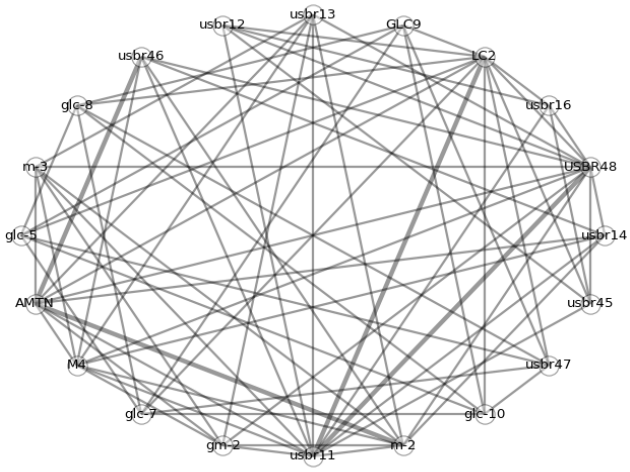

GSadjust User Guide v 1.0

U.S. Geological Survey
Southwest Gravity Program
February 8, 2019

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1. Overview

GSadjust is a cross-platform graphical user interface for least-squares network adjustment of combined absolute and relative gravity surveys. The software is a product of the [USGS Southwest Gravity Program]. The purpose of GSadjust is to facilitate the efficient processing of field gravity surveys. The program is useful for both synpotic ("snapshot") gravity surveys or surveys of gravity change over time. The program does not perform gravity inversion or otherwise interpret gravity data.

The objective of network adjustment is to determine a single, best-fit gravity value at each station based on all available measurements and their respective uncertainty. Typically the measurements are relative-gravity differences between stations, observed with a relative gravimeter, and absolute-gravity measurements at individual stations, observed with an absolute gravimeter. The reason relative-gravity differences are used instead of individual relative-gravimeter observations has to do with the nature of the relative-gravimeter, which is subject to constant, random drift and occasional tares, or offsets. Usually there will be more relative-gravity observations than absolute-gravity observations, and there will be redundant data (that is, more than the minimum data necessary to determine a gravity value at each station).

Although various software packages exist for least-squares network adjustment of survey measurements, gravity networks present unique considerations not present in other methods. First, the primary instrument used in spatially-distributed measurements of the Earth's gravity field is the relative gravimeter, the zero-point of which drifts randomly and unpredictably. Plotting gravimeter drift over time is considered essential for an accurate accounting of the meter's behavior. Second, it is widely recognized that gravity measurements are susceptible to various errors and "outlier" measurements are not uncommon. Network adjustments often proceed iteratively, including or excluding observations based on the statistical properties of the network. For these reasons the gravity-specific graphical interface GSadjust was developed for network adjustment.

GSadjust builds on the software PyGrav (Hector and Hinderer, 2016). Compared to PyGrav, GSadjust offers enhanced plotting and analysis of gravimeter drift, additional methods for drift correction (beyond inclusion as a parameter in the adjustment), and inclusion of absolute-gravity observations. GSadjust also offers additional functionality for network adjustment, including plotting results, enabling/disabling gravity differences, and calculating the change in gravity over time. GSadjust is written in Python 3.5 and the PyQt5 graphical user interface framework, and is public domain.

The software and related documentation on these web pages were developed in part by the U.S. Geological Survey (USGS) for use by the USGS in fulfilling its mission. The software can be used, copied, modified, and distributed without any fee or cost. Use of appropriate credit is requested. The USGS provides no warranty, expressed or implied, as to the correctness of the furnished software or the suitability for any purpose. The software has been tested, but as with any complex software, there could be undetected errors.

Mention of a particular trade name or manufacturer does not imply endorsement by the US Government.

Installing GSadjust

GSadjust is provided as Python source code that must be run in a specific Python environment. The source code can be downloaded here, either through the web interface or using "git clone":

https://github.com/jkennedy-usgs/sgp-gsadjust

The easiest way to ensure the proper Python environment exists is to use Miniconda, which allows multiple Python environments to coexist on a single machine.

1. Download and install the appropriate Miniconda installer for your platform (Windows, Mac, Linux, 32 or (probably) 64-bit): [https://conda.io/miniconda.html](https://conda.io/miniconda.html "Miniconda download") (Any Python version (e.g., 2.7 or 3.6) is okay)

2. Open a command window or terminal in the sgp-gsadjust (or sgp-gsadjust-master) directory and create a new conda environment:

```
conda env create --file environment.yml
```

   This creates a new conda environment named py35 with the appropriate python modules.

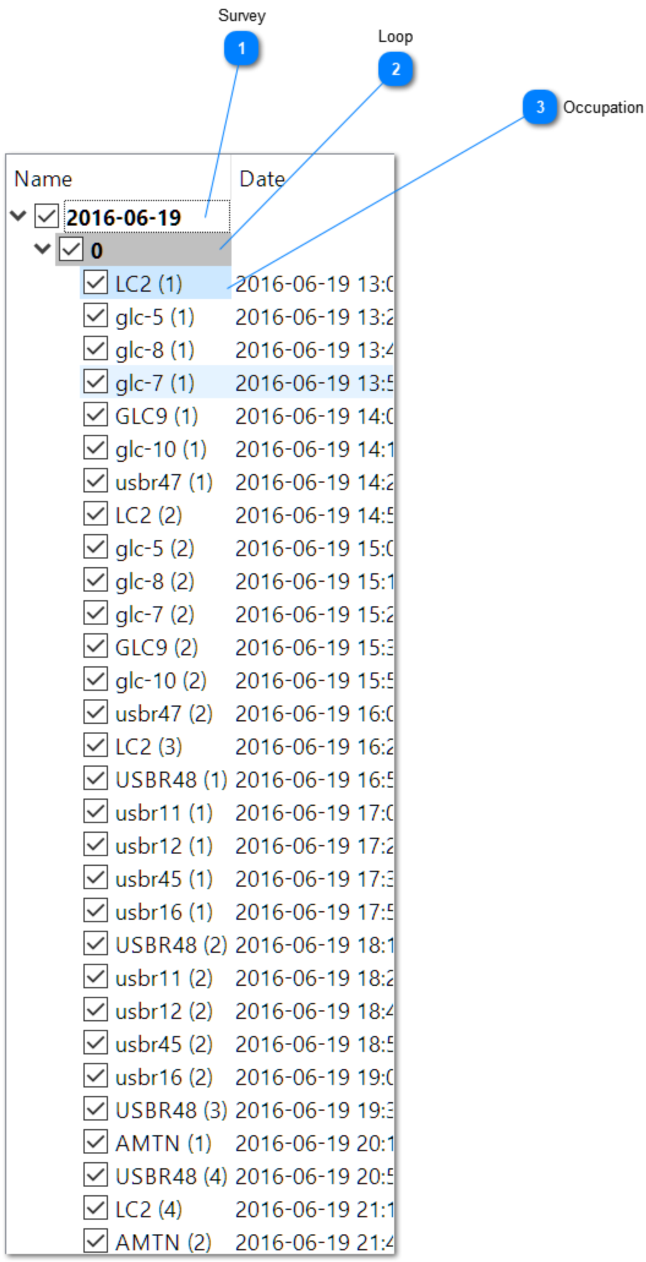
3. Activate the new Python environment by typing "activate py35" at the command line (only necessary if you've not previously installed git).

4. Clone the sgp-gsadjust repository (type "git clone https://github.com/jkennedy-usgs/sgp-gsadjust" at the command line) in the directory where you'd like to store the source code. Alternatively, use the download link on the Github webpage. If downloaded, unzip the sgp-gsadjust-master directory.

To run GSadjust on Windows, double-click gsadjust.bat in the sgp-gsadjust directory. On Mac or Linux, run the XXXXX shell script. This activates the conda environment and starts GSadjust.

Data Organization

Data in GSadjust are organized in a hierarchical tree. At the top-most level is the Campaign, which contains all of the data in a project, typically from a particular field area. The user does not generally interact with the Campaign object. Each Campaign has one or more Surveys, which represent all of the data combined in a network adjustment. If more than one Survey is present, gravity change over time can be calculated. Each Survey has one or more Loops; the drift correction is specified on a per-Loop basis. Each loop has two or more (station) Occupations. A station may be occupied one or more times in a Loop. Finally, each Occupation has one or more Samples. Typically during a relative gravimeter measurement several samples are taken (often at a 5 second interval for the Burris meter, or 90 second interval for Scintrex meters).



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[Surveys]

[Loops]

[Occupations]

Samples

A sample in GSadjust is a single observation (meter reading) at a station occupation. Usually any particular station occupation consists of several samples taken in relatively quick succession without moving the gravimeter. For the Burris meter, the minimum interval between samples is 5 seconds if ambient noise is sufficiently low. For Scintrex meters, the interval is usually longer, about 90 seconds.

All of the samples at a Station are displayed in the Data table, and plotted, on the Data tab.

Occupations

A (station) occupation includes all of the data collected during one setup at a station. If a station is visited multiple times during a survey, each visit is a unique occupation. Occupations are shown in the left-hand tree view with the station name, average date/time, and average g. Immediately after the station name, the occupation number is shown in parenthesis. For example, if the station LC2 were visited 3 times during a loop, the entries LC2 (1), LC2 (2), and LC2 (3) would appear in the left-hand tree view:

☑ LC2 (1)	2016-06-19 13:04:22	2588878.7
☑ glc-5 (1)	2016-06-19 13:29:31	2589673.4
☑ glc-8 (1)	2016-06-19 13:42:58	2591919.1
☑ glc-7 (1)	2016-06-19 13:55:32	2590909.6
☑ GLC9 (1)	2016-06-19 14:05:47	2593123.4
☑ glc-10 (1)	2016-06-19 14:17:39	2599628.7
☑ usbr47 (1)	2016-06-19 14:27:26	2601940.1
☑ LC2 (2)	2016-06-19 14:50:13	2588898.1
☑ glc-5 (2)	2016-06-19 15:08:17	2589700.3
☑ glc-8 (2)	2016-06-19 15:17:54	2591916.4
☑ glc-7 (2)	2016-06-19 15:28:33	2590910.6
☑ GLC9 (2)	2016-06-19 15:38:27	2593120.0
☑ glc-10 (2)	2016-06-19 15:53:10	2599627.9
☑ usbr47 (2)	2016-06-19 16:02:20	2601939.5
☑ LC2 (3)	2016-06-19 16:23:50	2588905.2

If samples are excluded by unchecking them in the main data view, the average date/time and g in the tree view is updated automatically.

Loops

A loop in GSadjust refers to all of the data for which a single drift-correction is applied. Traditionally, loops consist of a series of station occupations that start and finish at the same station (e.g., A-B-C-D-E-A). In the context of GSadjust, a loop may actually comprise two loops in the field, e.g. A-B-C-D-E-A-B-C-D-E-A (this double-loop approach is often used in high-precision surveys). Alternatively, stations in a GSadjust loop need not be visited in any particular order; the survey A-B-C-B-A-C-D-E-C-A could also be a defined as a single loop. Although often the same drift-correction method will be used throughout a campaign, the method could also vary by loop.

Surveys

A survey in GSadjust includes all of the loops (and their respective occupations and samples) that are combined in a single network adjustment. The survey represents a single snapshot in time, although in practice, data may be collected over a period of days to weeks if the gravity field is changing slowly.

If gravity change over time is evaluated, the change is calculated between surveys.

Campaign

A campaign in GSadjust includes all of the data in a project. Only one campaign can be opened or analyzed at a time. Campaigns consist of one or more surveys. If there are multiple surveys, gravity change over time can be calculated.

Campaign data, including checked/unchecked status, drift-correction method, and network adjustment options can be saved or loaded using the File > Save workspace... menu command.

Data Tree View

The Data Tree View is shown at the left side of the window throughout GSadjust. This view allows surveys, loops, and occupations to be activated or deactivated (with check boxes), and for stations to be organized (and re-organized) into loops.

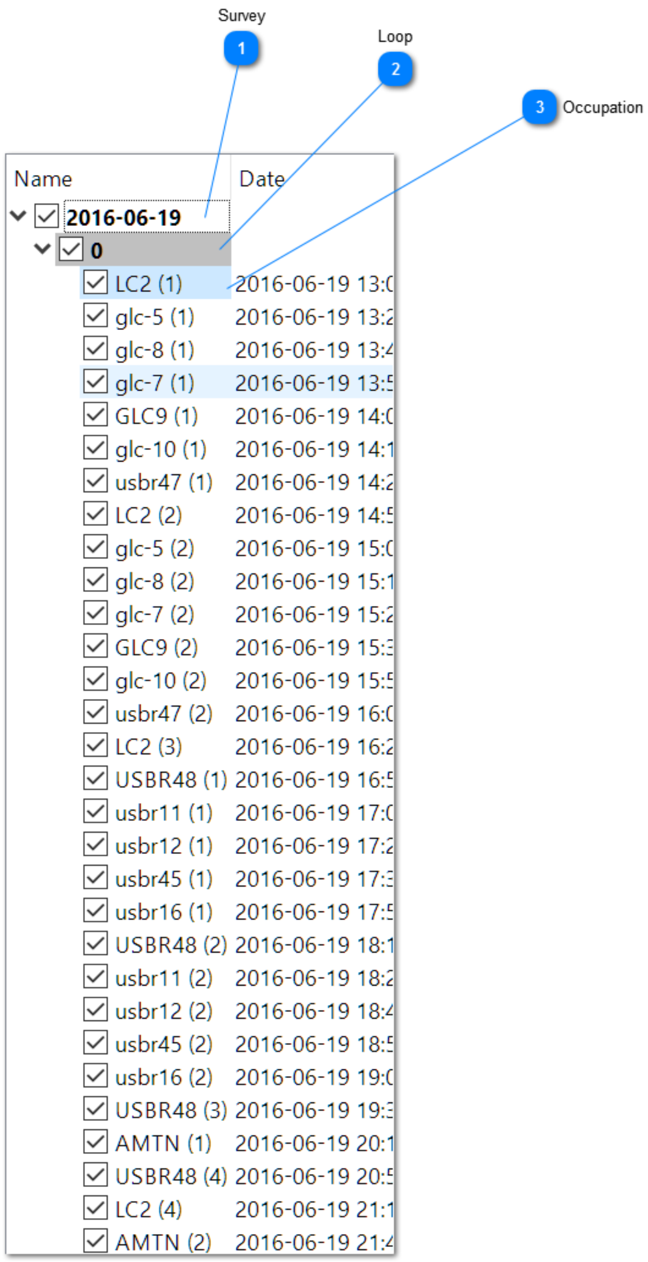
Stations may be deleted, duplicated, or moved to new loops using the context menu, which opens when right-clicking on a station name. Several consecutive stations can be selected by holding down the shift key.

Stations can be renamed by pressing the F2 key when the station is selected in the tree view. A dialog is presented with the option to rename all of the stations in the Campaign, or only the stations in the same Survey or same Loop.

