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Gsolve, a Python computer program with a graphical user interface to transform relative gravity survey measurements to absolute gravity values and gravity anomalies

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ABSTRACT

A Python program (Gsolve) with a graphical user interface has been developed to assist with routine data processing of relative gravity measurements. Gsolve calculates the gravity at each measurement site of a relative gravity survey, which is referenced to at least one known gravity value. The tidal effects of the sun and moon, gravimeter drift and tares in the data are all accounted for during the processing of the survey measurements.

The calculation is based on a least squares formulation where the difference between the absolute gravity at each surveyed location and parameters relating to the dynamics of the gravimeter are minimized with respect to the relative gravity observations, and some supplied gravity reference site values. The program additionally allows the user to compute free air gravity anomalies, with respect to the GRS80 and GRS67 reference ellipsoids, from the determined gravity values and calculate terrain corrections at each of the surveyed sites using a prism formula and a user supplied digital elevation model.

This paper reviews the mathematical framework used to reduce relative gravimeter survey observations to gravity values. It then goes on to detail how the processing steps can be implemented using the software.

Code metadata

Current Code version	3
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-16-00075
Legal Code License	GNU
Code versioning system used	Unique version numbers
Software code languages, tools, and services used	Gsolve is written in Python2.7 and the GUI using PyQt4. Gdal, the Geospatial data abstraction library is written in Python and C and C++. All libraries used are released under an open source software licence such as GNU
Compilation requirements, operating environments & dependencies	We recommend installing the latest Anaconda Python2.7 64-bit distribution as it will take care of installing the dependencies except gdal which can then be installed via the command prompt using "conda install gdal". Otherwise Gsolve uses the following external python libraries: PyQt4, Tkinter, tkfiledialogue, numpy, xlrd, xlwt, xlutils, matplotlib, ctypes and gdal. The GUI was set up for windows.
If available Link to developer documentation/manual	Not available
Support email for questions	jack.mccubbine@ga.gov.au

1. Introduction

The Earth's gravity field is routinely measured using high precision (1 microGal = 10 nm/s^2) relative gravimeters. Reilly [1] gives a

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robust least squares formula to transform relative gravity measurements to gravity values. The formula relies on the relative survey including at least one measurement at an absolute gravity reference site and takes into account tidal gravity effects and gravimeter drift. The least squares formula has been previously implemented by Woodward and Carman [2] in a FORTRAN computer program called DSOLVE.

We first review Reilly's [1] methodology to transform relative gravity survey observations to gravity values. We then give two alternative methods which constrain the relative gravity observation equations to existing gravity values differently. For the practical implementation of these formulas, we have developed a new Python computer program (Gsolve) with a graphical user interface. It further accounts for additional practical considerations of relative gravity surveying and gravimeter dynamics which are not included in Reilly's [1] original methodology. For example, tares in the observation data and different uncertainty levels in the gravity reference values.

Gsolve first converts relative gravimeter field observations to mGal (10^5 m/s^2) using a user supplied calibration table and/or a gravimeter calibration factor determined from the observations. It then corrects the observations for tidal gravity effects using the Longman [3] formula and finally solves for the gravity values at the observation sites by least squares whilst accounting for the gravimeter drift. The operation of the program to perform these processing steps is given in detail.

2. Methodological framework to transform relative gravity observations to gravity values

Reilly [1] gives the relative gravimeter reading $x_{i,j}$, made at location j and time t_i as

$$x_{i,j} = g_j - a - b(t_i - t_1) + z_{i,j} - e_i \quad (1)$$

where,

- g_j is the true gravity value at location j,
- $-b(t_i - t_1)$ is the value corresponding to the amount meter has drifted by time t_i,
- $z_{i,j}$ is the tidal gravitational effect at location j and time t_i (this is a known quantity that can be computed by the Longman [3] formula),
- a is the gravimeter zero point (i.e. the absolute gravity value where the relative gravimeters dial reads zero, in the absence of any drift or tidal effects), and
- e_i is a (small) error term associated to the meter reading at time t_i.

Collecting the known quantities and the error term on the right hand side gives an observation equation of the following form,

$$g_j - a - b(t_i - t_1) = x_{i,j} - z_{i,j} - e_i. \quad (2)$$

Implicit in all surveys using relative gravimeters, there is a subset of the N observations at M locations where there are previously recorded gravity values $\hat{g}_j$. With respect to the true gravity value g_j, the values $\hat{g}_j$ must also include a (small) error term ϵ_j. This leads to a second equation of the form,

$$g_j = \hat{g}_j + \epsilon_j. \quad (3)$$

In order to relate the relative gravity observations to the absolute gravity values, there must be at least one equation of this type. i.e. the relative gravity observations must be made at least one location where gravity is already known. The system of linear equations given by Eqs. (2) and (3) can then be used to determine the best fitting parameters $\tilde{g}_j$, $\tilde{a}$ and $\tilde{b}$ to the observations by least squares.

Method 1: Normal least squares. The system of linear equations given by Eqs. (2) and (3) can be written in the matrix form given by Eq. (4).

$$\begin{vmatrix} P & -\mathbf{1} & -\mathbf{T} \\ Q & 0 & 0 \end{vmatrix} \begin{vmatrix} \mathbf{g} \\ a \\ b \end{vmatrix} = \begin{vmatrix} \mathbf{x} - \mathbf{z} \\ \mathbf{h} \end{vmatrix} + \begin{vmatrix} \mathbf{e} \\ \boldsymbol{\epsilon} \end{vmatrix} \quad (4)$$

where,

- $\mathbf{g}$ is the vector of g_j's
- P is an $N \times M$ matrix with 1's in the column j and row i for observations at locations j and time t_i, with 0's everywhere else
- $\mathbf{1}$ is an $N \times 1$ vector of ones
- T is a $N \times 1$ vector of times $t_i - t_1$,
- Q is an $M \times M$ matrix with 1's on the diagonal for row j for locations which correspond to Eq. (3) with 0's everywhere else
- $\mathbf{x} - \mathbf{z}$ is the vector of meter reading minus the tidal effect for each observation and
- $\mathbf{h}$ is a $M \times 1$ vector with entries $\hat{g}_i$ for which the rows of matrix Q have a 1 in them and zero otherwise.

