University of Stuttgart
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A MATLAB Toolbox for the Scintrex CG-5 Gravimeter at GIS

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Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgement, the work presented is entirely my own.

Place, Date Signature

Abstract

This thesis is about a MATLAB toolbox for the Scintrex CG-5 gravimeter. The aim of this toolbox is to offer a basic data process for gravity measurement, which is compatible for most applications in geodesy. In particular, the toolbox covers:

1. data selection,
2. adjustment,
3. gravity gradient computation,
4. gravity visualization,
5. calibration factor estimation.

A graphical user interface enables users without deeper programming knowledge to operate this toolbox and obtain the results like adjusted values or figures.

Key words: Scintrex CG-5, gravimeter toolbox, GUI, gravity adjustment, gravimeter calibration, Bouguer anomaly

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Chapter 1

Introduction

Gravimetry is of great importance in geodesy and it is the basic way to study the Earth. By gravimetry (Latin: gravis=heavy; Greek: $\mu\varepsilon\tau\rho\varepsilon\omega$=to measure), we mean the measurement of gravity, which is the magnitude of the gravitational acceleration $\mathbf{g}$:

$$g = |\mathbf{g}| \tag{1.1}$$

and of the gravity gradient on or near the surface of the Earth (Torge, 1989). Gravimeters are instruments to measure gravity magnitude, while the gravity gradient can be determined by several measurements on different heights.
The purpose of this work is to build a toolbox that is compatible to most applications in geodesy.

1.1 Development of Gravity Measurement

There are three types of instruments for gravity measurement: free fall, pendulum and spring gravimeters. In the early days, the theory about gravity leads to the appearances of these instruments. In the meantime, the observations from instruments realize and improve the theories. This section introduce the basic theory and instrument for gravity measurement.
Free Fall Principle
The phenomenon of gravity acceleration was firstly described by Aristotle. According to his theory, the velocity of falling bodies is proportional to their weights (Torge, 1989). One of Galileo's student described in a biography, that Galileo dropped objects with different weights from the leaning tower of Pisa. This experiment disproved that theory and realized Galileo's prediction that the free fall is a uniformly accelerated motion, while some historians regard it as a thought experiment (Segre, 1989).
The free fall principle is based on the equation:

$$\ddot{z} = g, \tag{1.2}$$

in which z is the falling distance. This is the equation of motion of a falling proof mass in a height independent gravity field g, and it is integrated twice to produce:

$$z(t) = \frac{1}{2}gt^2 + v_0 t + z_0, \tag{1.3}$$

with the initial height z_0 and the initial velocity v_0 as integration constants. For the simple case of $z_0 = v_0 = 0$, we achieve:

$$g = \frac{2z}{t^2}. \tag{1.4}$$

From the equation (1.4), absolute gravity can be determined from measuring the time and the vertical distance of a falling proof mass.

Pendulum Principle and Torsion

Galileo also stated that the period of a pendulum only depends on its length. In the 17th century, Christian Huygens established the theory, describing the relation between the period S of a pendulum, the pendulum length l and the gravity acceleration g. For a pendulum with small amplitude, this relationship is given by (Schokin, 1963):

$$S = \pi\sqrt{\frac{l}{g}}. \tag{1.5}$$

Thus, the measurement of period and length allows a determination of absolute gravity.

From that on, for a very long time, pendulums became the most important instruments for measuring gravity.

With the development in the theory of gravitation, mechanics of rigid bodies and hydrostatics, the theoretical foundation of gravimetry is gradually improved. Reversible pendulums, 'invariable' pendulums and new time and length measurement instruments were invented to pursue a higher accuracy and precision. Based on pendulum observations, the theory in the field of geodesy was also improved. To assess the detailed structures of the gravity field, the construction of a field-usable torsion balance by Loránd Eötvös gained importance (Torge, 1989). In the early 20th century, pendulum and torsion balance observations were applied, which was costly and usable only in the flat areas for the survey of single structure. For the purpose of rapid survey in large areas, industry developed spring gravimeters.

Spring Gravimeter Principle

Spring gravimeters use elastic springs to access the force that is counteractive to gravity force, and the gravity difference can be obtained by the observation of change of length or angle. The theoretical foundations of this method were known for a long time. Already Robert Hooke formulated the law of elasticity in 1678, which stated that the force F needed to extend or compress a spring by some distance X is proportional to that distance:

$$F = kX. \tag{1.6}$$

Since the end of 17th century, this spring balance has been used for gravimetry (Torge, 1989). To achieve better observations, the spring gravimeter was modified from static spring to astatic spring.