Selecting surveys and loops

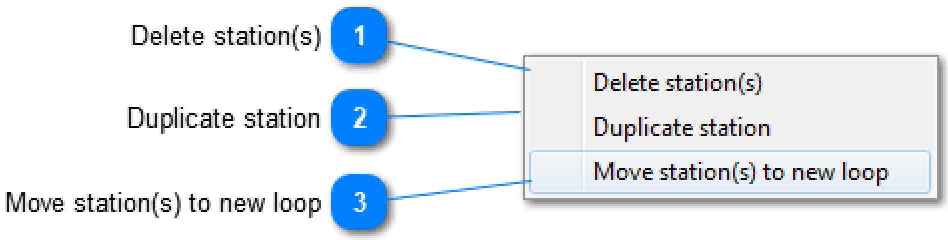
Certain actions and views in GSadjust act on, or show, the currently selected survey or loop. For example, when on the Drift tab, only the currently selected loop is shown, and the selected drift correction method applies only to that loop. On the Adjust tab, only the delta-g's and datum observations for the currently selected survey are shown, and the network adjustment is carried out on those observations.

A survey or loop is selected by double-clicking the respective name in the data tree view. The selected survey or loop is shown in bold. In addition, the selected loop has a shaded gray background.

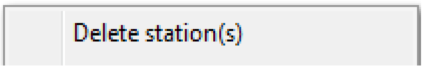

Survey
1
Loop
2
3 Occupation
Name
Date
2016-06-19
0
LC2 (1) 2016-06-19 13:0
glc-5 (1) 2016-06-19 13:2
glc-8 (1) 2016-06-19 13:4
glc-7 (1) 2016-06-19 13:5
GLC9 (1) 2016-06-19 14:0
glc-10 (1) 2016-06-19 14:1
usbr47 (1) 2016-06-19 14:2
LC2 (2) 2016-06-19 14:5
glc-5 (2) 2016-06-19 15:0
glc-8 (2) 2016-06-19 15:1
glc-7 (2) 2016-06-19 15:2
GLC9 (2) 2016-06-19 15:3
glc-10 (2) 2016-06-19 15:5
usbr47 (2) 2016-06-19 16:0
LC2 (3) 2016-06-19 16:2
USBR48 (1) 2016-06-19 16:5
usbr11 (1) 2016-06-19 17:0
usbr12 (1) 2016-06-19 17:2
usbr45 (1) 2016-06-19 17:3
usbr16 (1) 2016-06-19 17:5
USBR48 (2) 2016-06-19 18:1
usbr11 (2) 2016-06-19 18:2
usbr12 (2) 2016-06-19 18:4
usbr45 (2) 2016-06-19 18:5
usbr16 (2) 2016-06-19 19:0
USBR48 (3) 2016-06-19 19:3
AMTN (1) 2016-06-19 20:1
USBR48 (4) 2016-06-19 20:5
LC2 (4) 2016-06-19 21:1
AMTN (2) 2016-06-19 21:4

Tree view context menu

The Data Tree View has a right-click context menu from which stations can be deleted, duplicated, or moved to a new loop. Multiple stations can be selected by holding down the shift key (these operations won't work when non-adjacent stations are selected, as can be done by holding the control key).



1 Delete station(s)

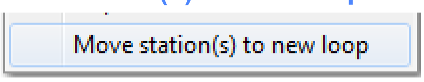


Deletes one or more selected stations (stations must be adjacent in the tree view). To restore deleted stations, data must be reloaded from a text file.

2 Duplicate station

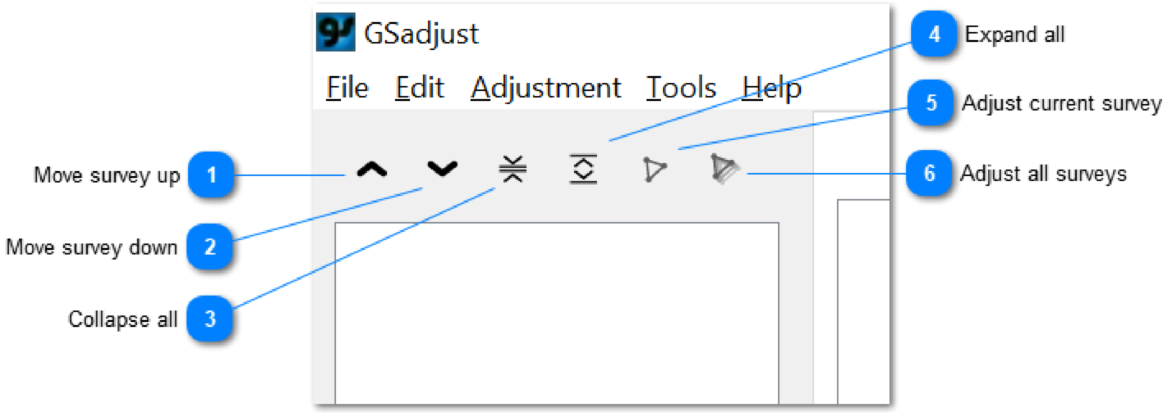
Duplicates the selected station. This feature is useful when creating loops.

3 Move station(s) to new loop



Creates a new loop with the selected stations.

Tree view toolbar



The tree view toolbar modifies the survey order, expands and collapses the view, and provides shortcuts for survey adjustment.

1 Move survey up

This button moves the currently selected survey upward (before the pervious survey in the tree view).

2 Move survey down

This button moves the currently selected survey downward (after the next survey in the tree view).

3 Collapse all

This button collapses all surveys and loops.

4 Expand all

This button expands all surveys and loops.

5 Adjust current survey

This button adjusts the currently selected survey (also available on the Adjustment menu).

6

Adjust all surveys

This button adjusts all surveys (also available on the Adjustment menu).

Workflow

The GSadjust workflow generally proceeds in three steps:

1. Import and organize data (Data tab)
2. Correct data for instrument drift (Drift tab)
3. Network adjustment (Network Adjustment tab)

In step 1, data are loaded from the text file output by the relative gravimeter (Scintrex or Burris). For each station occupation, individual readings can be deselected as needed, using the time-series plot of gravity readings as a guide. For larger surveys, stations may be grouped into loops as needed ("loop" refers to the set of station occupations for which a common drift correction is applied).

In step 2, loops are corrected for drift. Drift-correction options are:

- None
- Include in network adjustment
- Roman menthod (interpolate)
- Continuous model

Each loop can be assigned a unique drift method.

In step 3, the drift-corrected gravity differences are adjusted using the least squares method. Datum observations ("fixed" stations, i.e., those with a known gravity value) are assigned and/or loaded from a text file. Adjustment statistics are evaluated and, if needed, gravity differences can be excluded as outliers.

For all but the simplest surveys, it is usually worthwhile to complete all 3 steps before deselecting individual samples in the Data Table, or before spending much time on the drift correction. The reason is that errors in station name, tide correction, loop organization, etc. are not uncommon. It is more efficient to reveal these errors, by carrying out the network adjustment, before fine-tuning the individual occupations. For example, in the instance of station name errors, the imported data text file should be updated, and the file re-imported.

2. Quick-start tutorial

GSadjust is distributed with sample data sets for training purposes. Two fully-processed examples are available:

1. Simple example: this synthetic dataset includes 5 stations, 11 relative-gravity observations, and no absolute-gravity observations.

2. Complete example: this real-world dataset includes XX stations, XX relative-gravity observations, and XX absolute-gravity observations.

Simple example

This synthetic dataset consists of a single survey with a single loop consisting of 5 stations, 11 relative-gravity observations, and no absolute-gravity observations. In GSadjust terminology, in which "loop" refers to all of the observations for which a single drift correction is applied, the loop consists of two visits to each station, with the first station visited 3 times. The station order is 1-2-3-4-5-1-2-3-4-5.

1. Import data

    Select "Load raw Burris data..." from the File menu. Open Test1.txt in the test_data/synthetic directory. Loop 0 is created.

    In this synthetic example, there is only a single "observation" at each station. Therefore, the plots on the data tab show only a single point instead of a time series. Each station name can be selected in the tree view to show the associated data on the Data tab.

    Note that the "Update delta table" and "Update adjustment" status indicators in the bottom right are highlighted, indicating these steps have not yet been performed:

2. Apply drift correction

    Switch to the Drift tab by clicking "Drift". GSadjust displays a time series of the drift, with one line per station, starting at 0 for each station (see Drift tab for details).

    In this example, drift is initially negative, as indicated by downward-sloping lines, but then becomes positive, as indicated by upward-sloping lines.

    Four options are available for drift correction. The "None" and "Network adjustment" options do not change the plot. Selecting the "Roman" option updates the plot with vertical dashed lines to show the delta-g's, and a new table is shown in the bottom right with the average delta-g's. The "Continuous model" option displays an additional plot that shows the drift rate over time.

    For now, proceed with the "Continuous model" option. Select "1st order polynomial" for the drift model type and "Constant" for the behavior at start/end.

3. Populate delta table

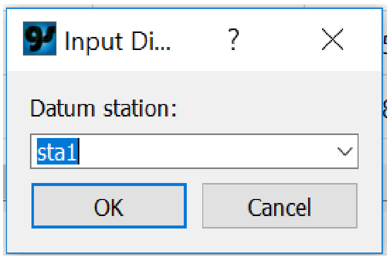
    Switch to the Network Adjustment tab. From the Adjustment menu, select "Populate delta table - all surveys" (because there is only one survey and one loop, the other Populate... options will have the same effect). The delta-g's from the Drift tab are copied to the table on the Network Adjustment tab.

Note that the "Update delta table" status indicator in the bottom right is no longer highlighted. If the drift-correction method is change on the Drift tab, the status indicator will be highlighted and the delta table will need to be re-populated.

4. Add datum observation

For this simple example, there are no absolute-gravity observations. Instead, an arbitrary datum is applied to one of the stations.

From the Adjustment menu, select "Add datum observation..." A dialog appears with a drop-down list of stations:



Select "OK" to select the default, sta1 (any other station is also acceptable, but will produce different results).

An arbitrary gravity value and standard deviation, 50,000 +/- 5 microGal, is applied to sta1 and shown in the datum observations table. This value can be changed by double-clicking it in the datum observations table.

5. Perform adjustment

From the adjustment menu, select "Adjust current survey" (because there is only one survey, "Adjust all surveys" will have the same effect). Alternatively, click the button on the tree view toolbar, or use the keyboard shortcut Ctrl+2. The adjustment will proceed using the default Numpy method.

Adjustment results (a single, best-fit gravity value at each station) are shown in the adjusted station values table at the upper right. Adjustment statistics are shown in the table at the lower right. Note that the Chi-test was accepted, and the a posteriori standard deviation is less than one. These indicate the adjustment was acceptable. The a posteriori standard deviation less than one indicates that the standard deviation of the observations were lower than the values shown in the relative-gravity differences and datum observations tables.

Note that the "Update adjustment" status indicator in the bottom right is no longer highlighted.

6. Export results

From the Tools menu, select "Write tabular data". A comma-separated value (.csv) file with the filename "GSadjust_TabularData_..." followed by the date is written to disk with the values shown in the adjusted station values table. Optionally, the table can be highlighted by clicking in the upper-leftmost cell, then right-clicking and selecting Copy to clipboard. Data can be pasted into Excel or a text file.

From the Tools menu, select "Write metadata text". A text file (.txt) with the filename "GSadjust_MetadataText_..." is written to disk with a narrative summary of the adjustment. This text can be used in a metadata file.

From the Tools menu, select "Write adjustment summary". A text file (.txt) with the filename "GSadjust_Summary_..." is written to disk showing the observations used in the adjustment and the results of the adjustment. This file includes all of the information necessary to re-create the adjustment results.

7. Save the workspace

To facilitate future re-processing or evaluation, the workspace should be saved by selecting "Save workspace as..." from the File menu. A file save dialog is shown; save with an appropriate filename. A ".p" extension is added if not specified. The workspace is written to file using the Python "pickle" protocol. This file can be re-loaded into GSadjust using the "Open workspace..." command on the File menu. It should not be edited outside of GSadjust.

Complete example

This real-world dataset includes XX stations and includes absolute-gravity measurements. Two surveys were carried out, each with two different relative-gravity meters.

1. Import data

    First, load data from the first meter (serial number B44) used on the first survey. Select "Load raw Burris data..." from the File menu. Open B44_2018-02-27.txt in the test_data/field/Burris directory. Loop 0 is created.

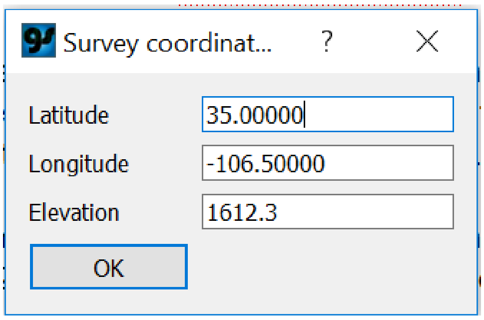
    In this real-world example, each station occupation consists of several samples. The gravity time series (and feedback, tilt correction, and Earth tide correction time series) are shown in the table and plots on the Data tab. The respective data for each station can be shown by selecting the station in the left-side tree view.

    Next, load data from the second meter (B108) used on the first survey. Select "Append loop to current survey..." from the File menu. Open B108.2018-02-27.txt in the test_data/field/Burris directory. Loop 1 is created.

2. Organize data

3. Update tide correction

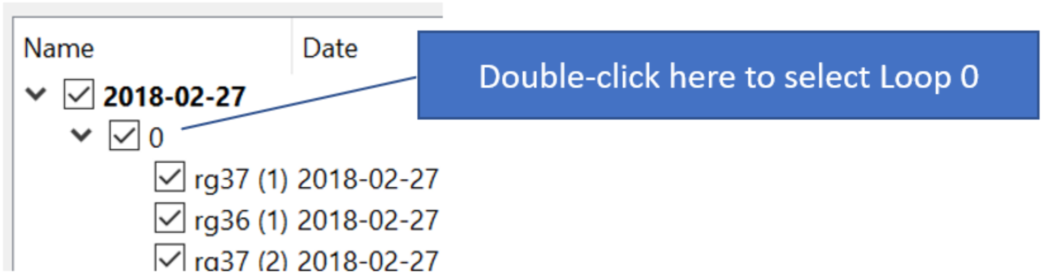
    Although the Burris relative-gravity meter (and Scintrex meters) apply a tide correction, for this study the Agnew model provides a more accurate correction. To update the tide corrections, from the Edit menu select Tide correction, then choose the "Agnew" option. A dialog is displayed to enter coordinates:



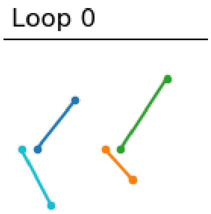
    The dialog is pre-populated with the mean latitude and mean longitude of the observations. After selecting OK, the meter-supplied tide correction is removed and the new tide correction applied (to revert to the meter-supplied tide correction, select Tide correction from the Edit menu, then "Meter-supplied").