A least squares solution can then be sought which minimizes the sum of the squared error terms in the vectors $\mathbf{e}$ and $\boldsymbol{\epsilon}$. This will give the best fitting parameter estimates of the absolute gravity at the surveyed locations $\tilde{\mathbf{g}}$, the gravimeter base line $\tilde{a}$ and the drift factor $\tilde{b}$.

This method does not decouple the reference sites from the system of observation equations and assumes the errors terms ϵ are non zero. This allows the least squares solution for the absolute gravity values at the reference sites to differ from the previously recorded values. This is advantageous when the reference absolute gravity values are uncertain, for example if the values are dated or were made with inaccurate instrumentation.

Method 2: Decoupled least squares, following Reilly [1]. Reilly's [1] original method solves Eqs. (2) and (3) by decoupling the reference gravity values from the observation equations.

Decoupling the reference gravity values is performed by modifying Eq. (2). For the observations made at reference gravity sites, the reference gravity values $\hat{g}_j$ are subtracted from the right hand side of the observation equations and the value g_j for that particular location is discarded. This gives a new observation equation of the form,

$$-a - b(t_i - t_1) = x_{i,j} - z_{i,j} - \hat{g}_j - e_i \quad (5)$$

In terms of Eq. (4), this corresponds to making amendments to P and $\mathbf{x} - \mathbf{z}$. Entries in column j of P such that the observation equations are of the form of (5) are set equal to zero, and the values $\hat{g}_j$ are subtracted from the vector $\mathbf{x} - \mathbf{z}$.

This method fixes the reference gravity values so that they do not change in the least squares solution, forcing the residual error terms ϵ to be exactly equal to zero. However the estimated gravity values parameter variances for the reference sites are non-zero, despite the solution fitting exactly to the given previously recorded gravity value. In relation to the two other described methods, this corresponds to a mid-level of confidence in the reference gravity values.

Method 3: Constrained least squares. This method solves a set of equations of the form of Eq. (1) with constraint equations that are similar to an error-less form of Eq. (2) using the method of constrained least squares. The least squares matrix equation is formulated as follows.

Consider the equation

$$X\beta = Y - e \quad (6)$$

where, $X = [P, -\mathbf{1}, -\mathbf{T}]$, $\beta = \begin{vmatrix} \mathbf{g} \\ a \\ b \end{vmatrix}$, $Y = [\mathbf{x} - \mathbf{z}]$ with P, T, x, z, $\begin{vmatrix} \mathbf{g} \\ a \\ b \end{vmatrix}$ and e are as specified in method 1. Constraints are given by the matrix equation,

$$K\beta = c \tag{7}$$

where K has dimension $k \times (M+2)$ for some k. Here k is the number of reference gravity sites and so K has the same form as Q but with the zero rows removed. c is a $k \times 1$ vector, and contains the specified gravity values in each row for the location corresponding to the column with a 1 in it in matrix K. This equation is similar to an error-less form of Eq. (3). Similar to method 2, the reference gravity values at locations j are fixed.

The aim here is to minimize,

$$S = (Y - X\beta)'(Y - X\beta) + \lambda'(K\beta - c)^2) \tag{8}$$

where λ is a $k \times 1$ vector of Lagrange multipliers.

S has a minimum where (1) $\frac{\partial S}{\partial \beta} = 0$ and (2) $\frac{\partial S}{\partial \lambda} = 0$. This is given by,

$$2X'(Y - X\lambda) - K'\lambda = 0 \tag{9}$$

or (for $\hat{\lambda} = \lambda/2$)

$$X'(Y - X\beta) - K'\hat{\lambda} = 0 \tag{10}$$

which implies,

$$X'X\beta - K'\hat{\lambda} = X'Y \tag{11}$$

and

$$K\beta = c \tag{12}$$

This can be written in matrix form as follows,

$$\begin{vmatrix} X'X & K' \\ K & 0 \end{vmatrix} \begin{vmatrix} \beta \\ \hat{\lambda} \end{vmatrix} = \begin{vmatrix} X'Y \\ c \end{vmatrix} \tag{13}$$

where the best fitting parameters are found by,

$$\begin{vmatrix} \tilde{\beta} \\ \tilde{\lambda} \end{vmatrix} = \begin{vmatrix} X'X & K' \\ K & 0 \end{vmatrix}^{-1} \begin{vmatrix} X'Y \\ c \end{vmatrix}. \tag{14}$$

The error terms ϵ are considered to be zero and the $\hat{g}_j$ parameter variances are also zero. This method is most appropriate when the reference gravity values are considered to be error free and is best suited to a high level of confidence in the reference gravity values.

Here, three methods to transform relative gravity observations to gravity values have been given. Despite their theoretical differences, in general, each method should return almost identical gravity values. However, the derived gravity value variances may differ between the methods due to the theoretical considerations of the precision of the reference gravity values.

3. Gsolve

Gsolve is a Python computer program designed to make the routine processing of relative gravity survey data user friendly through the use of an intuitive graphical user interface. The program transforms relative gravity observations to gravity values and can further be used to reduce the derived gravity values to gravity anomalies.

The relative gravity transformation process performed by the software corrects the gravimeter readings for drift, tidal gravitational effects and jumps in the gravimeter zero point (hereafter referred to as a tare) and additional gravimeter calibration factors. Further, the gravity anomaly reduction tools can calculate free air gravity anomalies (relative to the GRS80 and GRS67 reference ellipsoids) and can compute gravimetric terrain corrections with a user supplied digital elevation model. Details of the program are given in the following subsections.

3.1. Relative gravity data processing

Importing survey data. The relative gravity measurements, location identities, the time and date (in UTC) and location of each observation must first be imported or manually entered into the program. These input data will be used to construct the system of linear equations. Fig. 1 shows the graphical user interface where this operation is performed; this is the first page the user is shown upon running the program.