A static spring is a simple, vertically suspended spring. Suppose without mass, the original length of the spring is l_0, and the length extends to l with attaching mass. According to equation (1.6) we have:

$$mg = k(l - l_0), \tag{1.7}$$

which leads to $g = \frac{k}{m}(l - l_0)$, with k the spring constant. As this constant is difficult to determine with sufficient accuracy, static springs are normally used for relative gravity measurement.

Astatic spring was invented by Lucien J. B. LaCoste in 1932, who also developed the concept of

zero-length spring. The figure 1.1 is the LaCoste-Romberg design, in which a bar with a mass m attached can rotate around a pivot, and a spring keeps the bar from going down (Sneeuw, 2006). In equilibrium the gravity torque and the spring torque should be equal:

$$\text{Gravity torque: } mga \sin\delta = mga \cos\beta$$
$$\text{Spring torque: } k(l - l_0)b \sin\alpha = k(l - l_0)b\frac{y}{l} \cos\beta$$

Due to the sine law $\frac{\sin\alpha}{y} = \frac{\sin(\beta + \frac{1}{2}\pi)}{l}$, we can obtain:

$$g = \frac{k}{m}\frac{b}{a}\left(1 - \frac{l_0}{l}\right) y. \tag{1.8}$$

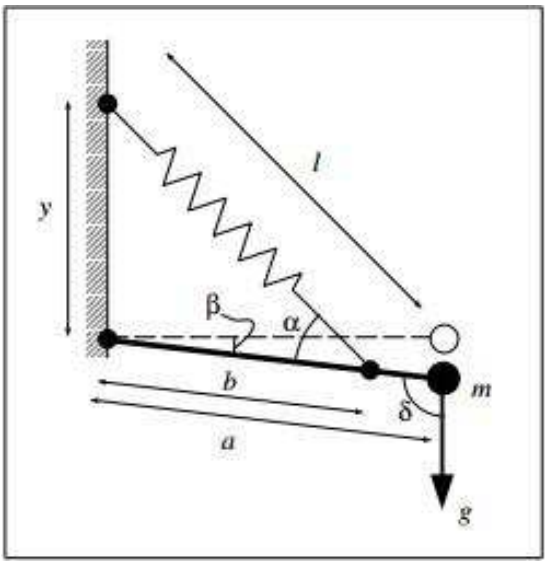

Figure 1.1: *Astatic spring (from the electronic lecture notes of Physical Geodesy, Sneeuw, 2006)*

As there are many constants in equation (1.8), that need to be determined in high accuracy, astatic springs are also used for relative gravity. A zero-length spring is a spring with $l_0 = 0$, which can be produced by twisting the wire when winding it (Sneeuw, 2006).

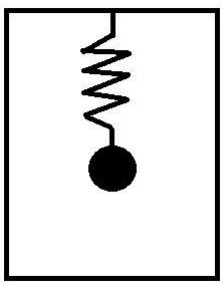

Figure 1.2: *Basic principle of Scintrex CG-5*

Nowadays, spring gravimeters are usually used for relative gravity measurements, while pendulums and free-fall apparatus provide absolute gravity measurements. In this work, the toolbox is designed for Scintrex CG-5, which provides fast, reliable and precise relative gravity measurement. The basic principle of Scintrex CG-5 is spring balance (figure 1.2). When the gravity changes, the force on the proof mass will likewise change and the spring length varies also, this variation will be reflected by the voltage sensor and then be automatically transformed to gravity readings.

1.2 Field Measurement with Scintrex CG-5

This work deals with the data derived from Scintrex CG-5 (figure 1.3). In figure 1.4, the upper part indicates the survey information (Name, Time, Location), set-up parameters (Tilt, Drift) and correction options. The main part is the measurement data and correction parameters. Figure 1.5 is the specifications of CG-5, illustrating the properties. The aim of this section is to introduce briefly how to obtain the measurement data in the field.