4. Apply drift correction

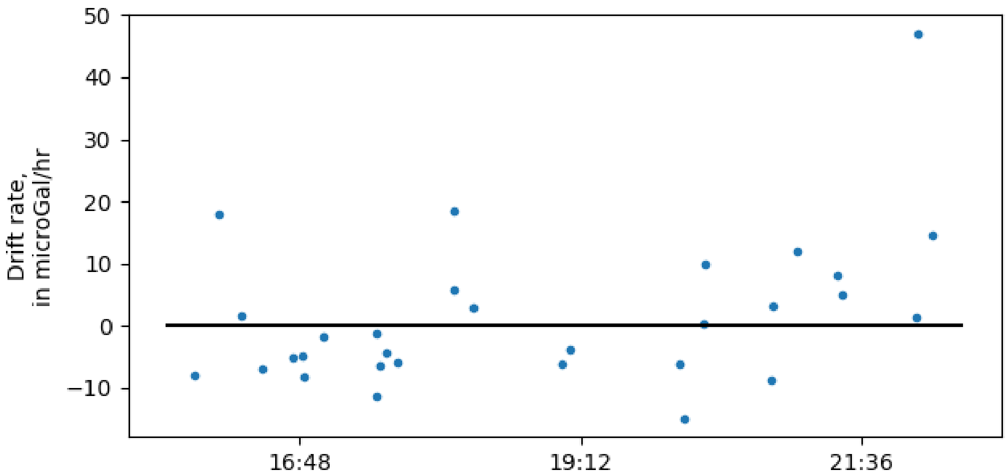
    Next, click on the Drift tab. The plot title should show Survey 2018-02-27, Loop 0. If a different survey is shown, double-click "0" under the 2018-02-27 survey to select Loop 0:



The drift plot shows generally negative drift (downward-sloping lines) during the first part of the survey, followed by variable drift during the latter part. Poor meter behavior is indicated by overlapping periods of positive and negative drift:



This variable drift is also visible when when the "Continuous model" drift correction model is selected:



5. Populate delta table

6. Import datum observations

7. Perform adjustment

8. Correct misnamed station

9. Perform adjustment

10. Change adjustment options

11. Perform adjustment

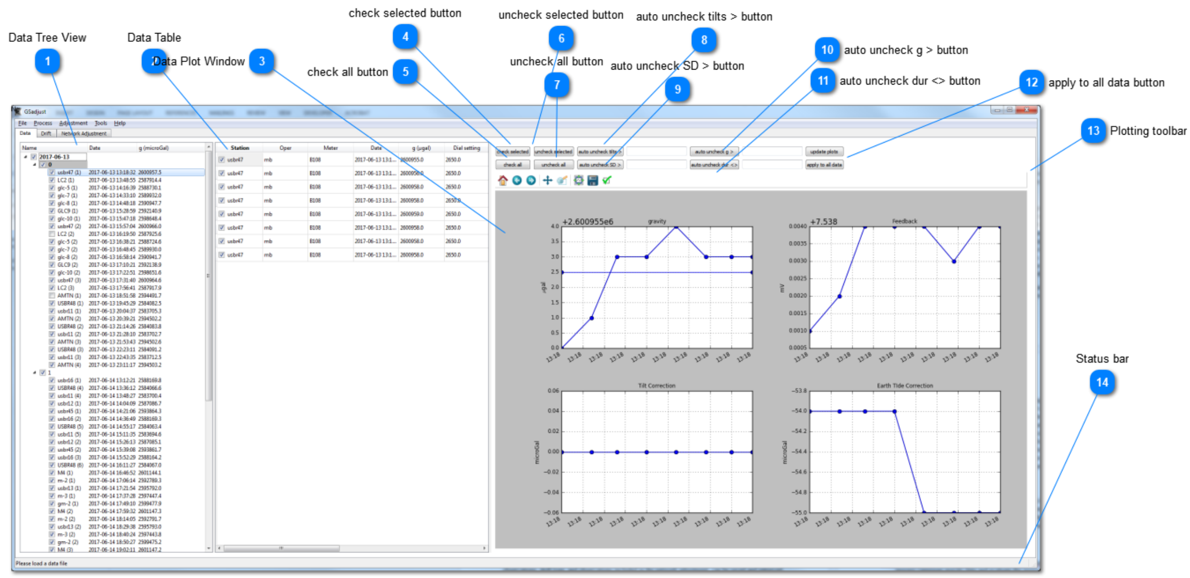
12. Update station data
13. Perform adjustment
14. Calculate gravity change over time
15. Export results

Data sets included with GSadjust

<TODO>: Insert description text here... And don't forget to add keyword for this topic

3. Data tab

The data tab provides functions for viewing and selecting/deselecting the observations to be included in the drift correction and adjustment.



Data Tree View

The Data Tree View shows the hierarchical structure of the data set, and is common to all tabs.

Data Table

- The Data Table shows all of the samples for a particular station occupation. The columns vary depending on the meter type:

Burris	**Scintrex**
Station name	Station
Operator	Gravity (g)
Meter number	Standard deviation
Date/time	Tilt x
Gravity (g)	Tilt y
Dial setting	Temp
Feedback	Duration
Tide correction	Rejected
Elevation	Elapsed time
Latitude	Date/time
Longitude	

3 Data Plot Window

The Data Plot window shows graphically the gravity value and accompanying data for a particular station occupation. For the Burris meter, the plots shown are gravity, feedback, tilt correction, and Earth tide correction. For the Scintrex meter, the plots shows are gravity, Tilt X, Tilt Y, and standard deviation.

4 check selected button

check selected

Rows in the Data Table can be selected using the mouse; multiple rows can be selected by holding down the shift or control keys. If unchecked rows are selected, this button checks them.

5 check all button

check all

Checks all rows in the Data Table.

6 uncheck selected button

uncheck selected

Rows in the Data Table can be selected using the mouse; multiple rows can be selected by holding down the shift or control keys. If checked rows are selected, this button unchecks them.

7 uncheck all button

uncheck all

Unchecks all rows in the Data Table.

8 auto uncheck tilts > button

auto uncheck tilts >

Unchecks observations with tilts (X or Y) greater than the specified value. Used only for Scintrex data.

9 auto uncheck SD > button

auto uncheck SD >

Unchecks observations with standard deviations greater than the specified value. Used only for Scintrex data.

10 auto uncheck g > button

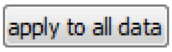
auto uncheck g >

Unchecks observations with g values greater than the specified value.

11 auto uncheck dur <> button

Unchecks observations with durations longer than the specified value. Used only for Scintrex data.

12 apply to all data button

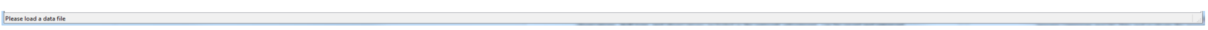


Applies any thresholds for tilt, g, standard deviation, or duration to all samples in a Campaign.

13 Plotting toolbar

This is the standard Matplotlib (plotting utility for Python) tool bar. More info is under the Plot toolbar

14 Status bar



The status bar at the bottom of the window shows messages about the current processing status.

Plot toolbar

This is the standard Matplotlib (plotting utility for Python) tool bar.

1 Home button

Reset original view

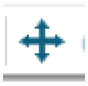
2 Back button

Back to previous view

3 Forward button

Forward to next view

4 Pan check

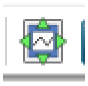


Pan axes with left mouse, zoom with right

5 Zoom check

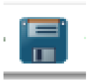
Zoom to rectangle

6 Subplots button



Configure subplots

7 **Save button**



Save the figure

8 **Customize button**

Edit curves line and axes parameters

Loading data

Burris or Scintrex data can be loaded with the respective menu commands on the File menu (Load raw Burris data... or Load raw Scintrex data). These open a standard file open dialog, allowing the user to select a file. The file to be opened is the raw data file output by the gravity meter software.

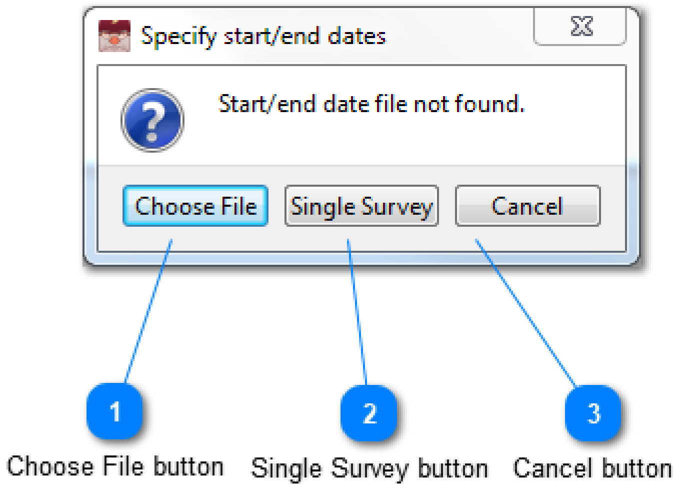
After selecting a file, GSadjust looks for a start/end date file with the same filename as the data file but with the suffix "_start_end_dates.txt". For example, if the data file is named "2016-06_Mesilla.txt", GSadjust will look for start/end dates in the file "2016-06_Mesilla_start_end_dates.txt". If the file is found, stations will be divided into surveys based on the dates in the file.

If the start/end date file is not found, the Specify start/end dates dialog is shown.

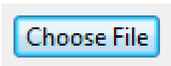
Surveys can also be created by appending a data file to create a new survey.

Specify start/end dates window

The start/end dates window is shown when loading a data file without an accompanying start/end date file (a file with the same filename as the data file but with the suffix "_start_end_dates.txt".

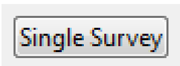


Choose File button



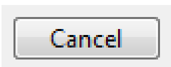
This displays a File Open... dialog where the user can specify a start/end date file.

Single Survey button



This causes all data to be loaded into a Single survey. Once loaded, data can only be further separated into Loops, not Surveys. If more than one Survey is to be processed, it must be specified using a start/end date file or by appended a data file as a new survey.

Cancel button



Start/end date file

The start/end date file is a text file that specifies the times that bracket each Survey. The file has the same filename as the data file but with the suffix "_start_end_dates.txt". The file consists of two dates per line:

YYYY/MM/DD HH:MM:SS YYYY/MM/DD HH:MM:SS

Any data recorded between the date/times specified will be added to a unique Survey. And data not between the date/times specified will be ignored.

For example, the following start/end date file:

2016/06/19 00:00:00 2016/06/22 23:59:00
2016/08/23 00:00:00 2016/08/26 23:59:00

Would create two Surveys, each with data collected over 4 days. The first date on each line is used as the name of the Survey.

Data Formats

GSadjust can import data exported by ZLS (Burris) and Scintrex (CG-3, CG-5, CG-6) relative-gravity meters. Data from each of these meters is written in a space delimited text format.

When a data file is initially loaded, the appropriate menu option should be selected ("Load raw CG-3/CG-5 data", "Load CG-6 data", or "Load raw Burris data"). If additional data are loaded using the "Append survey to campaign" or "Append loop to survey" menu options, a dialog will be shown allowing the user to specify the data format.

ZLS (Burris)

The Burris file is output from the ZPARSE.exe program run on a Windows computer. The file read by GSadjust is the one generated from discrete observations, and has the filename "YYYYMMDD_SINGLE.txt", where YYYYMMDD indicates the date.

The Burris file may be hand-edited to, for example, remove data from previous surveys. Care should be taken if the file is edited in Excel, which will typically result in a change in the date format (from YYYY-MM-DD to MM/DD/YYYY). The date format must be changed back to the original format if this is the case.

Scintrex (CG-3 and CG-5)

Like the Burris output file, the Scintrex data file is space delimited. The Scintrex file will typically have a header with information such as the meter operator and the serial number.

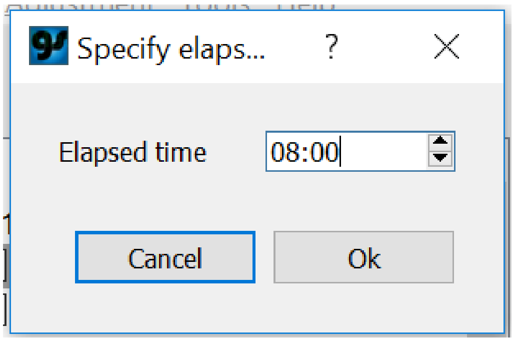
Scintrex (CG-6)

The Scintrex CG-6 file is similar to the CG-3/CG-5 format.

Splitting data into loops

Often data from several loops and (or) several days are combined in a single file. In that case, GSadjust can automatically divide data into loops based on a time threshold.

After loading a data file, either by loading raw data or appending a loop or survey, divide a loop with the "Divide selected loop..." command on the Edit menu. A dialog appears to specify the time threshold:



If there is a gap during which no data were collected that is longer than the elapsed time specified, the data before the gap will retain the original loop name and data after the gap will be put in a new loop. If there are multiple gaps longer than the threshold (for example, if data were collected over several days with gaps each night) multiple loops will be created.

See Creating loops for further information.

Appending data

After a data have been loaded, either by importing data or loading a previously saved workspace, additional data can be appended. This is useful for ongoing projects where intermediate analysis takes place before data collection is complete; as additional data are collected they can be appended as a new loop or survey.

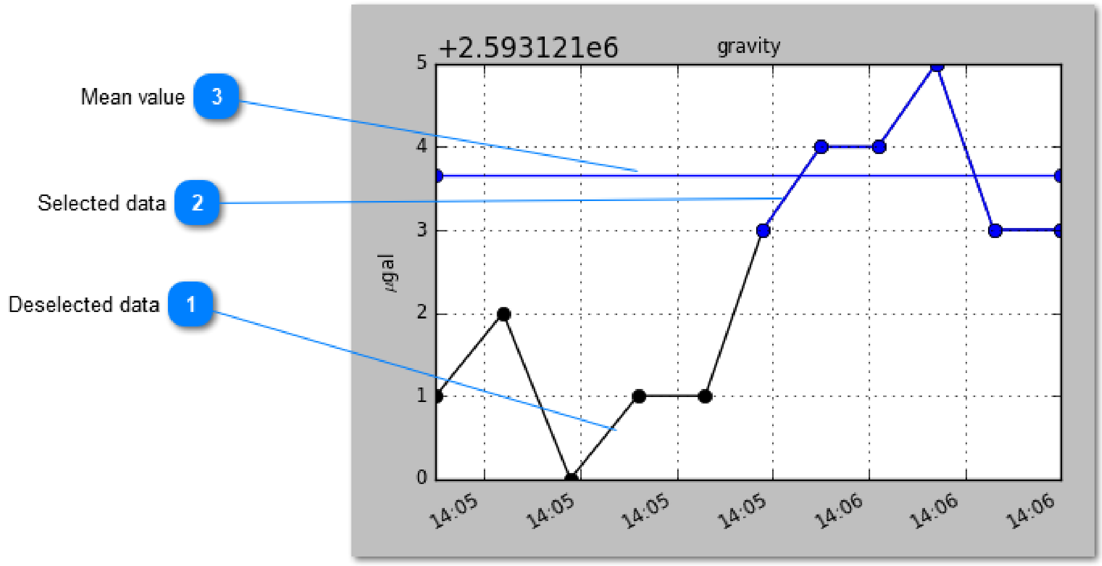
There are two append options on the File menu: either a new loop can be appended to the currently selected survey, or a new survey can be appended to the campaign. The former option is useful primarily for adding a new day's data for a survey currently in progress. The latter option is useful primarily for appending data after all of the data for a particular survey have been collected. After appending a survey to a campaign, the data can be separated into loops.

Selecting data

Data are selected or deselected using checkboxes. In the Data tree view, surveys, loops, or stations may be selected or deselected. In the station table, individual samples may be selected or deselected. By default, all of the samples, stations, loops, and surveys are selected after importing.

Data plots

In the station data view, the currently selected samples are shown with blue markers. Deselected samples are shown with black markers. The mean value of the selected data is shown as a horizontal solid blue line.



Deselected data

1

Data are deselected by unchecking the text box in the Station table. Deselected data are shown in black.

Selected data

2

Data are selected by default. Selected (checked) data are shown in blue.