The user can either import the data from an excel spread sheet (by pressing (1)) with the specified format given by the example survey data file example_survey_data.xls or enter the observations manually one by one (by pressing (3)). Rows of data can be removed using button (4) and the survey data can be exported as a spreadsheet from Gsolve by clicking (2).

Gravity surveys with relative gravimeters are usually undertaken as a series of daily observations (or "loops") that include one or more repeat observations at the first site for each day. Collecting the raw observations in this manner allows the gravimeter drift rate and gravimeter zero point to be determined over separate time period. This helps to account for "tares" in the data where the zero point of the gravimeter changes due to knocks and bumps.

The user can assign individual loop numbers to portions of the observation data. When solving the system of linear equations, given by Eqs. (2) and (3), Gsolve computes separate gravimeter zero points values a and drift coefficients b for each loop. This is advantageous since it can be used to account for tares in the gravimeter zero point value and variable drift rates between separate days of data.

Absolute gravity reference sites and gravimeter calibration tables stored in Gsolve. Gsolve stores 2 databases, the first contains the absolute gravity reference sites to be used for Eq. (3) and the second contains gravimeter calibration tables supplied by the manufacturer to transform the gravimeter dial readings into gravity units $x_{i,j}$.

Fig. 2 shows the graphical user interface which can be used to interact with the databases. New gravimeter calibration tables can be imported and saved in the Gsolve database by clicking button (5) and following the on-screen instructions (the file format is given by calibration_table_example.xls), tables in the database can be viewed by selecting one of the drop down options from (6) and tables can be deleted from the database by clicking (7). New absolute gravity values can be added to the database by clicking "Import" (8) and importing a files with the same format as example_absolute_gravity.xls, or by clicking "Add New" (9) and entering the reference site details manually.

Setting up the system of linear equations. The graphical user interface to solve the systems of linear equations by least squares is given by Fig. 3.

First the gravimeter calibration table (stored in the Gsolve database) must be specified using the drop down menu (12). Next the user must specify the reference absolute gravity site to construct equations of the form of Eq. (3), by clicking (13). The program will prompt the user to find them in the database by matching the surveyed site names with those stored or to enter them manually, any falsely added reference site can be removed by selecting the row and clicking (14).

The user must then select whether or not to calculate separate gravimeter zero points $\tilde{a}$ and drift rates $\tilde{b}$ for each loop identified in the survey data by clicking (15). Typically, processing the data with multiple loops results in smaller $\tilde{g}_j$ parameter standard error estimates since tares in the gravimeter zero points between separate loops are better accounted for.

The software allows the user to select a residual confidence interval. This can be changed by editing the value in (16), the

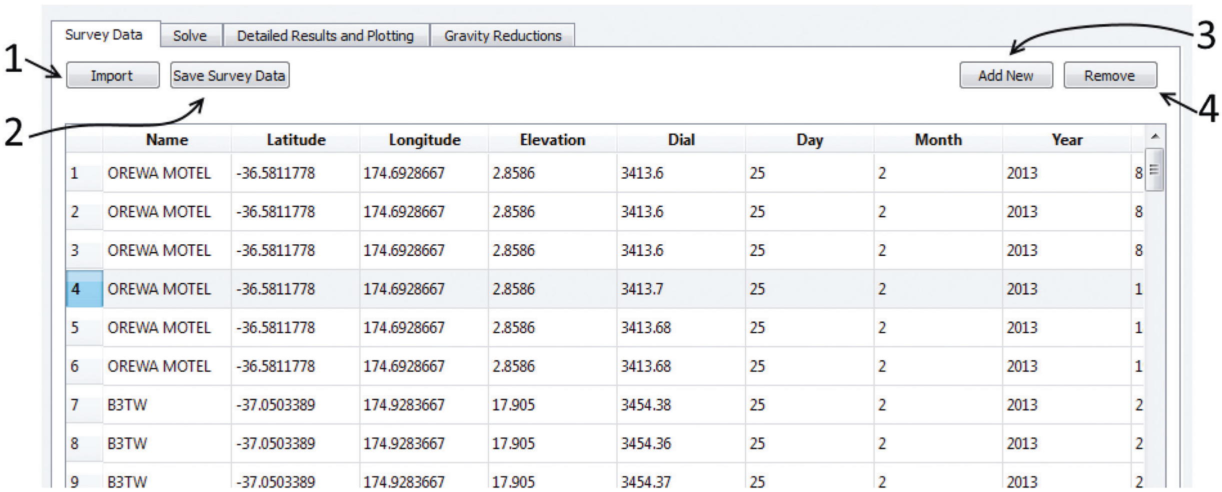

Fig. 1. Graphical user interface to import relative gravity survey data into Gsolve.

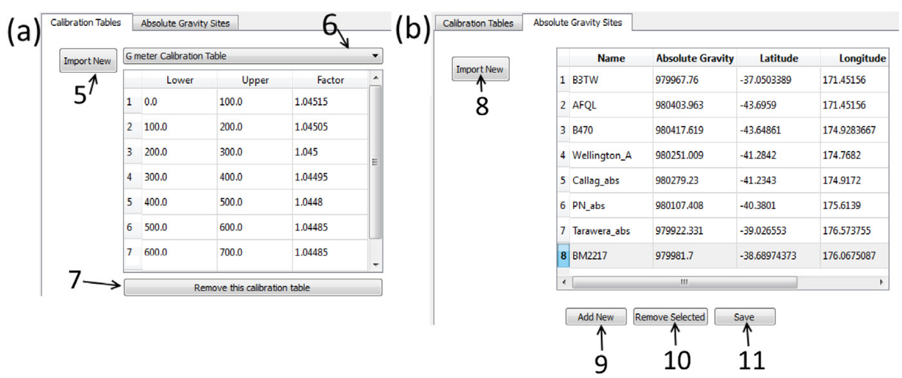

Fig. 2. (a) shows the graphical user interface to view, import and delete gravimeter calibration tables from the Gsolve database. (b) shows the graphical user interface to view, import, modify, save and delete absolute gravity reference sites from the Gsolve database.

default is 100%. When this value is less than 100%, Gsolve will produce an initial solution, identify outliers outside of the specified confidence interval then compute a new solution with the outliers removed. This is useful for removing the influence of erroneous measurements on the determined parameters $\tilde{g}_j$, $\tilde{a}$ and $\tilde{b}$.