Figure 1.3: *Scintrex CG-5*

```
/       CG-5 SURVEY
/       Survey name:    vtuttg
/       Instrument S/N: 40191
/       Client:         rs
/       Operator:
/       Date:           2013/ 3/26
/       Time:           09:16:25
/       LONG:           8.2000000 E
/       LAT:            48.6000000 N
/       ZONE:           0
/       GMT DIFF.:      0.0
/       CG-5 SURVEY
/       Survey name:    jOuttg
/       Instrument S/N: 40191
/       Client:         rs
/       Operator:
/       Date:           2013/ 3/26
/       Time:           09:18:10
/       LONG:           8.2000000 E
/       LAT:            48.6000000 N
/       ZONE:           0
/       GMT DIFF.:      0.0

/       CG-5 SETUP PARAMETERS
/       Gref:                   0.000
/       Gcal1:          6721.453
/       TiltxS:         660.409
/       TiltyS:         655.239
/       Tiltx0:         -123.232
/       Tilty0:         145.640
/       Tempco:         -0.127
/       Drift:          0.257
/       DriftTime Start:        13:58:55
/       DriftDate Start:        2013/03/25

/       CG-5 OPTIONS
/       Tide Correction:    YES
/       Cont. Tilt:          NO
/       Auto Rejection:      NO
/       Terrain Corr.:       NO
/       Seismic Filter:      NO
/       Raw Data:            NO
/———LINE———STATION———ALT.———GRAV.——SD.—TILTX—TILTY-TEMP——TIDE——DUR-REJ———TIME——DEC.TIME+DATE—TERRAIN——DATE
 1.0000000  21.0000000   16.8944   4855.711 0.032   12.3   -5.6 -1.12 0.015  57   0 09:19:26     41330.38787    0.0000  2013/03/26
 1.0000000  21.0000000   16.8944   4855.710 0.025   12.9   -6.8 -1.08 0.016  57   0 09:20:29     41330.38860    0.0000  2013/03/26
 1.0000000  21.0000000   16.6502   4855.708 0.024   12.9   -8.7 -1.05 0.016  57   0 09:21:29     41330.38930    0.0000  2013/03/26
 1.0000000  21.0000000   16.4061   4855.705 0.027   13.0   -7.9 -1.02 0.016  57   0 09:22:29     41330.38999    0.0000  2013/03/26
 1.0000000  21.0000000   16.1619   4855.704 0.045   12.7   -8.7 -0.99 0.017  57   0 09:23:29     41330.39068    0.0000  2013/03/26
 1.0000000  21.0000000   16.1619   4855.702 0.045   12.4   -9.7 -0.97 0.017  57   0 09:24:29     41330.39138    0.0000  2013/03/26
 1.0000000  21.0000000   15.9178   4855.699 0.073   12.2   -9.8 -0.96 0.018  57   0 09:25:29     41330.39207    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.697 0.043   12.3  -10.5 -0.94 0.018  57   0 09:26:29     41330.39276    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.695 0.024   11.9  -10.4 -0.93 0.018  57   0 09:27:29     41330.39346    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.694 0.054   12.3  -11.0 -0.92 0.019  57   0 09:28:29     41330.39415    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.694 0.054   12.3  -11.0 -0.92 0.019  57   0 09:28:29     41330.39415    0.0000  2013/03/26
 1.0000000  21.0000000   15.1854   4855.692 0.020   12.0  -11.5 -0.91 0.019  57   0 09:29:29     41330.39484    0.0000  2013/03/26
 1.0000000  21.0000000   14.9412   4855.691 0.022   11.5  -11.8 -0.91 0.020  57   0 09:30:29     41330.39554    0.0000  2013/03/26
 1.0000000  21.0000000   14.9412   4855.690 0.027   11.7  -12.2 -0.90 0.020  57   0 09:31:29     41330.39623    0.0000  2013/03/26
 1.0000000  21.0000000   14.6971   4855.690 0.052   12.3  -13.1 -0.90 0.020  57   0 09:32:29     41330.39692    0.0000  2013/03/26
 1.0000000  21.0000000   14.4530   4855.688 0.061   12.2  -13.9 -0.89 0.021  57   0 09:33:29     41330.39762    0.0000  2013/03/26
/ 1.0000000  21.0000000   13.7205   4855.679 0.070   12.3  -14.0 -0.89 0.021  24   0 09:34:30     41330.39832    0.0000  2013/03/26
 1.0000000  12.0000000   12.7440   4765.971 0.060   -1.6   -0.6 -0.58 0.027  57   0 09:50:46     41330.40960    0.0000  2013/03/26
 1.0000000  12.0000000   12.7440   4765.968 0.070   -1.7   -0.2 -0.56 0.027  57   0 09:51:49     41330.41033    0.0000  2013/03/26