Mean value

3

The mean (average) of the selected data is shown as a horizontal solid blue line.

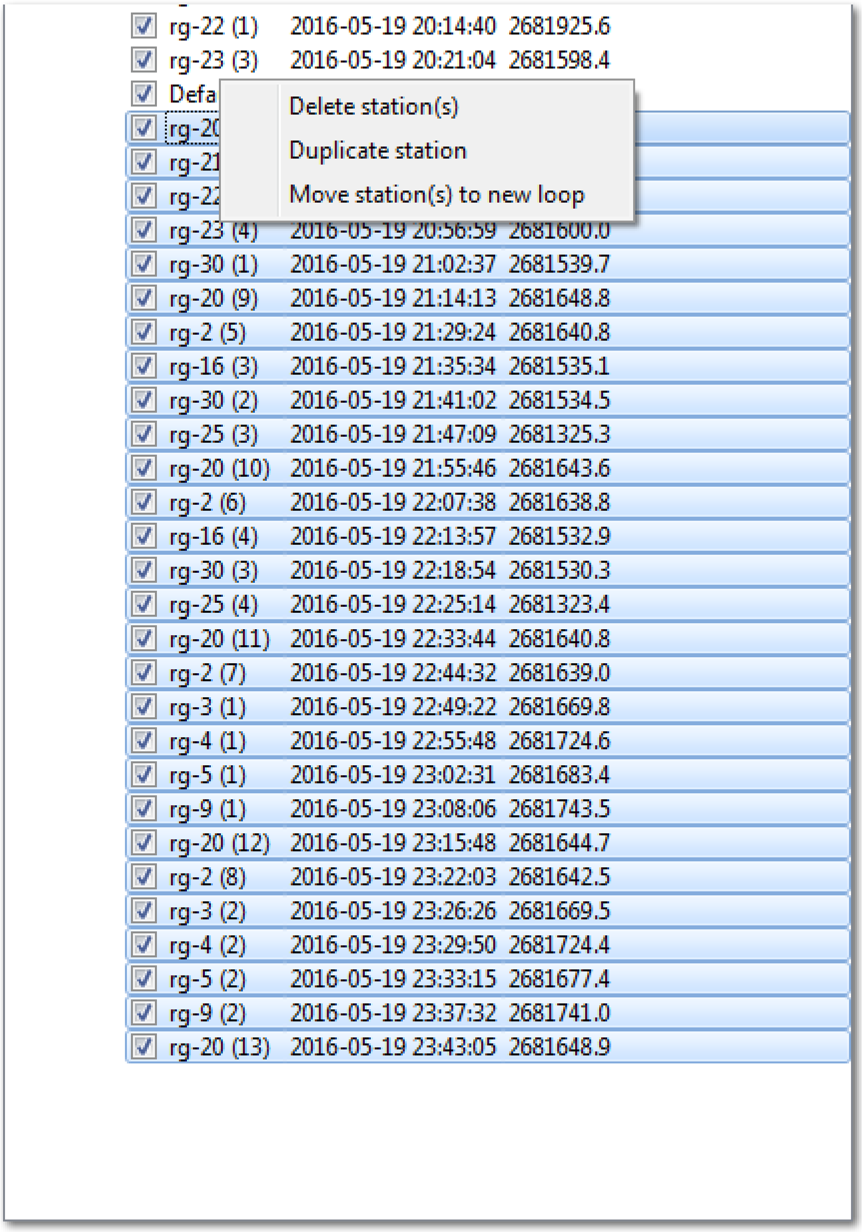
Editing data

Some of the values in the Data Table can be manually edited. These include the operator, latitude, longitude, and elevation. Values are edited by double-clicking the cell, or pressing F2.

Creating loops

Loops in GSadjust (the group of stations for which a single drift correction is applied) are created after a file is loaded. Alternatively, individual data files can be loaded by first opening one data file to create a new survey, and then appending additional data files to create new loops.

To create a new loop within the current Survey, select the group of stations to me moved to the new loop by selecting the first station, holding shift, and selecting the last station. This will select a group of stations to be moved. Then, right click to bring up the Data Tree View Popup menu, and select Move station(s) to new loop. A new loop is created.



Alternatively, stations may me grouped into loops based on the time threshold between station occupations using the "Divide selected loop..." command on the Edit menu. This opens a dialog where a time threshold can be specified. If that length of time elapses between any two station occupations, the subsequent stations are assigned to a new loop. This command is useful when loops (which define the group of stations for which a common drift correction is appplied) consist of all of the stations observed in one day.

If the same station is occupied as the last station on one day, and the first station the following day, all of the samples are grouped into a single station occupation. This results in a station with an assigned time midway between the two individual setups, and an averaged g value. To more accurately represent the survey, the occupation should be duplicated (by selecting it and using the right-click context menu). Then, the original occupation (observed first) should have all of the samples collected on the second day unchecked in the Data Table, and the duplicate station should have all of the samples collected on the first day unchecked. This should be done prior to using the "Divide selected loop into subloops..." command.

4. Drift tab

The drift tab provides functions for plotting drift and applying drift corrections. Four options exist:

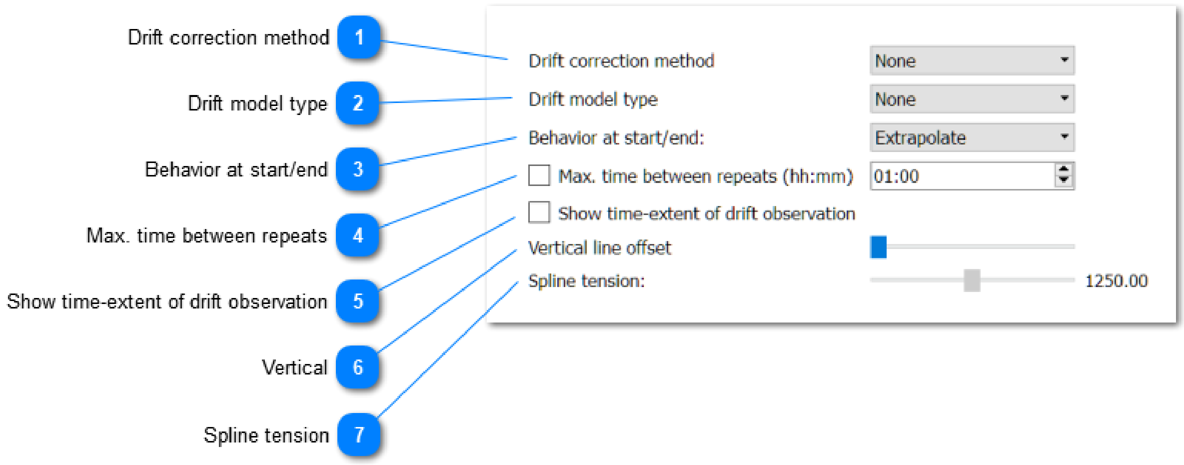
- No drift correction
- Network-adjustment drift correction
- Roman method
- Continuous method

The drift correction method is selected in a dropdown box on the right sight of the drift window. The plots and tables shown on the drift tab can vary depending on the drift correction method. For the no correction, network-adjustment , and Roman method options, a plot of gravity change vs. time at each station is shown. For the continuous method option, an additional plot of drift observations vs. time is shown. For the no correction, network-adjustment, and continuous method options, a single table of gravity differences (Delta-g's) is shown, along with relevant details. Delta-g's are only calculated between successive stations. For the Roman method option, two tables are shown: one with all possible Delta g's, and another with average Delta-g's (where more than one Delta-g exists between two stations).

Plotting options

Several options exist on the right-hand side of the drift tab for controlling the drift method used and the appearance of the drift plots. Some of the options (drift model type, behavior at start/end, show time-extent of drift observation, and spline tension) are only available when the Continuous method correction is used.

Clicking on a line in the main plot window will show the station name at the top left of the plot.



1 Drift correction method

Drop down box to specify drift correction method: none, network adjustment, Roman, or continuous.

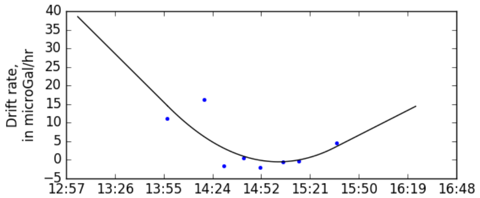
2 Drift model type

Continuous drift model only: Specify either a polynomial or spline model of continuous drift.

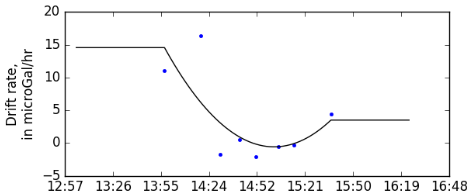
3 Behavior at start/end

Continuous drift model only: The model only extends to the first and last drift observation, which is a smaller time-span than the first and last station occupation (the drift observation is plotted at the midpoint in time between the two occupations that comprise the drift observation). The drift model can be extrapolated, or extended at a constant value. If extrapolated, a straigt line is extended with the same slope as the drift model; in some cases this can lead to extreme drift corrections for the first and/or last occupations, and a constant value is preferable.

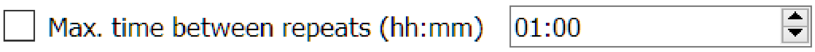
Extrapolate:



Constant:

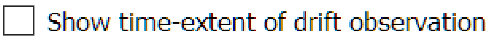


4 Max. time between repeats



For some surveys, a large amount of time may elapse between repeated station occupations, and these may not be reliable measurements of drift. This option allows drift observations to be excluded based on the time between station repeats. Note: the minimum counter value is 00:10. If the counter is above this, but will not decrease when the down arrow is clicked, it may be necessary to place the cursor (by clicking the mouse) on either the hour or minutes field.

5 Show time-extent of drift observation



Continuous drift model only: When checked, the lower plot of drift rate vs. time includes horizontal lines that extend to the time of the two station occupations that comprise the drift observation. This option can be useful in determining whether drift observations are useful for determining the drift model (repeated stations with long elapsed times can be unreliable for estimating drift).

6 Vertical

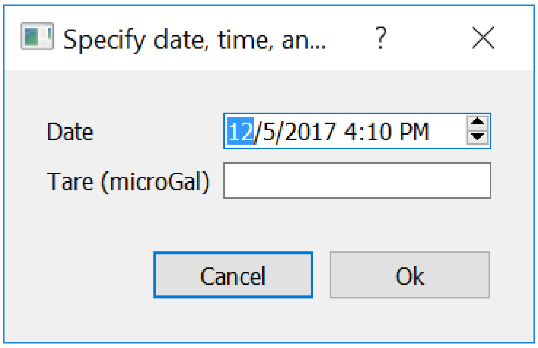
This slider controls the (arbitrary) vertical offset between lines in the station drift plot. Varying the slider may be useful to visualize the data, and helps the user understand the arbitrary nature of the vertical position of each line.

7 Spline tension

Continuous drift model only: When using a spline as the drift model, this slider controls the spline tension. Greater values, to the right, result in a smoother spline and possibly a poorer match to the drift observations. Smaller values, to the left, result in a wavier spline and drift observations are more likely to be matched exactly.

Tares and the tare table

Tares, or offsets, occur when the gravimeter-reading "jumps" during a survey; a tare affects all subsequent observations, but does not affect observations recorded prior to the tare. Tares may be added using the "Process > Add tare..." menu item, which brings up the dialog:



Here, the user may specify a date and magnitude of a tare. The tare value is simply subtracted (or added, if negative) to all relative-gravity observations within the currently-active loop that are recorded after the specified time.

The tare table, shown on the Drift tab, shows tares that have been added. More than one tare can be applied simultaneously, and tares are cumulative. That is, if a 10 microGal tare occurs one hour into a survey, and a 20 microGal tare two hours into a survey, after two hours a 30 microGal tare will be subtracted from all subsequent observations.

Tares shown in the tare table can be temporarily disabled by unchecking the respective check box. The delta-g observations shown on the Drift tab are updated immediately. Delta-g's shown on the adjustment tab, however, must be manually updated.

Tares may also be permanently removed by right-clicking on the tare in the Tare table and selecting "Delete tare."

Tares

	Date	Time	Tare (microGal)
1	☑ 12/5/2017	5:53 PM	-10.0

No drift correction

The "None" drift correction method calculates delta-g's between measured values at successive stations, without further correction. Although not generally used, the method may be useful for evaluating the magnitude of the drift correction, relative to the un-corrected delta-g's. The default standard deviation when using the "None" method is 3.0 microGal (the standard deviation used in the adjustment can be modified in the Network adjustment options dialog).

Network-adjustment drift correction

Network-adjustment drift correction includes polynomial coefficients of a time-dependent function for drift in the network adjustment solution. With this method, a linear model (1st, 2nd, or 3rd order) is fit to the data:

$$D(t) = \sum_{p=1}^{a} d_p (t - t_0)^p$$

where *D(t)* is the cumulative drift at time *t*, (t-t_0) is elapsed time, d_p are the model coefficients, and *a* is the degree of the polynomial. The coefficients d_p are parameters in the network adjustment, determined as part of the least-square solution.

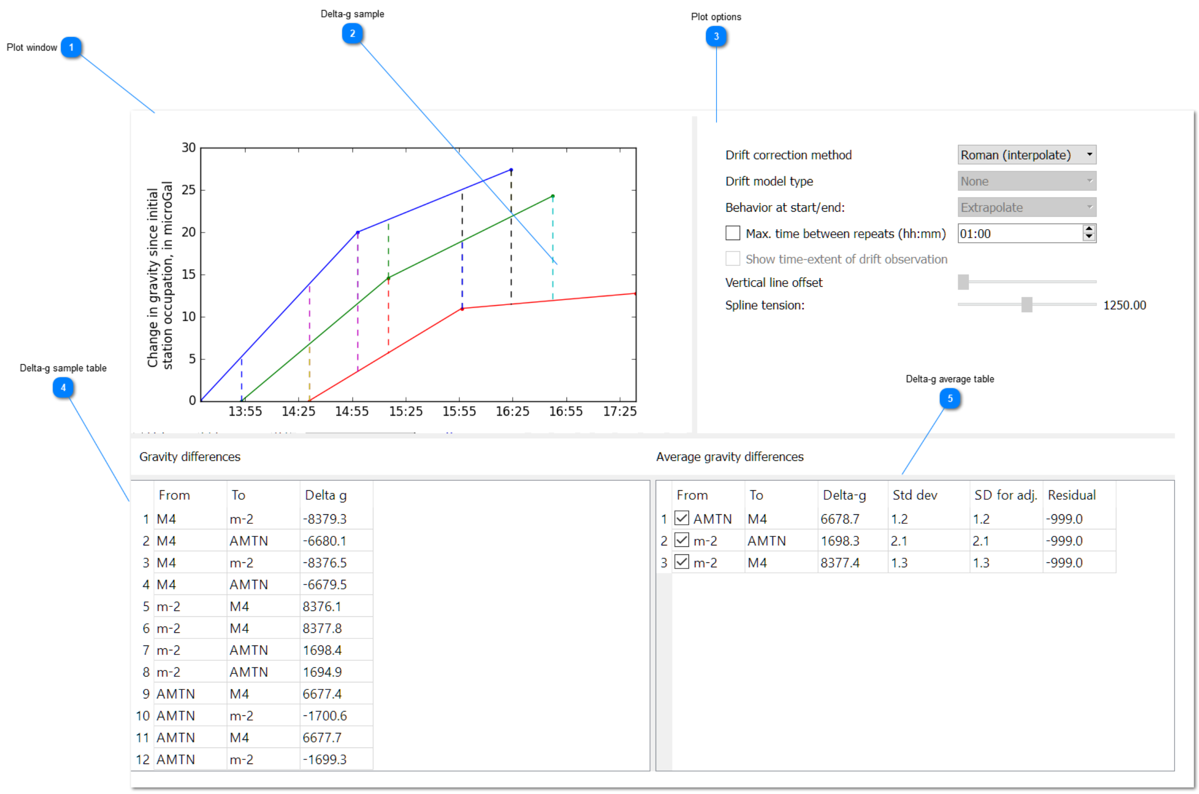
Linear drift models can be used with either the network-adjustment drift correction option, or the continuous model option. When a linear model is suitable, the network-adjustment drift correction may be preferable, because uncertainty in the drift-model parameters is propagated into the uncertainty estimate of the final station values. One advantage of the continuous model, however, is the possibility to extend the drift model as a constant value, as opposed to extrapolating the linear model, at the beginning and end of the loop (see "Behavior at start/end" under Plotting options). The suitability of a linear drift model can be evaluated using the continuous model option, after which the drift method can be changed to the network-adjustment option before adjusting the network.