Additional gravimeter calibration factor. Reilly [1] identified a method to determine a further calibration scaling factor β for the relative gravimeter readings. This is useful where the gravimeter calibration table is unavailable or imprecise. To compute this value by least squares, Eq. (4) must be modified to give Eq. (15),

$$\begin{vmatrix} P & -\mathbf{1} & -\mathbf{T} & \mathbf{x} \\ Q & 0 & 0 & 0 \end{vmatrix} \begin{vmatrix} \mathbf{g} \\ a \\ b \\ \beta \end{vmatrix} = \begin{vmatrix} \mathbf{x}-\mathbf{z} \\ \mathbf{h} \end{vmatrix} + \begin{vmatrix} \mathbf{e} \\ \epsilon \end{vmatrix} \tag{15}$$

To determine the value of β the survey data must be referenced to at least two absolute gravity sites. The β value can be determined by Gsolve by clicking (18). Alternatively it can be specified by the user in (17), using a previously derived value, and is used to calibrate the gravimeter readings prior to determining the least squares solution. The default option is to not calculate β and to set it equal to zero, i.e. it is excluded from the calculation.

Solving the systems of linear equations. The user can then specify the least squares method to be used, (i.e. normal least squares, decoupled least squares or constrained least squares) to find the absolute gravity at each surveyed location.

The least squares calculation is finally initiated by pressing "Solve" (20). The gravimeter readings are first calibrated using the specified calibration table (and β factor). Tidal gravity effects are then calculated and subtracted from the observations using the Longman [3] formula, then the system of linear equations is arranged and the least squares solution to parameters $\tilde{\mathbf{g}}$, $\tilde{a}$, $\tilde{b}$ and β are determined.

The least squares determined absolute gravity at each site is shown in the table along side standard errors of the determined value and the number of observations used. The data in the table can be exported to an xls file by clicking (21) and following the on-screen instructions.

Detailed output. A detailed output of the least squares solution is given in the "Detailed Results and Plotting" tab. This is shown in Fig. 4. For each observation in the survey the site name, position, dial and calibrated dial reading, date and time, tidal effect, loop identity and residuals are given in the table. The drift rate per hour for each loop is given by (22) and the β value (whether specified or calculated) is given by (23).

The drift function and observation residuals around the drift function of any individual loop can be plotted using (25) and similarly a cumulative distribution function of the observation residuals can be plotted using (24). These plots are useful to help identify outliers or whether the use of a confidence interval would be appropriate (i.e. whether or not there appears to be large outliers from the drift function or long tails in the cumulative distribution plots). The detailed output data can be exported to an xls file by clicking (26).

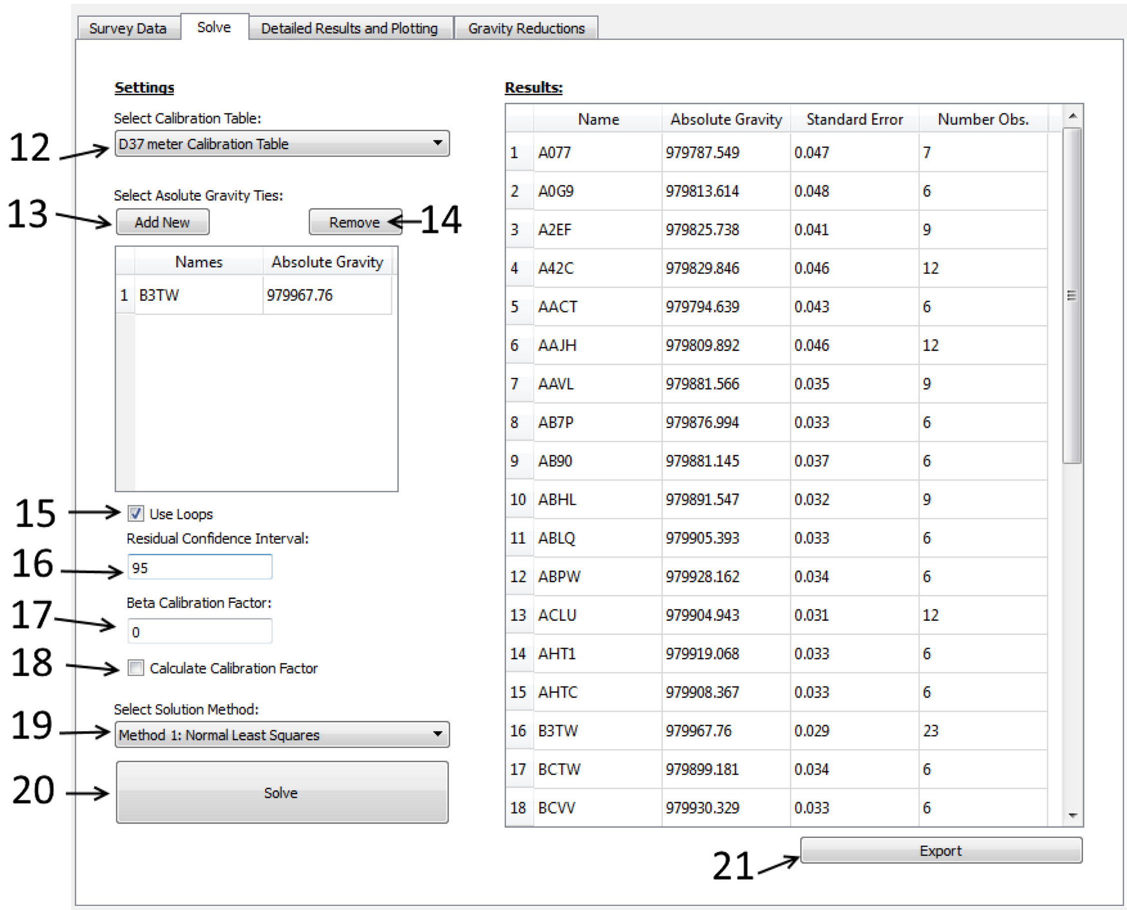

Fig. 3. Specify the gravimeter calibration table to be used, the absolute gravity reference sites, the settings of the least squares solution and calculate the absolute gravity values.