 1.0000000  12.0000000   12.0116   4765.969 0.046   -1.9   -0.8 -0.55 0.027  57   0 09:52:49     41330.41102    0.0000  2013/03/26
 1.0000000  12.0000000   11.7674   4765.968 0.037   -0.8   -1.2 -0.54 0.028  57   0 09:53:49     41330.41171    0.0000  2013/03/26
 1.0000000  12.0000000   11.5233   4765.969 0.056   -0.2   -1.6 -0.55 0.028  57   0 09:54:49     41330.41241    0.0000  2013/03/26
 1.0000000  12.0000000   11.0350   4765.966 0.048   -0.6   -2.1 -0.56 0.028  57   0 09:55:49     41330.41310    0.0000  2013/03/26
 1.0000000  12.0000000   11.0350   4765.967 0.068    0.2   -2.7 -0.57 0.028  57   0 09:56:49     41330.41379    0.0000  2013/03/26
 1.0000000  12.0000000   10.5467   4765.966 0.058   -0.1   -2.6 -0.59 0.029  57   0 09:57:49     41330.41449    0.0000  2013/03/26
 1.0000000  12.0000000   10.3026   4765.966 0.059   -0.4   -2.6 -0.61 0.029  57   0 09:58:49     41330.41518    0.0000  2013/03/26
 1.0000000  12.0000000   10.0584   4765.965 0.046   -1.5   -2.8 -0.63 0.029  57   0 09:59:49     41330.41587    0.0000  2013/03/26
 1.0000000  12.0000000   10.0584   4765.965 0.055   -1.7   -2.7 -0.64 0.029  57   0 10:00:49     41330.41657    0.0000  2013/03/26
 1.0000000  12.0000000    9.8143   4765.966 0.040   -1.8   -2.7 -0.66 0.030  57   0 10:01:49     41330.41726    0.0000  2013/03/26
 1.0000000  12.0000000    9.5702   4765.966 0.034   -2.4   -2.8 -0.68 0.030  57   0 10:02:49     41330.41795    0.0000  2013/03/26
 1.0000000  12.0000000    9.3260   4765.966 0.042   -3.3   -3.1 -0.69 0.030  57   0 10:03:49     41330.41865    0.0000  2013/03/26
 1.0000000  12.0000000    9.3260   4765.966 0.057   -3.9   -3.5 -0.70 0.030  57   0 10:04:49     41330.41934    0.0000  2013/03/26
 1.0000000  12.0000000    9.0819   4765.967 0.044   -4.5   -3.2 -0.71 0.031  57   0 10:05:49     41330.42003    0.0000  2013/03/26
 1.0000000  12.0000000    8.8377   4765.966 0.044   -4.7   -3.5 -0.72 0.031  57   0 10:06:49     41330.42073    0.0000  2013/03/26
 1.0000000  12.0000000    8.5936   4765.967 0.056   -4.8   -3.9 -0.73 0.031  57   0 10:07:49     41330.42142    0.0000  2013/03/26
 1.0000000  12.0000000    8.5936   4765.965 0.053   -5.1   -4.1 -0.74 0.031  57   0 10:08:49     41330.42211    0.0000  2013/03/26
 1.0000000  12.0000000    8.3495   4765.965 0.051   -5.1   -4.2 -0.75 0.032  57   0 10:09:49     41330.42281    0.0000  2013/03/26
 1.0000000  12.0000000    8.1053   4765.965 0.054   -4.9   -4.7 -0.75 0.032  57   0 10:10:49     41330.42350    0.0000  2013/03/26
 1.0000000  12.0000000    8.1053   4765.965 0.042   -5.3   -4.9 -0.76 0.032  57   0 10:11:49     41330.42419    0.0000  2013/03/26
 1.0000000  12.0000000    7.6170   4765.967 0.058   -5.0   -4.5 -0.76 0.032  57   0 10:12:49     41330.42489    0.0000  2013/03/26
 1.0000000  12.0000000    7.6170   4765.966 0.059   -5.1   -5.5 -0.76 0.033  57   0 10:13:49     41330.42558    0.0000  2013/03/26
 1.0000000  12.0000000    7.3729   4765.965 0.041   -4.9   -5.4 -0.76 0.033  57   0 10:14:49     41330.42627    0.0000  2013/03/26
 1.0000000  12.0000000    7.1288   4765.965 0.055   -5.3   -5.2 -0.76 0.033  57   0 10:15:49     41330.42697    0.0000  2013/03/26
 1.0000000  12.0000000    7.1288   4765.965 0.050   -5.2   -6.1 -0.76 0.033  57   0 10:16:49     41330.42766    0.0000  2013/03/26
 1.0000000  12.0000000    6.8846   4765.964 0.054   -5.2   -6.3 -0.76 0.033  57   0 10:17:49     41330.42835    0.0000  2013/03/26
 1.0000000  12.0000000    5.9081   4765.963 0.075   -6.2   -6.1 -0.76 0.034  53   0 10:18:50     41330.42906    0.0000  2013/03/26
 1.0000000   7.0000000    4.4432   4715.947 0.031    0.8   -5.8 -0.50 0.037  57   0 10:42:57     41330.44578    0.0000  2013/03/26
 1.0000000   7.0000000    4.4432   4715.949 0.090    1.5   -5.9 -0.48 0.037  57   0 10:44:00     41330.44651    0.0000  2013/03/26
```