Roman method drift correction

The Roman (1942) method interpolates a gravity value when there is more than one gravity observation at a station. A total of three station occupations-two at one station, and one at an additional station-are used to calculate a delta-g sample [Item (2) below)]. An interpolated value is calculated for the station with two occupations, and differenced with the measured value at the other station, to calculate delta-g.

In the window below, delta-g's are shown as vertical dashed line. Each measurement is shown relative to the first measurement at that station (in other words, if the measured values were plotted, the solid lines would have a vertical separation equal to the gravity difference between the stations). For the survey shown, which consists of two complete loops at three stations, there are a total of 12 delta-g's, shown on the Delta-g sample table (4).

As part of the Roman method drift correction, the redundant delta-g's (12 observations are possible, but only 3 are required to identify a gravity value at each station) are averaged. The averaging process is a simple form of network adjustment, with equal weight given to all observations. For surveys and/or campaigns with only a single loop (including [vertical gradients](#)), the values in the Delta-g average table (5) can serve as final results.



	From	To	Delta g
1	M4	m-2	-8379.3
2	M4	AMTN	-6680.1
3	M4	m-2	-8376.5
4	M4	AMTN	-6679.5
5	m-2	M4	8376.1
6	m-2	M4	8377.8
7	m-2	AMTN	1698.4
8	m-2	AMTN	1694.9
9	AMTN	M4	6677.4
10	AMTN	m-2	-1700.6
11	AMTN	M4	6677.7
12	AMTN	m-2	-1699.3

	From	To	Delta-g	Std dev	SD for adj.	Residual
1	AMTN	M4	6678.7	1.2	1.2	-999.0
2	m-2	AMTN	1698.3	2.1	2.1	-999.0
3	m-2	M4	8377.4	1.3	1.3	-999.0

1 Plot window

The main plot window shows the relative-gravity observations at each station, relative to the first occupation at that station.

2 **Delta-g sample**

Each vertical dashed line represents a delta-g calculated using the Roman method. There is a corresponding entry in the Delta-g sample table for each dashed line.

3 **Plot options**

See Plotting options

4 **Delta-g sample table**

This table displays all of the possible delta-g's calculated using the Roman method.

5 **Delta-g average table**

This table displays the average delta-g between any two stations in the Delta-g sample table. If there is only one delta-g between two stations, it will also be included in the average table.

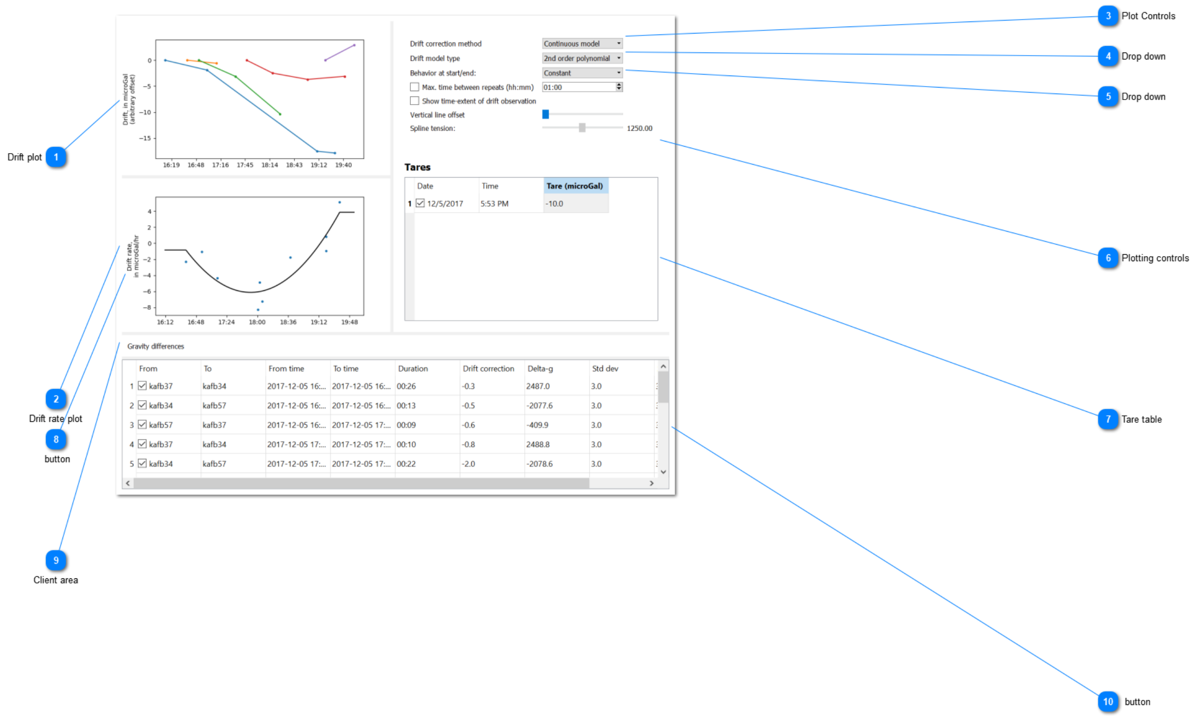
Roman, I. (1946). An observational method to overcome zero drift error in field instruments. Geophysics, 11(4), 466–490. https://doi.org/10.1190/1.1437276

Continuous-model correction

The continuous-model drift correction treats model drift as a continuous function. The main advantage over the [network-adjustment drift correction]() is that it allows a non-linear spline model, which is often the best fit for survey data recorded using a ZLS Inc. Burris relative-gravity meter (in contrast, Scintrex meters typically have higher, more linear drift rates).

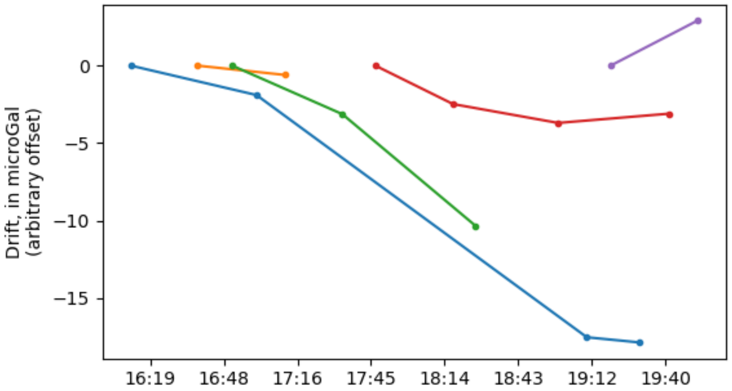
The continuous drift model is developed from repeated station occupations (that is, when a station is visited more than once, with other stations occupied in between). Each station-repeat provides one observation of relative-meter drift. Ideally, repeats will occur with relatively little elapsed time between, over a period when the drift is nearly linear. As the length of time between station repeats increases, drift is likely to become increasingly non-linear, and the drift estimate less suitable for forming the continuous drift model. The elapsed time can be visualized on the continuous-drift plot with the "Show time extent of drift observation" option under [Plotting options]().

Successful application of the continuous-model drift correction depends on accurate observations of gravity-meter drift, which in turn depends on repeat occupations with minimal elapsed time in between. To accomplish that, it may be necessary to adapt the survey design. In particular, observing stations in loops (i.e., visiting 5 or 6 stations before returning to the initial station) may allow too much time to elapse for a representative drift estimate to be obtained.



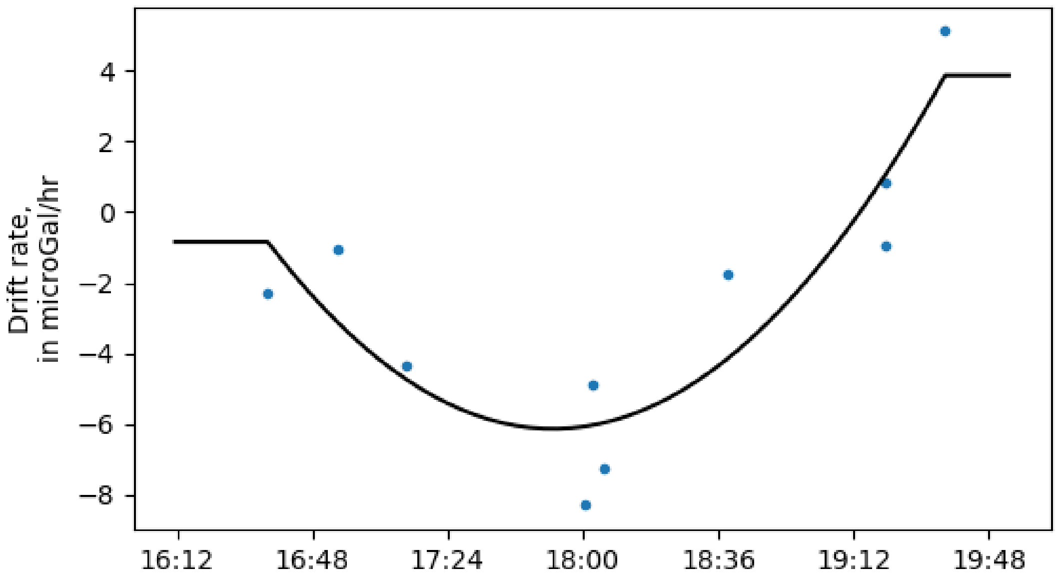
1 Drift plot

This plot shows the change in gravity at each station, relative to the initial occupation at that station. Each line depicts a unique station. Steeper lines (positive or negative) indicate a larger drift rate. The points that make up each line can be filtered using the "Max. time between repeats" option. A vertical offset between each line can be added with the "Vertical line offset" slider control.

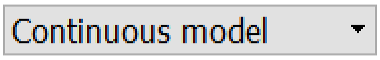


2 Drift rate plot

This plot shows the drift rate, calculated each time a station is repeated. Each point in this plot represents the slope (i.e., the drift rate) of the line directly above in the drift plot.



3 **Plot Controls**

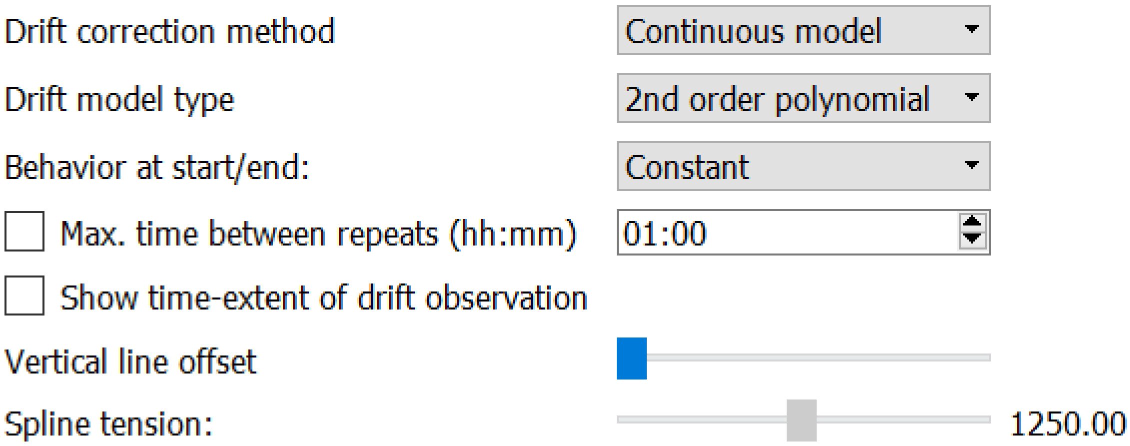


4 **Drop down**

5 **Drop down**

6 **Plotting controls**

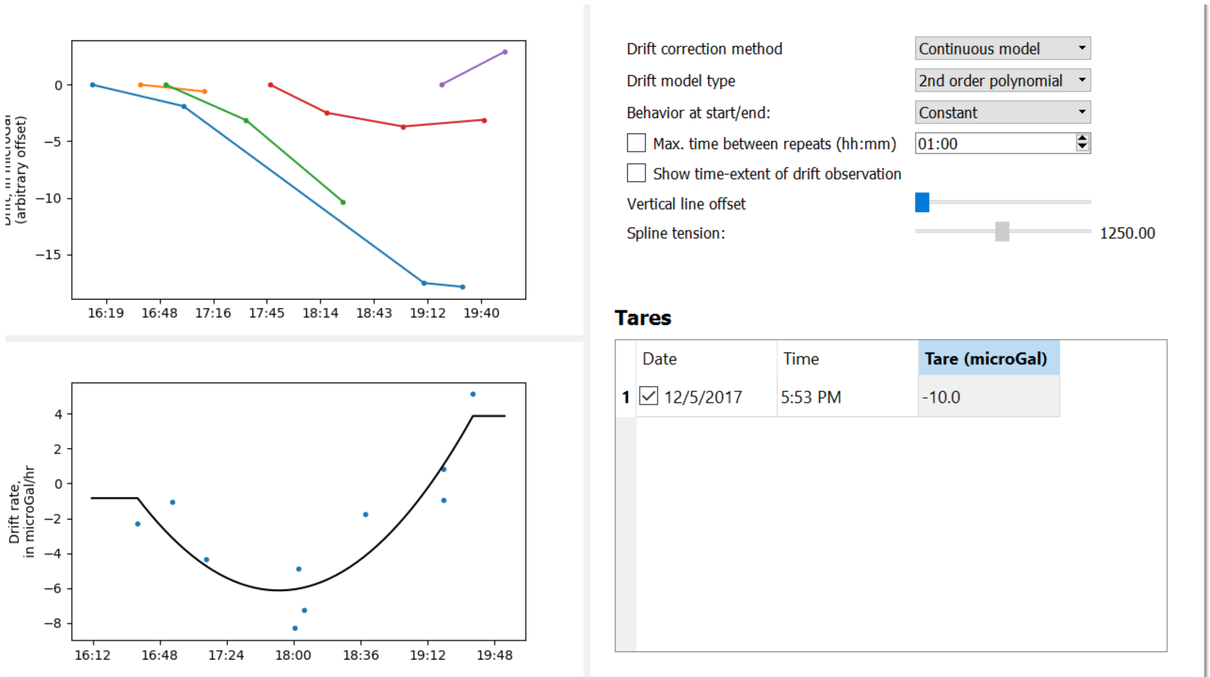
See Plotting options for more information.