3.2. Computing gravity anomalies

Free air anomalies. Once absolute gravity values have been obtained at each observation site, Gsolve can also be used to determine free air gravity anomalies. The free air anomaly Δg_{FA} is defined as the difference between the observed gravity g and the gravity of an Earth approximating ellipsoid evaluated at the elevation and latitude of the observation. i.e.

$$\Delta g_{FA} = g - \gamma(\phi) - \delta g_{FA} \tag{16}$$

where $\gamma(\phi)$ is the ellipsoidal gravity and δg_{FA} is the free air effect which is estimated using the linear formula $-0.3086H$ mGal/m with H the observation point height in meters. $\gamma(\phi)$ can be computed with respect to the GRS80 or GRS67 reference ellipsoid parameters. This is done by selecting the corresponding ellipsoid from the drop down menu and clicking the update button (27). The graphical user interface to view and export (using button (28)) the gravity correction values and gravity anomalies is shown in Fig. 5.

The ellipsoidal gravity is calculated using the Moritz [4] formula given by Eq. (17),

$$\gamma(\phi) = \gamma_a \frac{1 + k\sin^2(\phi)}{\sqrt{1 - e^2\sin^2(\phi)}} \tag{17}$$

where ϕ is the ellipsoidal latitude. The parameters used for GRS80 ellipsoid are,

- $\gamma_a = 978032.67715$ (mGal)
- $k = 0.001931851353$
- $e^2 = 0.00669438002290$

and for the GRS67 reference ellipsoid are

- $\gamma_a = 978031.84558$ (mGal)
- $k = 0.001931663383$
- $e^2 = 0.00669460532856$

Terrain corrections. The Bouguer anomaly Δg_{BA} is defined as the free air gravity anomaly corrected for the gravitational effect of the topography around the observation site. The gravitational effect of the topography is typically corrected for in two parts, the Bouguer slab δg_{bs} and the terrain correction δg_{TC} so that,

$$\Delta g_{BA} = \Delta_{FA} - \delta g_{bs} + \delta g_{TC}. \tag{18}$$

The Bouguer slab correction, δ_{bs} in mGal is given by Eq. (19).

$$\delta g_{bs} = -0.0419\rho H \tag{19}$$

where H is the observation height in meters and ρ is the rock density in g/cm^3. Typically a value of 2.67 g/cm^3 is used.

Gsolve can be used to determine terrain corrections, δg_{TC} from a digital elevation model (DEM). The process uses the Naggy [5] prism formula. The user can read in a digital elevation model (DEM) in a any of the 50+ formats supported by the Python library GDAL (2016), a simple xyz format is used as an example here and is given as an example dataset by the file "NLDEM.txt".

The user interface to import the DEM is shown in Fig. 6. Button (29) allows the user to select their DEM file and the format is automatically deciphered and then plotted, the resolution is specified in text box (30). To proceed with the computation the user must

