | -33.1122±0.0143          | 291     | -6.8343±0.0110           |
| 61      | 77.3607±0.0033           | 292     | -2.8881±0.0109           |
| 62      | 67.4256±0.0039           | 293     | 0.2841±0.0113            |
| 63      | 65.1710±0.0043           | 301     | -5.8504±0.0111           |
| 81      | 39.1201±0.0121           | 302     | -4.7470±0.0068           |
| 82      | 44.6946±0.0160           | 303     | -2.4296±0.0110           |
| 83      | 40.3663±0.0147           | 321     | -54.5234±0.0056          |
| 91      | 38.5025±0.0118           | 322     | -24.5200±0.0056          |
| 92      | 20.7533±0.0115           | 331     | -4.3001±0.0121           |
| 102     | 31.9230±0.0113           | 332     | 12.1316±0.0106           |
| 112     | 63.9337±0.0046           | 333     | -7.1038±0.0116           |
| 121     | 60.1040±0.0059           | 339     | 5.9045±0.0058            |
| 122     | 57.2591±0.0056           | 341     | -6.2377±0.0060           |
The measurements residuals calculated using Equation 16.

Table 2. Results from goodness-of-fit test.

| Parameters       | Value |
|------------------|-------|
| A priori variance| 1     |
| (reference variance) | 0.0046 |
| Redundancy       | 4     |
| Confidence level | 95%   |
| Tested value     | 0.0194|
| Lower critical value | 0.7089 |
| Upper critical value | 9.4877 |
| Test result      | Fail  |

Comparisons with GRAVNET Software

The results presented in Table 1, Table 2, and Figure 5 may indicate quality of the internal precision produced by pyGABEUR-ITB. Concerning the accuracy, the results should be compared against the other software. In this section, comparisons with GRAVNET software (Hwang et al., 2002) are briefly summarized. Relative gravity measurement data in Palu and Donggala adjusted using GRAVNET software (Hwang et al., 2002) are used to validate the result from pyGABEUR-ITB. The results are depicted in Figure 6. It could be presented in the form of RMS and standard deviation, of about 2 x 10^{-5} mGal and 0.0048 mGal, respectively. These values are negligible, indicating that pyGABEUR-ITB and GRAVNET statistically produces the same results.

The adjustment method used in either pyGABEUR-ITB or GRAVNET is similar. The differences are only in handling geophysical effects and estimating the instrumental drift. In pyGABEUR-ITB, as mentioned before, the drift error is estimated for each loop, while GRAVNET estimates the drift as a single value for the entire loops. According to these comparisons, one may conclude that the accuracy of different geophysical models used by pyGABEUR-ITB or GRAVNET are comparable.

CONCLUSIONS

Development of a free and interactive software for adjustment of relative gravimeter data has been summarized in this paper. The weighted constraint adjustment with at least one reference station is employed to adjust the data. Performance of the software is quite good since it can properly handle some geophysical effects and instrumental drifts. Furthermore, the software produces similar results with those estimated by GRAVNET software.

Although in this current test the software is applied to analyze the gravity network with a single reference site, it provides an easy way to add additional reference sites by simply selecting the fixed points and set their corresponding variances (see Figure 4). As for the geophysical effects, the user can select which effect will be reduced. This may provide the user who wants to know the magnitude of the individual effect to the estimated gravity values at all sites.

The software (at the current form) is recently suited to process the data from the gravimeter that adopts the principle of vertical spring balance such as the CG-5 and CG-6 Scintrex gravimeters. The users who work with the other gravimeters may easily modify the source codes, which are available upon request. One thing that the users might have to be aware is the term $\Delta F(\vec{r})$ in Equation 1. Since the CG-5 and CG-6 Scintrex gravimeters use the vertical spring balance principle, this term is negligible and hence pyGABEUR-ITB does not deal with it. In the near future, pyGABEUR-ITB will be extended to be able to automatically adapt the use of various observation principles.
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