7 **Tare table**

	Date	Time	Tare (microGal)
1	☑ 12/5/2017	5:53 PM	-10.0

8 **button**



Gravity differences

	From	To	From time	To time	Duration	Drift correction	Delta-g	Std dev
1	kafb37	kafb34	2017-12-05 16:...	2017-12-05 16:...	00:26	-0.3	2487.0	3.0
2	kafb34	kafb57	2017-12-05 16:...	2017-12-05 16:...	00:13	-0.5	-2077.6	3.0
3	kafb57	kafb37	2017-12-05 16:...	2017-12-05 17:...	00:09	-0.6	-409.9	3.0
4	kafb37	kafb34	2017-12-05 17:...	2017-12-05 17:...	00:10	-0.8	2488.8	3.0
5	kafb34	kafb57	2017-12-05 17:...	2017-12-05 17:...	00:22	-2.0	-2078.6	3.0

9 Client area

Gravity differences

10 button

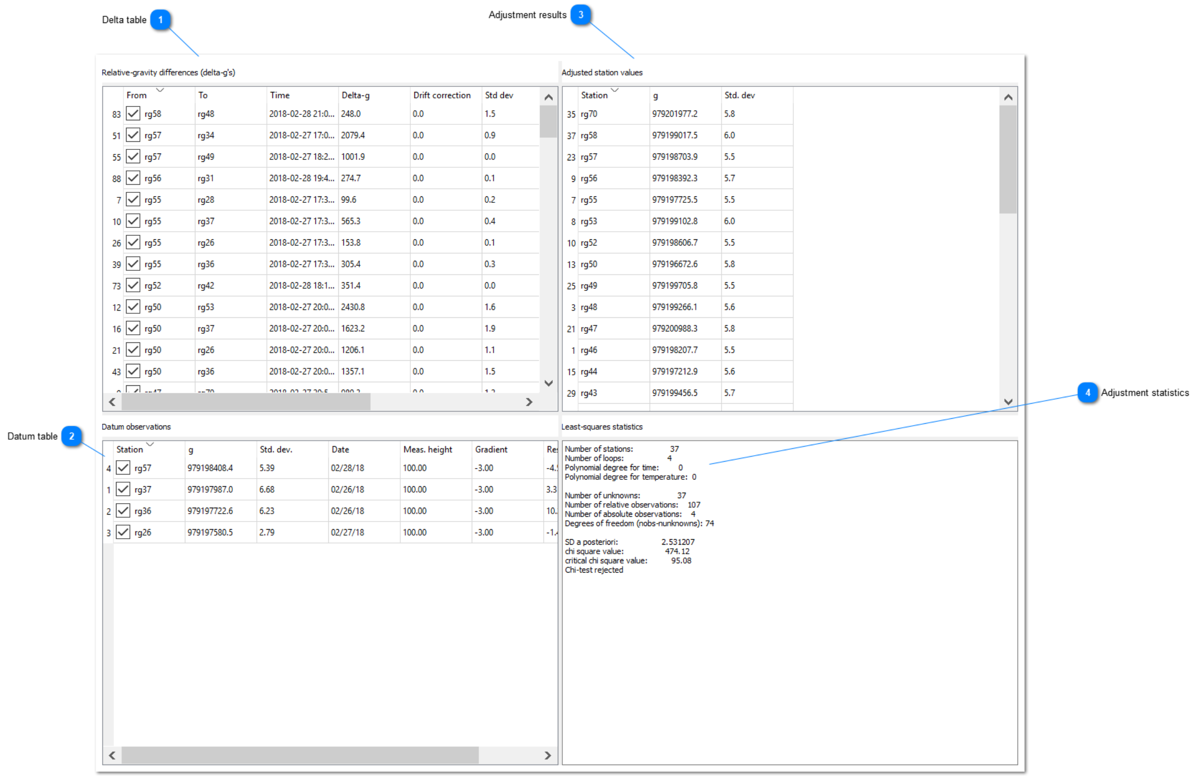
	From	To	From time	To time	Duration	Drift correction	Delta-g	Std dev
1	kafb37	kafb34	2017-12-05 16:...	2017-12-05 16:...	00:26	-0.3	2487.0	3.0
2	kafb34	kafb57	2017-12-05 16:...	2017-12-05 16:...	00:13	-0.5	-2077.6	3.0
3	kafb57	kafb37	2017-12-05 16:...	2017-12-05 17:...	00:09	-0.6	-409.9	3.0
4	kafb37	kafb34	2017-12-05 17:...	2017-12-05 17:...	00:10	-0.8	2488.8	3.0
5	kafb34	kafb57	2017-12-05 17:...	2017-12-05 17:...	00:22	-2.0	-2078.6	3.0

5. Network adjustment tab

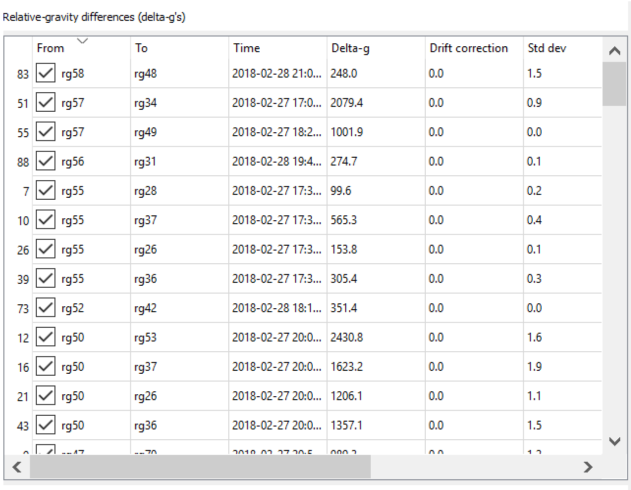
The network adjustment tab provides information about the least-squares network adjustment. The basic workflow is to:

1. Populate the delta table with relative-gravity differences
2. Add datum observations manually or from a file
3. Perform the network adjustment
4. Evaluate the adjustment statistics
5. Revise by removing outliers and/or adjusting the standard deviations
6. Export results

The parts of the network adjustment tab are:



1 Delta table

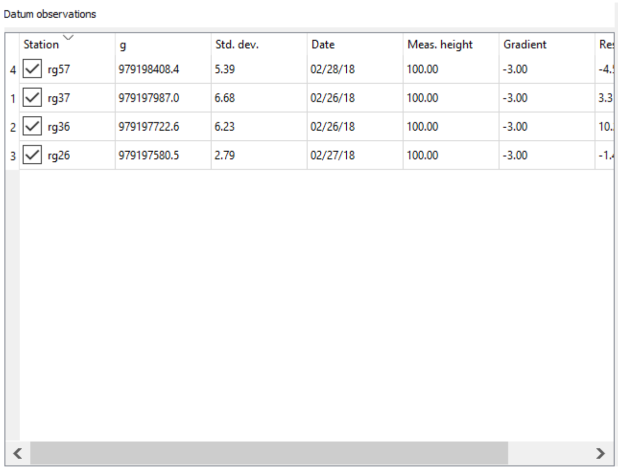


Relative-gravity differences (delta-g's)

	From	To	Time	Delta-g	Drift correction	Std dev
83	☑ rg58	rg48	2018-02-28 21:0...	248.0	0.0	1.5
51	☑ rg57	rg34	2018-02-27 17:0...	2079.4	0.0	0.9
55	☑ rg57	rg49	2018-02-27 18:2...	1001.9	0.0	0.0
88	☑ rg56	rg31	2018-02-28 19:4...	274.7	0.0	0.1
7	☑ rg55	rg28	2018-02-27 17:3...	99.6	0.0	0.2
10	☑ rg55	rg37	2018-02-27 17:3...	565.3	0.0	0.4
26	☑ rg55	rg26	2018-02-27 17:3...	153.8	0.0	0.1
39	☑ rg55	rg36	2018-02-27 17:3...	305.4	0.0	0.3
73	☑ rg52	rg42	2018-02-28 18:1...	351.4	0.0	0.0
12	☑ rg50	rg53	2018-02-27 20:0...	2430.8	0.0	1.6
16	☑ rg50	rg37	2018-02-27 20:0...	1623.2	0.0	1.9
21	☑ rg50	rg26	2018-02-27 20:0...	1206.1	0.0	1.1
43	☑ rg50	rg36	2018-02-27 20:0...	1357.1	0.0	1.5

The delta table shows the relative-gravity differences and associated information. See delta-g observations for more information.

2 Datum table



Datum observations

	Station	g	Std. dev.	Date	Meas. height	Gradient	Re
4	☑ rg57	979198408.4	5.39	02/28/18	100.00	-3.00	-4.
1	☑ rg37	979197987.0	6.68	02/26/18	100.00	-3.00	3.3
2	☑ rg36	979197722.6	6.23	02/26/18	100.00	-3.00	10.
3	☑ rg26	979197580.5	2.79	02/27/18	100.00	-3.00	-1.

<TODO>: Insert description text here...

3 Adjustment results

Adjusted station values

	Station	g	Std. dev
35	rg70	979201977.2	5.8
37	rg58	979199017.5	6.0
23	rg57	979198703.9	5.5
9	rg56	979198392.3	5.7
7	rg55	979197725.5	5.5
8	rg53	979199102.8	6.0
10	rg52	979198606.7	5.5
13	rg50	979196672.6	5.8
25	rg49	979199705.8	5.5
3	rg48	979199266.1	5.6
21	rg47	979200988.3	5.8
1	rg46	979198207.7	5.5
15	rg44	979197212.9	5.6
29	rg43	979199456.5	5.7

<TODO>: Insert description text here...

4 Adjustment statistics

Least-squares statistics

```
Number of stations:            37
Number of loops:               4
Polynomial degree for time:       0
Polynomial degree for temperature:  0

Number of unknowns:              37
Number of relative observations:    107
Number of absolute observations:    4
Degrees of freedom (nobs-nunknowns): 74

SD a posteriori:              2.531207
chi square value:              474.12
critical chi square value:       95.08
Chi-test rejected
```

<TODO>: Insert description text here...

Delta-g observations

Delta-g observations are shown in the Delta table on the network adjustment tab:

Relative-gravity differences (delta-g's)

	From	To	Time	Delta-g	Drift correction	Std dev	SD for adj.	Residual
83	rg58	rg48	2018-02-28 21:0...	248.0	0.0	1.5	1.5	0.6
51	rg57	rg34	2018-02-27 17:0...	2079.4	0.0	0.9	0.9	-1.5
55	rg57	rg49	2018-02-27 18:2...	1001.9	0.0	0.0	0.0	0.0
88	rg56	rg31	2018-02-28 19:4...	274.7	0.0	0.1	0.1	-0.0
7	rg55	rg28	2018-02-27 17:3...	99.6	0.0	0.2	0.2	-0.1
10	rg55	rg37	2018-02-27 17:3...	565.3	0.0	0.4	0.4	-0.5
26	rg55	rg26	2018-02-27 17:3...	153.8	0.0	0.1	0.1	-0.2
39	rg55	rg36	2018-02-27 17:3...	305.4	0.0	0.3	0.3	2.0
73	rg52	rg42	2018-02-28 18:1...	351.4	0.0	0.0	0.0	-0.0
12	rg50	rg53	2018-02-27 20:0...	2430.8	0.0	1.6	1.6	-0.6
16	rg50	rg37	2018-02-27 20:0...	1623.2	0.0	1.9	1.9	-5.5
21	rg50	rg26	2018-02-27 20:0...	1206.1	0.0	1.1	1.1	0.3
43	rg50	rg36	2018-02-27 20:0...	1357.1	0.0	1.5	1.5	3.2
9	rg47	rg70	2018-02-27 20:5...	989.3	0.0	1.2	1.2	-0.4

Delta-g observations (also called relative-gravity differences) must be populated using menu commands on the Adjustment menu. Delta-g's for all surveys can be populated at once, or individual surveys, or individual loops. The latter options are useful, for example, to verify that individual loops can be adjusted correctly before adjusting the entire Campaign.

Delta-g's can be unchecked to exclude them from the network adjustment. For the "none", "adjustment", or "continuous" drift methods, the start/end times, and duration between them are shown. For the Roman method, the time at which the delta-g is calculated is shown.

Two columns for standard deviation are shown: that calculated from the station observations and/or drift method, and the standard deviation used in the network adjustment. The latter can be adjusted if needed by specifying a minimum value, or multiplier (see Network adjustment options). This is helpful to avoid giving too much weight to delta-g's with very small standard deviations.

Any of the datum observation fields can be edited by double-clicking on the respective cell.

Before network adjustment, the Residual column shows the default value -999. After network adjustment this column shows the difference between the adjusted delta-g and the measured delta-g. Clicking the column header sorts by residual magnitude.

If changes are made to the samples that comprise each station occupation, or the drift method, the Delta table must be cleared (Adjustment menu > Clear delta table) and repopulated.

Datum observations

Datum observations are shown in the Datum table on the network adjustment tab:

Datum observations

	Station	g	Std. dev.	Date	Meas. height	Gradient	Residual
4	☑ rg57	979198408.4	5.39	02/28/18	100.00	-3.00	-4.5
1	☑ rg37	979197987.0	6.68	02/26/18	100.00	-3.00	3.3
2	☑ rg36	979197722.6	6.23	02/26/18	100.00	-3.00	10.2
3	☑ rg26	979197580.5	2.79	02/27/18	100.00	-3.00	-1.4

Datum observations form the "baseline" from which delta-g's are observed. At least one datum observation must be present for each survey to perform an adjustment. A datum observation can be an arbitrary value, such as 0 or 50000, or it can be a measured absolute-gravity value. There are three options for adding datum observations:

1. Adding manually
2. Importing from text file
3. Importing from g files

When datum observations are added, they are associated with the currently selected survey. Datum observations can be excluded from the network adjustment by unchecking their respective checkbox.

Datum observations, as shown in the Datum table, include the following fields:

- Station name
- Gravity (microGal)
- Standard deviation (microGal)
- Date
- Measurement height (meters)
- Gradient (microGal/m)
- Residual

The first three (name, gravity, standard deviation) are required. The station name must match exactly at least one station with a delta-g observation (names are case sensitive). The date is not used (datums are associated with the selectded survey when they are added). The measurement height and gradient are used to transfer an absolute-gravity measurement from the measaured height (about 71 cm or 131 cm for the A-10 and FG-5 absolute-gravity meters, respectively) to the land surface (i.e., the height of the relative-gravity meter). The gravity value for the respective datum measurement is increased by the amount [measurement height] * abs([gradient]) (the gradient shown in the Datum table is negative to indicate gravity decreases with elevation). Finally, the residual column in the Datum table shows the difference between the specified absolute-gravity value and the network adjusted value. If only one Datum observation is specified, the residual will be zero.

Any of the datum observation fields can be changed by double-clicking on the respective cell.

Adding manually

Datum observations are added manually using the menu option Adjustment > Add datum observation..., which brings up the following dialog:

The dropdown list shows all of the current stations in the Delta-g table. After clicking OK, the selected station is added to the Datum table with a default value of 50,000 +/- 5 microGal.