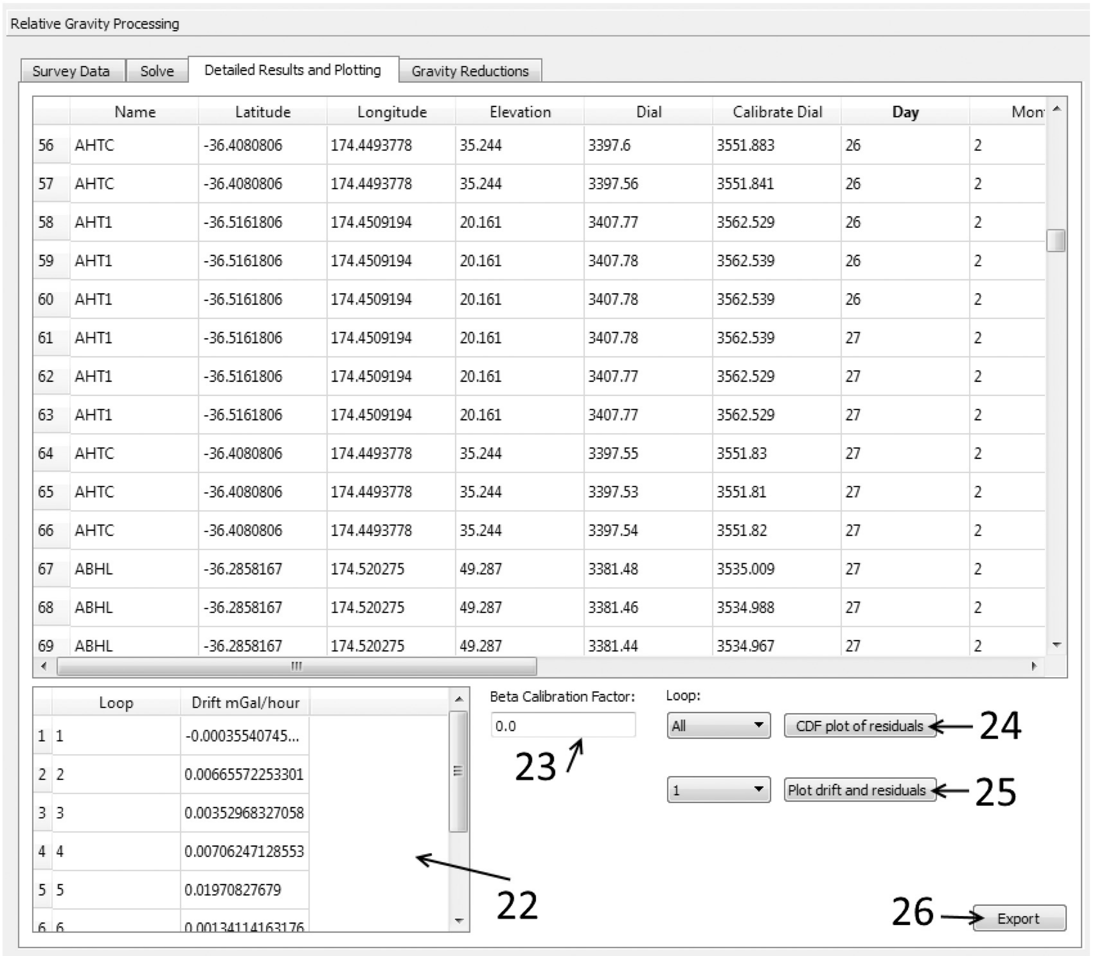

Fig. 4. Detailed results output graphical user interface.

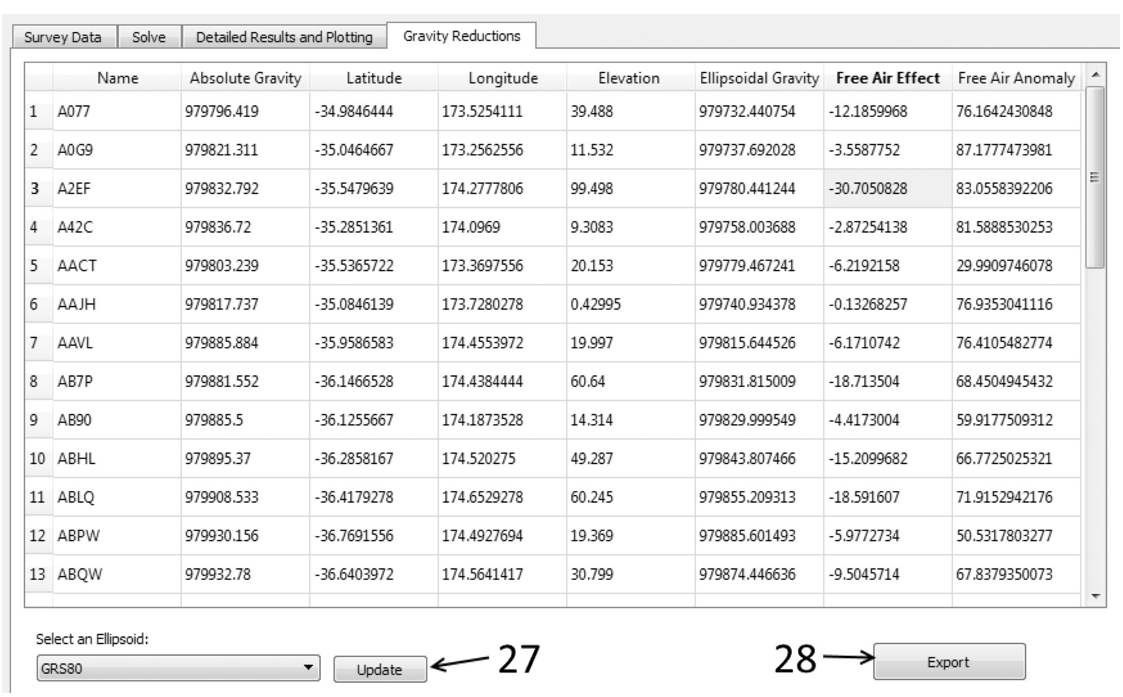

Fig. 5. Graphical user interface of surveyed site gravity anomaly derivation. Here a choice of the GRS80 or GRS67 reference ellipsoids can be made and the data can be exported to an xls file.

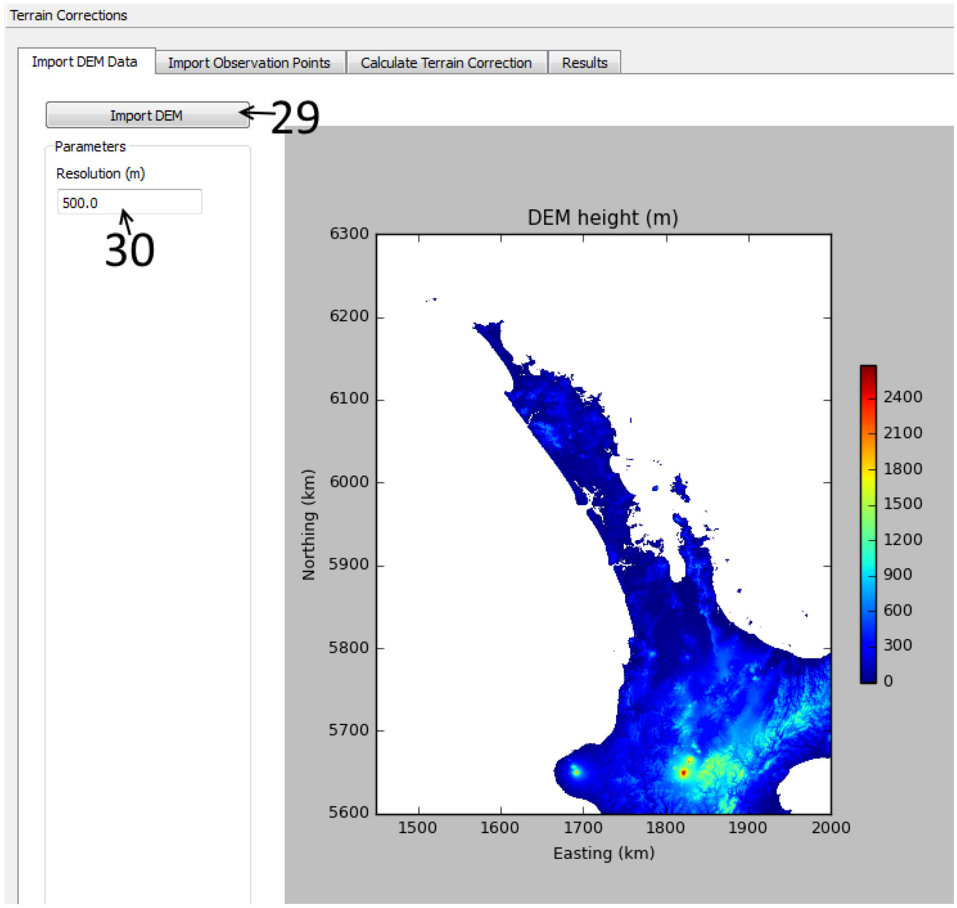

Fig. 6. Graphical user interface to import a digital elevation model file.

first import the location data file. This contains the Eastings and Northings of the gravity sites. The graphical user interface to do this is shown in Fig. 7.

This input file is the same file type as read in for the relative gravity data processing but must have two additional channels, Eastings and Northings, on the locations sheet of the xls file. The Eastings and Northings must be in meters and in terms of the same projection as the DEM. These additional columns are shown in the example file "example_survey_data.xls".

When the gravity sites are read in (by clicking (31)), the program prompts the user to specify which type of elevation of the gravity observation sites to use for the correction. The prompts present three options,

1. Gsolve can determine the heights from the DEM. this is selected by clicking "yes" to the first option,
2. the user can save DEM heights for the survey sites in the survey data input file and Gsolve will read them (where they stored in the 7th column of the input data locations sheet). this is performed by clicking "No" to the first option and "Yes" to the second option,
3. or the user can save field observed heights (e.g. GPS) in the survey input data file and Gsolve will read them in (where they are stored in the 4th column of the locations sheet). This is performed by clicking "No" to the first and second options.

If the gravity sites are located within the bounds of the DEM, option 1 is typically used. If the gravity sites are located outside the bounds of the DEM then but DEM heights have been computed previously these can be placed in column 7 of the survey data file (e.g. example_survey_data.xls) of the "locations" sheet and option 2 should be used. The user may, in some circumstances, find it preferable to use heights established in the field or some other height for the terrain correction, in which instance option 3 can be used.

The user must then select the "Calculate Terrain Correction" tab to specify the inner (32) and outer (33) radius of the terrain correction (i.e. the correction only accounts for the topography inside an annulus with the specified inner radius and outer radius) and the rock density (34) in g/cm^3 using the graphical user interface shown by Fig. 8. To initiate the calculation the user needs to click the button (35). When the calculation is complete the 'x' marks on the plot turn white and the terrain correction at each site is given on the plot.

The final results of the terrain correction calculation are given in the graphical user interface under the "Results" tab and this can be seen in Fig. 9. The results table contains the gravity site name, position data and the terrain correction. The parameters of the computed terrain correction are also given and the data can be exported using button (36).

The software enables the user to calculate terrain correction in several steps. For example, if terrain corrections are to be performed on and offshore, the user can first use DEM data onshore with a density value of 2.67 g/cm^3 and then use bathymetry data with a density value of 1.67 g/cm^3. Or, similarly the user may find it advantageous to use several DEM's of different resolution to speed up the calculations. For example an inner terrain correction out to a radius of 170 m from the gravity site may be calculated with a 2m resolution DEM, an intermediate terrain correction from 170 m out to 2160 m may be calculated with a 20 m DEM and an outer correction out to 21 900 m or beyond may be calculated with a

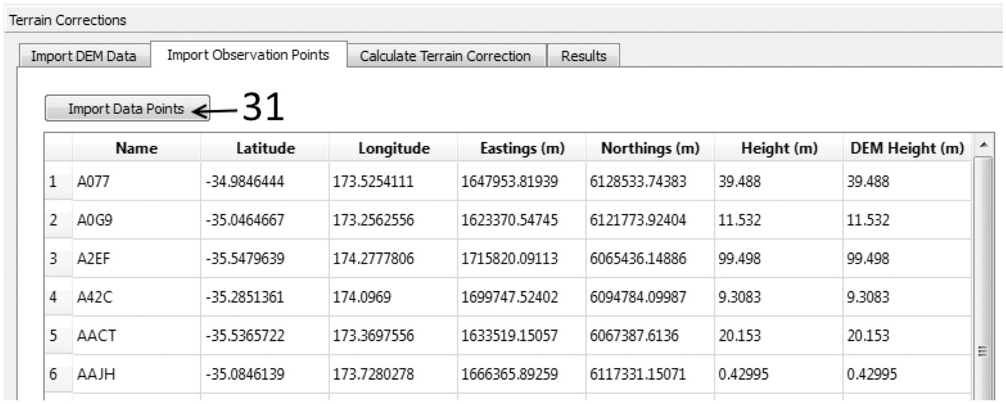

Fig. 7. Graphical user interface to import gravity site data for terrain corrections.