Importing from text file

Datum observations are added from a text file using one of two menu options: Adjustment > Import abs. g (simple)..., or Adjustment > Import abs. g (complete)... Either choce opens a standard file open dialog. The file formats are:

Simple format
Three column text file
Complete format

Importing from g files

Datum observations can be added directly from *.project.txt files generated by 'g' software (Micro-g Lacoste, Inc.) using the menu option Adjustment > Import abs. g from database, which brings up the following dialog:

After selecting the Load button, the chosen directory is scanned for *.project.txt files. The information from the files found is loaded into the

Network adjustment

Least-squares network adjustment is the process for solving the system of equations that represent all of the survey observations (relative-gravity differences, and absolute-gravity observations), along with any additional parameters that describe relative-gravity meter drift and calibration.

In brief, network adjustment solves the system of equations, represented in matrix form as:

$$\mathbf{L} + \mathbf{V} = \mathbf{AX}$$

where $\mathbf{L}$ is an n x 1 vector of relative-gravity (delta-g's) and absolute-gravity measurements , $\mathbf{V}$ is a n x 1 vector of residuals, $\mathbf{A}$ is the n x m design matrix, and $\mathbf{X}$ is a m x 1 vector of unknowns, that is, the gravity value at each station and gravimeter parameters that describe drift and meter calibration. The value n is the total number of observations (both delta-g's ad absolute-gravity), and m is the number of unknowns (number of gravity stations plus the number of gravity-meter parameters).

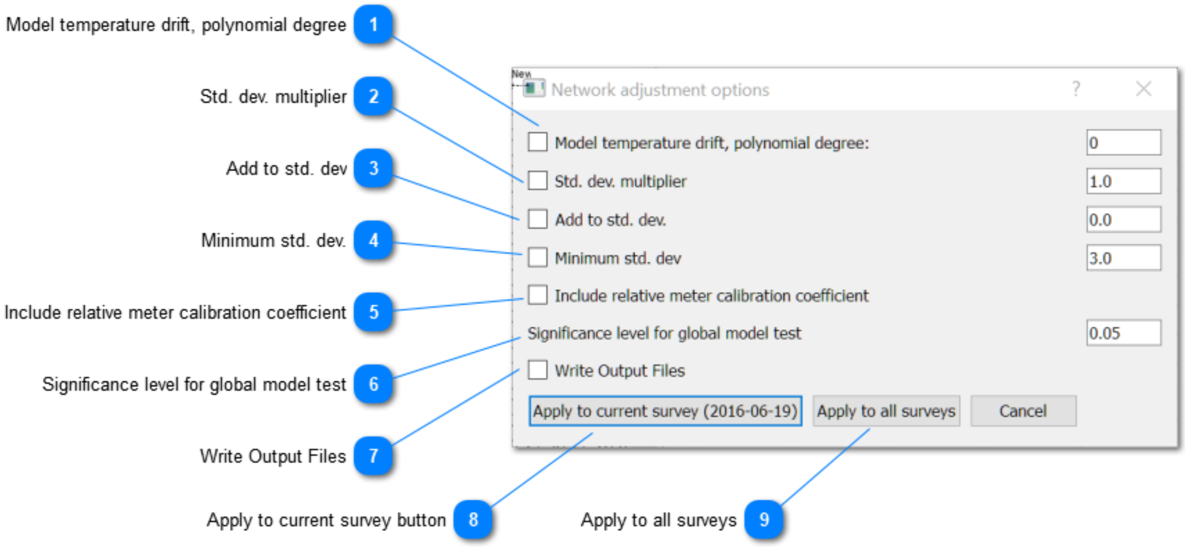
GSadjust can solve the system of equations using the least squares routine in the Python Numpy package (using the linalg.inv method), or using the program Gravnet. The solution to use is selected with the Adjustment > Adjustment type... menu. Prior to adjustment, adjustment options, including whether to include a calibration coefficient, are set using the Network adjustment options dialog.

After successful adjustment, station values are shown in the Adjustment results table in the upper right part of the Network adjustment tab. Statistics about the adjustment results and meter parameters (drift and calibration, if included in the adjustment) is shown in the lower right part.

Note that the delta-g's shown in the Delta table on the Network adjustment tab are effectively static once the Delta table is populated. If changes are made to the samples that comprise each station occupation, or the drift method, the Delta table must be cleared (Adjustment menu > Clear delta table) and repopulated.

Oftentimes it is helpful to adjust the network in pieces (individual loops or surveys) prior to adjusting the campaign (or a survey) as a whole. This can be accomplished using the "Populate delta table - selected survey" and (or) "Populate delta table - selected loop" options on the Adjust menu.

Network adjustment options dialog



1 Model temperature drift, polynomial degree

When checked, a linear model of specified degree is included in the network adjustment to account for temperature effects on g reported by a relative gravimeter. The model coefficients are solved for during the network adjustment. Only available for Scintrex data. Must be an integer value.

2 Std. dev. multiplier

When checked, multiplies the delta-g standard deviation (determined from the data and/or drift-correction method) by the specified value. The result is shown in the "SD for adj." column of the Delta Table, and used in the network adjustment. May be used in conjunction with "Add to std. dev." (multipler is applied first).

3 Add to std. dev

When checked, adds the specifed value to the delta-g standard deviation (determined from the data and/or drift-correction method). The result is shown in the "SD for adj." column of the Delta Table, and used in the network adjustment. May be used in conjunction with "Add to std. dev." (multipler is applied first).

4 Minimum std. dev.

When checked, the delta-g standard deviation used in the adjustment is the greater of the specified value, or the standard deviation determined from the data and/or drift-correction method. The value used in the network adjustment is shown in the "SD for adj." column of the Delta Table.

5 **Include relative meter calibration coefficient**

When checked, a relative-meter calibration coefficient is calculated during the network adjustment. The calibration coefficient is a multiplier applied to all relative-gravity observations. It is calculated from the datum observations in a network, and 2 or more datum observations are required.

6 **Significance level for global model test**

Significance level for the chi-square test used to evaluate adjustment residuals.

7 **Write Output Files**

When checked, network-adjustment output files are saved to disk. These are either the standard files output by Gravnet, or, when using Numpy inversion, a summary of the adjustment output produced by GSadjust.

8 **Apply to current survey button**

Applies the network-adjustment options to the survey cuurently selected in the data tree view at the left side of the window (The current survey is highlighted in bold).

9 **Apply to all surveys**

Applies the network-adjustment options to all surveys in the campaign.

Evaluating the adjustment

The network adjustment summary and statistics are shown in the bottom right of the Network adjustment tab. If using Gravnet for adjustment, the adjustment results are taken from the *.gra file written by Gravnet. If using Numpy for adjustment, similar output is shown.

In either case, the primary metrics for evaluating the adjustment is the Chi-square goodness of fit test, the reference factor, and the observation residuals.

Chi-square test

The Chi-square test is a standard metric when adjusting survey observations of all types. The test involves calculating the Chi-square statistic:

$$\chi^2 = \sum_{i=1}^{m} v_i^2 p_i^2$$

from the residuals (v_i, the difference between observed and adjusted delta-g's and datum values) and their respective weights (p_i). The statistic is compared to a critical value, calculated for the network degrees of freedom (number of observations) and the significance level. The default significance level is 0.05 (5 percent) but can be changed in the Network adjustment options dialog.

The result of the Chi-square test ('accept' or 'reject') is shown in the bottom right of the Network adjustment tab.

Plots

Two plots are useful for evaluating the adjustment. The first, shown when the "Adjustment > Plot residual histogram" menu item is selected, is a histogram of the delta-g residuals (i.e., the difference between each observed delta-g and the adjusted delta-g). This plot should approximately follow a normal distribution, with no large outliers. The second plot, "Adjustment > Plot adjusted datum vs. measured", shows a bar plot of the difference between the datum observations (e.g., absolute-gravity measurements) and the adjusted values. The closer these residuals are to zero, the better the adjustment.

Outliers and standard deviation

Outliers and the standard deviation of the observations can both have a significant impact on the adjustment results. The relative gravimeter - both metal and quartz-spring versions - is suspect to periodically recording a "bad" measurement. At times these may be tares (offsets that persist across subsequent measurements) or extreme drift, but at other times, only a single reading seems to be bad (based on repeat observations at that station). The ability to quickly and iteratively remove potential bad measurements is an important function of GSadjust.

Similarly, the standard deviation of the observations may need updating when adjusting a network. The weight of each observation is proportional to 1 over the variance (standard-deviation squared). For example, an observation (delta-g or datum) with standard deviation of 5 microGal would have 1/25 the weight of an observation with a standard deviation of 1 microGal. This range of standard deviations (or greater) is not uncommon for field surveys.

Outliers

Observations can be removed from the adjustment by unchecking the appropriate checkbox. If the checkbox next to a station in the Data tree view is unchecked, the respective delta-g table on the Drift tab will be updated. In this case, the delta-g table on the Network adjustment tab will need to be updated using one of the "Populate delta table..." commands (the delta-g tables also need to be updated after changing the drift method).

In addition to unchecking individual station occupations, delta-g's can be unchecked on the Network adjustment tab. The delta-g table does not need to be updated, but the "Adjust network" command must be run to update the adjustment results. After the initial adjustment, by sorting the delta-g table by the adjustment residual (by clicking the column header), the worst observations can be identified and potentially removed. By cross-referencing the residuals with stations and occupation times, it may be possible to identify problem stations, or periods of bad data.

Datum observations can also be removed from the adjustment by unchecking the respective checkbox. The "Adjust network" command must be run to update the adjustment results.

Standard deviation

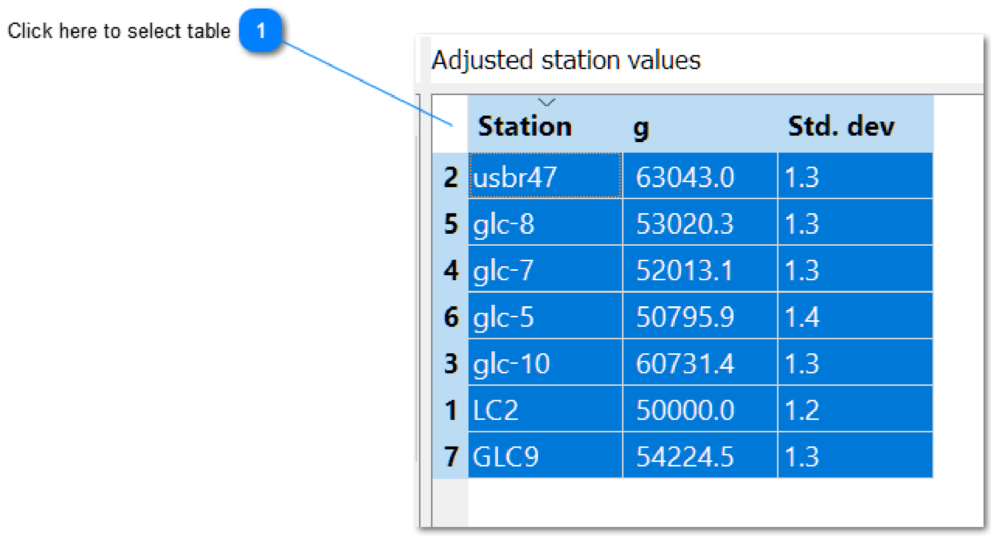
The standard deviation of the observations may need updating based on the adjustment results. As noted, it may be undesirable to have a wide range of standard deviations, thus giving some undue weight. A second reason to update the standard deviation of the observations is to meet the the Chi-square test criteria. if the *a priori* standard deviations are too low (that is, the observations are worse than estimated), the Chi-square test will be rejected.

Standard deviations of delta-g's and datums can be edited directly by double-clicking the respective cells on the Network adjustment tab. More efficiently, a minimum standard deviation, additive term, or multiplier can be applied to all of the delta-g's in a survey or campaign can be applied in the Network adjustment options dialog.

Exporting results

After performing the network adjustment, results can be obtained by copy-paste or exporting to a tabular text file. In addition, if the "Write output files" option is checked in the [Network adjustment options window](), station gravity values (and other information) are written to disk.

To copy adjusted gravity values to the clipboard, click the upper-left corner of the Results table. This will highlight the table. Next, right-click on the table and select "Copy to clipboard". The table can now be pasted into a text editor or spreadsheet program (the keyboard shortcut Ctrl-C cannot be used to copy in this context).



	Station	g	Std. dev
2	usbr47	63043.0	1.3
5	glc-8	53020.3	1.3
4	glc-7	52013.1	1.3
6	glc-5	50795.9	1.4
3	glc-10	60731.4	1.3
1	LC2	50000.0	1.2
7	GLC9	54224.5	1.3

Click here to select table

To export results to a tabular (.csv) text file, select the command "Write tabular data" on the Tools menu. This will write a file named GSadjust_TabularDataYYYYMMDD-HHMM.csv, with the date and time the file was written. The file will have the columns station name, latitude, longitude, and elevation, and for each survey, g and the standard deviation of g from the network
adjustment.

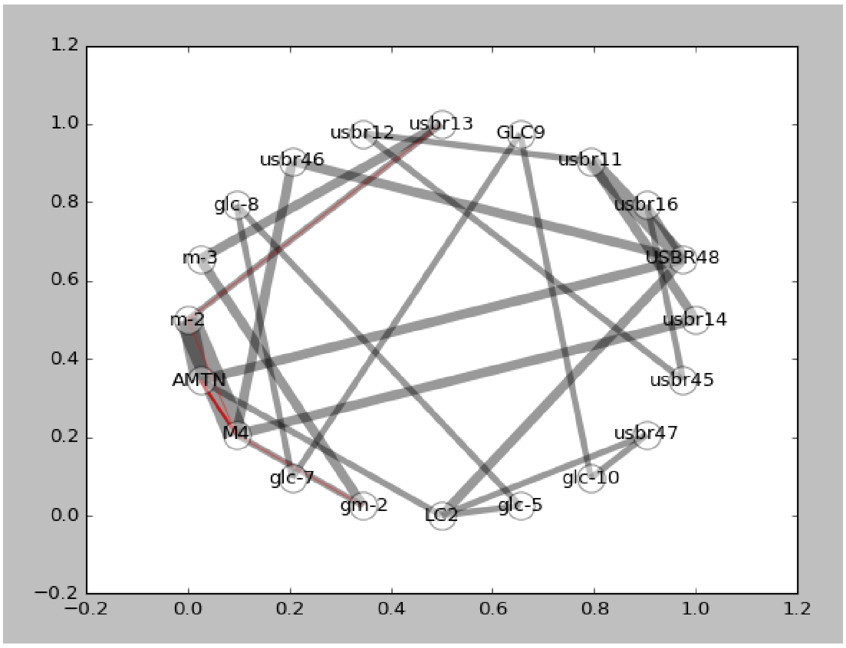
In addition, a table of gravity change between surveys can be exported from the [Compute gravity change]() window.

6. Other tools

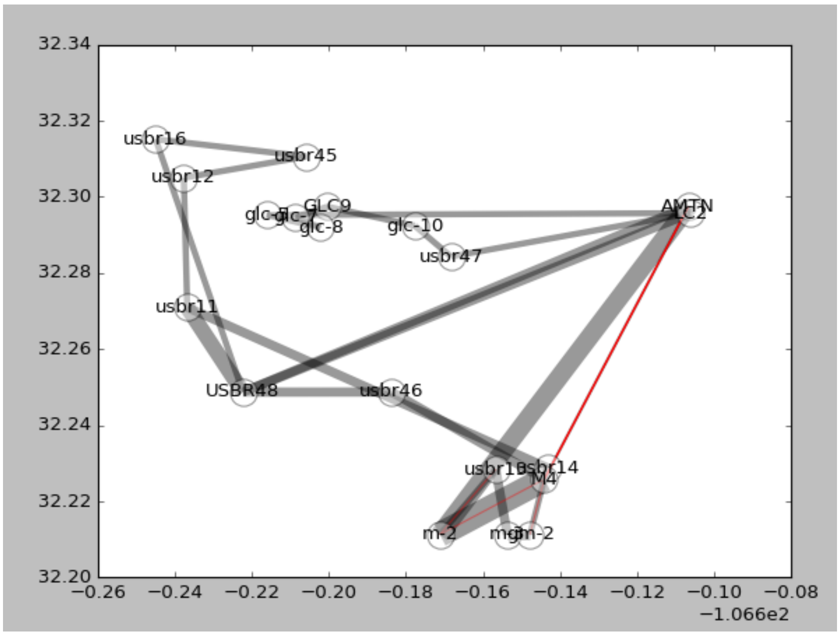
Network visualization

Network graphs of the relative-gravity observations are available using the menu options Network graph - circular and Network graph - map view, on the Tools menu. The first option plots stations equally spaced around a circle, whereas the latter plots stations according to their spatial location (in cartesian coordinates; map projections are not supported). For either option, line weight is proportional to the number of delta-g's between any two stations. Enabled delta-g's (unchecked in the Delta Table) are plotted as gray lines. Disabled delta-g's are plotted as red lines.

Network graph - circular



Network graph - map view (Latitude/Longitue coordinates)



usbr16
usbr45
usbr12
GLC9
glc-7
glc-8
glc-10
usbr47
AMTN
LC2
usbr11
USBR48
usbr46
usbr14
M4
m-2
m-2
32.34
32.32
32.30
32.28
32.26
32.24
32.22
32.20
−0.26 −0.24 −0.22 −0.20 −0.18 −0.16 −0.14 −0.12 −0.10 −0.08
−1.066e2

Metadata export

When publishing network-adjusted gravity data, it should be accompanied by a description of the processing. Complete geospatial metadata, typically provided in XML format, meets the FGDC or ISO 19115 standard. Many tools exist to prepare such metadata, and typically a specialized editor is required to meet the specific format and fields required by the standards.

To assist in the preparation of metadata, the Tools > Write metadata text menu command will write narrative text to a file in the data directory with details of the network adjustment, including:

- Minimum and maximum delta-g residuals
- Minimum and maximum datum observation residuals
- Average standard deviation of the adjusted gravity values
- Number of delta-g's included in the adjustment
- Number of excluded delta-g's
- Number of datum observations included in the adjustment
- Number of excluded datum observations

Typically this metadata text would be included in the Attribute Accuracy Report section of FGDC metadata.

Vertical gradient calculation

Vertical gradients (the change in gravity with vertical position, in units of microGal/m) are typically measured by moving a relative-gravity meter between the land surface and (or) two or more positions on a tripod. Typical tripod heights are 71 cm (the height of the A-10 absolute-gravity meter) and 131 cm (the height of the FG-5 absolute-gravity meter).

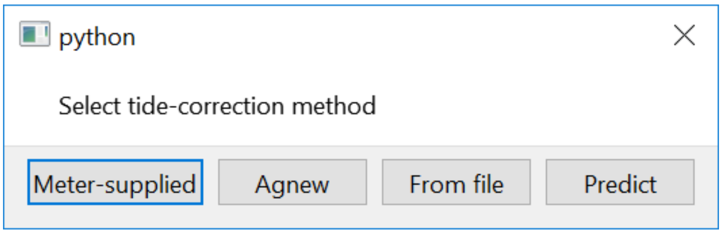
If data are collected at two heights (typically, one at the land surface and one elevated, but any two heights are possible) GS adjust can calculate the vertical gradient by dividing the gravity difference by the height interval. This process requires the Roman drift method be used. The height interval is specified by the menu option Process > Vertical gradient interval... The default value is 64.2 cm; if the tripod is set to this height the sensor of a LaCoste and Romberg D or G relative-gravity meter is located at approximately the measurement height of the A-10 absolute-gravity meter.

Vertical gradients are calculated with the menu option Process > Write vertical gradient file...This opens a file save dialog. The resultant file, a text file with the extension .grd, has a single value and uncertainty (in units of microGal/cm).

At this time GSadjust will only calculate a two-point, first-order linear gradient.

Tide correction

Although most modern relative-gravity meters provide real-time tide correction based on station location, GSadjust provides the option to replace the meter-provided tide correction with calculated tides using the Agnew model, from the software Predict, or from a Tsoft-format text file. The tide correction is changed using the Process > Tide correction menu item. This shows a dialog box in which the method can be selected:



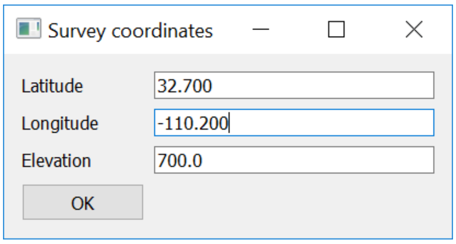
Note: The Agnew and Predict methods were originally developed for PyGrav (Hector and Hinderer, 2016). The accuracy of this code has not been independently verified.

Meter-supplied

If the tide model has been changed after loading a data file (using one of the options below), selecting Meter-supplied in the dialog will restore the original meter tide correction. If the tide model has not been changed, this option will have no effect.

Agnew

The Agnew correction calculates a theoretical solid-Earth tide based on station and time (Agnew 2007, Agnew 2012). The station occupation times must be recorded in UTC. The tide is calculated for a single location. When the Agnew option is selected, the user is prompted to enter coordinates:



The default coordinates are calculated as the average of the station locations.

From file

This option allows theoretical tides to be loaded from a Tsoft-format file (van Camp and Vauterin, 2005). Tsoft provides the capability to calculate tides (and ocean loading) for a given location. The tsoft input file should have a single channel (the tide signal). The tide at the time of each station occupation is taken as the closest-in-time value in the Tsoft file (the tide value is not interpolated). Therefore, the measurement interval of the Tsoft file should be 60 s or less.

Predict

The Predict option calculates a theoretical tide using the Predict software package (Wenzel, 1996). This option was originally developed for PyGrav (Hector and Hinderer, 2016). It has not been tested with GSadjust and is presently disabled, although the functionality still exists in the source code. The Predict executable is not included with GSadjust.

Agnew, D.C., 2007, 3.06 - Earth Tides, in Schubert, G. ed., Treatise on Geophysics, Amsterdam, Elsevier, p. 163–195.

Agnew, D.C., 2012, SPOTL: Some Programs for Ocean-Tide Loading

Hector, B., & Hinderer, J. (2016). pyGrav, a Python-based program for handling and processing relative gravity data. Computers & Geosciences, 91, 90–97. https://doi.org/10.1016/j.cageo.2016.03.010

Van Camp, M., & Vauterin, P. (2005). Tsoft: graphical and interactive software for the analysis of time series and Earth tides. Computers & Geosciences, 31(5), 631–640. https://doi.org/10.1016/j.cageo.2004.11.015

Wenzel, H.G., The Nanogal Software: Earth Tide Data Processing Package Eterna3.30. Bull. D'Inf. Maree Terr., 1996, 124, 9425-9439.

7. Considerations

Dynamic data links between tabs and status indicators

GSadjust makes use of Python's object-oriented functionality to link data across the data, drift, and network adjustment tabs. If station gravity values change (by unchecking samples in the Data Table on the Data tab), the respective gravity differences relative to that station on the Drift and Network Adjustment tabs are immediately updated. This facilitates an iterative workflow.

Although the gravity differences are updated, the network adjustment is *not* automatically repeated if station gravity values change. The user must repeat the "Adjust network" command on the Adjustment menu. If station gravity values have changed since the previous adjustment, a circular red indicator in the bottom right if the GSadjust window is shown. The indicator is cleared after performing the adjustment.

Although station gravity values are updated automatically, changes to the drift correction are not. That is, after populating the delta table, the drift method associated with each delta will not change, even if a different drift correction method is chosen. To apply a different drift correction, the delta table must be re-populated using one of the commands on the Adjustment menu.

In addition to the station gravity values, the check status of each station in the left-hand tree view affects the data to be analyzed. The effect of unchecking a station differs, depending on whether the Drift tab or the Network adjustment tab is active. If the drift tab is active, unchecking a station causes it to disappear from the drift plot and from the table of gravity differences. When the delta table on the Network adjustment tab is populated, it will not include any gravity differences relative to the unchecked station. On the other hand, if the Network adjustment tab is visible when a station is unchecked, the relative-gravity differences relative to that station are disabled and shown in light gray font. Usually two relative-gravity differences will be disabled: one between the previous station and the unchecked station, and one between the unchecked station and the subsequent station. Disabled (gray) relative-gravity differences are *not* included in the Network adjustment.

By disabling relative-gravity differences through unchecking one of the constituent stations, the influence of potentially bad station occupations can be rapidly assessed.

Numpy vs Gravnet inversion

Two options exist for the least-squares solution of the network adjustment, Numpy or Gravnet (Hwang et al., 2002). Gravnet is a Fortran program, and a compiled executable for Windows is provided with GSadjust. Gravnet uses Cholesky decomposition to invert the design matrix and solve the network adjustment system of equations. The numpy inverse solution (using numpy.linalg.inv) uses the LAPACK linear algebra package's Gaussian elimination routine.

For most network adjustment solutions the Numpy and Gravnet solutions will be identical, and run equally fast. There are three main differences in functionality:

- Gravnet only accomodates a single relative-gravity meter when calculating a calibration coefficient; the Numpy solution will calculate a unique calibration coefficient for each relative-gravity meter.
- When drift is included as a polynomial to be solved for in the least squares solution, Gravnet is limited to a single polynomial for all observations in a Survey. That is, if the drift method on the Drift tab is set to "Network adjustment", all Loops in the same Survey must also be set to "Network adjustment", all with identical polynomial degrees. With the Numpy solution, the drift method can be set independently for each loop. If necessary, the "Network adjustment" method may be used for some loops, and an alternative method used for other loops within the same survey.
- Gravnet includes Pope's t-test method to test for outliers; Numpy inversion does not perform outlier tests.

Gravnet can also solve for circular (screw) error, but this option is not currently implemented in GSadjust.

Gravnet is provided as a Windows executable; it will not run on non-Windows computers unless the Fortran source code is compiled for the specific platform.

Hwang, C., C. Wang, and L. Lee (2002), Adjustment of relative gravity measurements using weighted and datum-free constraints, Comput. Geosci., 28, 1005–1015.

Vertical gradients

The vertical gravity gradient, expressed in microGal/cm, has two functions in combined absolute/relative gravity surveys. First, the gradient is used in the absolute gravity data-collection software ('g', by Micro-g LaCoste) to calculate g, because gravity varies over the height of the free-fall. Especially for the A-10 meter, having a relatively short free-fall, the vertical gradient has only a minor effect on g and a standard value (-3, or -3.086, microGal/cm) is often used. Second, and more importantly, the vertical gradient is used to calculate g at the transfer height at which it is reported. Typically the transfer height is 100 cm, whereas the A-10 measures at about 71 cm, and the FG-5 at about 131 cm.

The latter application of the vertical gradient is important when combining relative and absolute measurements, which are typically made at different measurement heights. Generally the absolute-gravity measurement is transferred from the transfer height to the land surface (or, the measurement height of the relative-gravity meter). GSadjust uses the transfer height and gradients shown for each datum in the Datum Table to transfer the absolute-gravity value to the land surfacer (these are imported from the *.project.txt files output by 'g' if the "Import abs. g - complete" menu option is selected). An offset equal to [transfer height] * [gradient] is added to each datum. If the imported/specified absolute-gravity value (or datum) should be used as-is, the transfer height should be set to zero. If the gradient is the same for every datum, it will have no effect; a constant offset will be added to each datum.

The adjusted-gravity value at each station in the Results Table has the transfer offset applied (that is, it is the gravity value at the land surface). When comparing adjusted to measured values at datum stations, the offset is taken into account.

Vertical gradients are typically measured over a discrete interval using a relative-gravimeter and a tripod or similar stand. A mini loop is measured between the ground and the measurement height of the A-10 or FG-5 meter; typically the ground is occupied 3 or 4 times, and the tripod 2 or 3 times (additional occupations may improve accuracy). If this type of survey, with only two stations, is processed with GSadjust, the menu option "Write vertical gradient file..." can be used to calculate a vertical gradient, in microGal/cm, and write it to file. The gradient is calculated over the interval specified in the dialog opened by the "Vertical gradient interval..." menu command.

Saving and loading the workspace

At any point the current workspace can be saved using the "Save workspace..." menu command. This writes the stations, loops, and surveys of the campaign, along with their checkbox states, drift method(s), delta-g's, and datums, to a file with a *.p extension. The file is written using the Python "pickle" protocol and cannot be read or edited outside GSadjust. Adjustment results are *not* saved. Saved workspaces can be imported using the "Load workspace..." menu command.

Warning: Pickle files can contain malicious code. Only load workspace files from trusted sources.

Keyboard navigation

GSadjust is designed for efficient keyboard navigation. Several menu commands have keyboard shortcuts. Standard Windows shortcuts are also available, such as ctrl-tab and ctrl-shift-tab to move between the Data, Drift, and Network Adjustment tabs. A useful shortcut on the data tab can be used to quickly deselect samples at a station occupation. With focus on the Data Tree, press tab to change focus to the Data Table. Press spacebar to uncheck a sample, then down-arrow to advance to the next sample. Continue with spacebar and down-arrow, repeatedly, to deselect multiple samples. After deselecting the desired samples, press shift-tab to move back to the Data Tree, then down-arrow to advance to the next station occupation. Repeat the process to deselect samples for each subsequent station occupation.

An alternative for rapidly deselecting multiple samples at a station is to hold the shift or control keys while clicking the stations to be unchecked in the Data table. Then, select the "uncheck selected" button in the Data plot window.

Multiple meters

GSadjust can accomodate data from more than one relative gravimeter, and, if absolute-gravity observations are present, determine the calibration coefficient for each meter during the least-squares network adjustment. The presence of multiple meters is determined automatically based on the serial numbers read from the raw data files. The calibration coefficient option must be selected in the Network adjustment options dialog on the Adjust menu. If this option is selected, a calibration coefficient will be determined for all meters (there is no option to calculate a coefficient for some meters and not others used on the same Campaign). If the calibration coefficient is to be determined for multiple relative-gravity meters, the Numpy adjustment option must be selected; Gravnet cannot accomodate more than one meter. If multiple meters are used on a Campaign, they must all be the same type (Burris or Scintrex).

Calculating gravity change over time

If two or more Surveys are present in a Campaign, GSadjust can calculate the change in gravity over time using the Process > Compute gravity change menu option. This opens a new window that displays a table of gravity change. Change is calculated between each successive survey, and cumulative change is calculated from the first survey.

To export results, select cells in the table (Ctrl-a to select all), and select the "Copy to clipboard" button at the bottom of the table.

A more complete table, that includes station coordinates, gravity values and uncertainty for each survey, as well as gravity change, can be shown by selecting the "Show full table" button at the bottom of the table. This complete table can be saved to a text file by selecting the Tools > Write tabular data menu option.