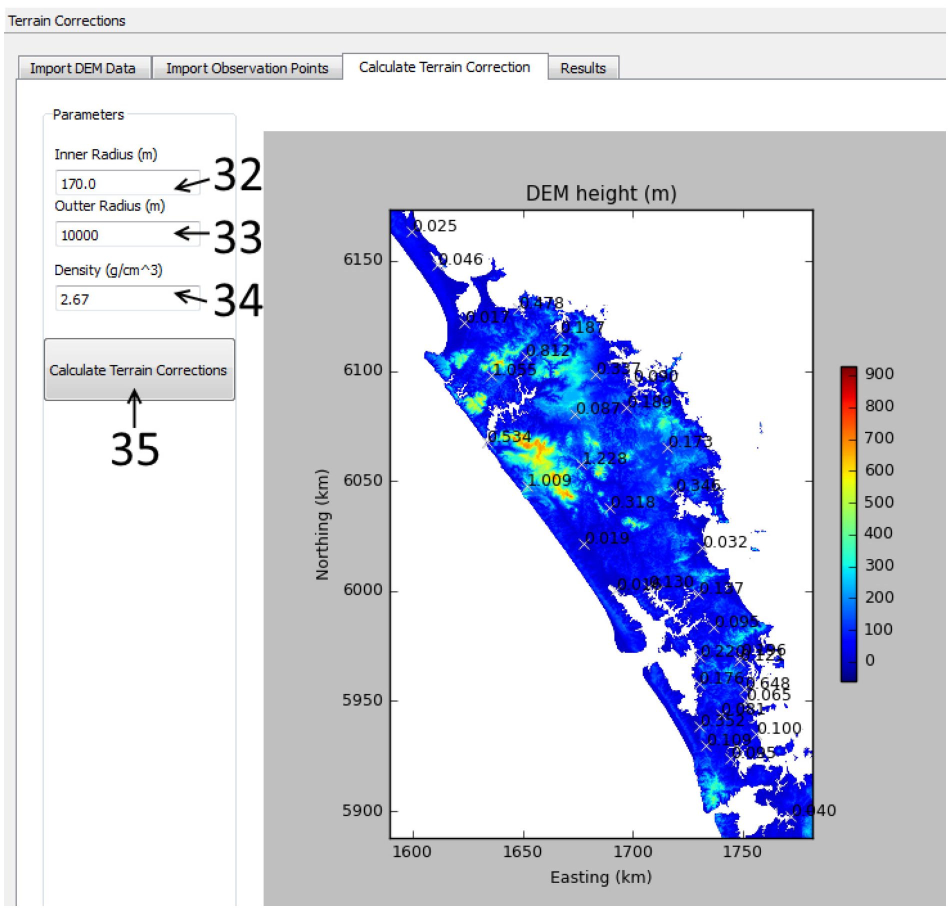

Fig. 8. Graphical user interface to set parameters and calculate terrain corrections.

200 m DEM. Individual terrain corrections may then be summed to determine the total correction for each gravity site.

4. Conclusions

Reilly's [1] least squares method to reduce relative gravity readings to absolute gravity values has been reviewed. Further, two alternative least squares formulations of the problem have been given. Each method relates the relative gravity measurements to the reference gravity values with different degrees of precision.

A new Python computer program, called Gsolve has been presented. The purpose of the program is to assist in the routine reduction of relative gravity survey data to gravity values by least squares. It has an intuitive graphical user interface for users unfamiliar with a command line interface so that it can be more easily adopted than older FORTRAN based programs. The processing chain used by the program accounts for tidal gravitational effects of the sun and moon, gravimeter drift and tares in the survey data. It also determines a further calibration factor for the gravimeter, when two or more reference absolute gravity sites are used.

In addition to the transforming relative gravity observations to gravity values, it is further able to compute free air gravity anomalies relative to the GRS80 and GRS67 reference ellipsoids

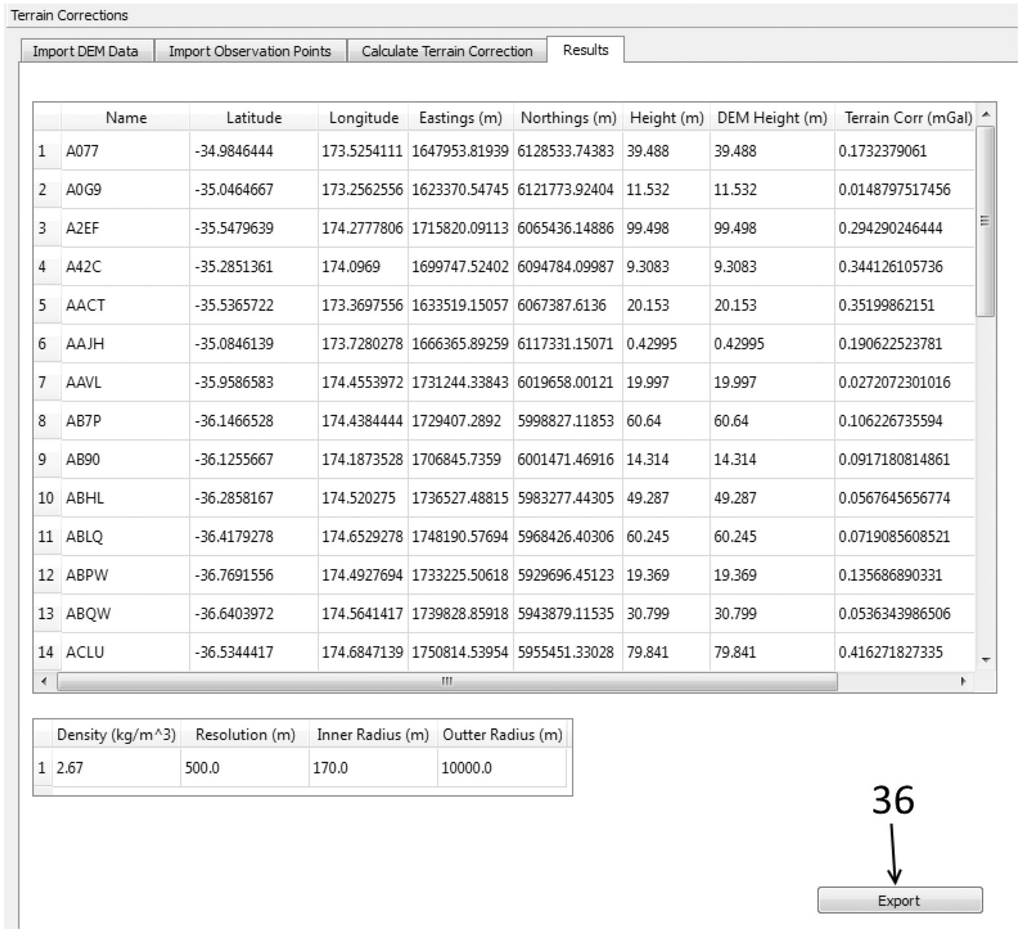

Fig. 9. Graphical user interface to set parameters and calculate terrain corrections.

and calculate terrain corrections from a user supplied digital elevation model and specified density parameter. This provides the user with all the necessary tools to calculate Bouguer gravity anomalies in a robust and consistent manner.

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