Figure 1.4: *Scintrex CG-5 derived data*

CG-5 SPECIFICATIONS

Sensor Type:	Fused Quartz using electrostatic nulling
Reading Resolution:	1 microGal
Standard Field Repeatability:	<5 microGal
Operating Range:	8,000 mGal without resetting
Residual Long-Term Drift:	Less than 0.02 mGal/day (static)
Automatic Tilt Compensation:	±200 arc sec
Tares:	Typically less than 5 microGals for shocks up to 20 G
Automated Corrections:	Tide, Instrument Tilt, Temperature, Drift, Near Terrain, Noisy Sample, Seismic Noise Filter
Operating Temperature:	-40°C to +45°C (-40°F to 113°F)
Ambient Temperature Coefficient:	0.2 microGal/°C (typical)
Pressure Coefficient:	0.15 microGal/kPa (typical)
Magnetic Field Coefficient:	1 microGal/Gauss (typical)
Memory:	Flash Technology (data security)
Dimensions:	30 cm (H) x 22 cm x 21 cm (12" (H) x 8.5" x 8")
Weight (including batteries):	8 kg (17.5 lbs)
Battery Capacity:	2 x 6.6 Ah (11.1 V) rechargeable Lithium-Ion Smart Batteries. Full day operation in normal survey conditions with two fully charged batteries
Power Consumption:	4.5 W at +25°C (77°F)
Standard System:	CG-5 Console, Tripod base, 2 rechargeable batteries, Battery Charger 110/240 V, External Power Supply 110/240 V, RS-232 and USB Cables, Carrying Bag, Data dump and utilities software, Operating Manual (CD), Transit Case

GPS

Enables GPS station referencing from an external 12 channel smart GPS antenna being connected via the RS-232 port. Standard GPS accuracy: <15 m DGPS (WAAS) <3 m. Client has the option to use other higher accuracy GPS receivers outputting NMEA data string through serial port.

RF Transmitter

The CG-5 Autograv gravity meter is equipped with a radio frequency remote start transmitter to allow measurements to be taken without disturbing the meter by touch.

OPTIONS

High Temperature Option - For use in climates that may exceed the operation temperature of +45°C (113°F). Allows operating temperatures of up to +55°C (131°F). This option is intended to be used in climates above freezing and needs to be ordered at the time of purchase.

Battery Belt - Suggested for cold weather operation.

Training Programs

Software Packages

ISO 9001:2000 registered company. All specifications are subject to change without notice.

Specification Sheet Part Number 867711 Rev. 1

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e-mail: info@microglacoste.com
Website: www.microglacoste.com

Figure 1.5: *Scintrex CG-5 specifications*

Before measurement in field, it is recommended to run the gravimeter around 12 hours to check its stability (drift of the spring). When carrying the gravimeter, user should handle with caution as the spring inside the gravimeter is made of quartz glass. The first step for measuring is to place the gravimeter on levelled tripod or fixed stable station with a rough levelling. Then opening the instrument, the user should type in the needed information (figure 1.6) and set up options (figure 1.7). For each measurement, the user should set 'Line' (relevant to measurement sequence, the same line for different points) and 'Station' (unique for each point) as the identification for current measurement. After setting the station designation, the gravimeter needs further levelling by the foot screws. When the levelling is acceptable, user can click 'MEASURE' and the measuring screen (figure 1.8(a)) is displayed. The final data is showed (figure 1.8(b)) and the user chooses to record it or cancel it in case of poor quality. After the measurement, the gravimeter should be closed and transported to next point with care. For next points, there is no need to input the survey information and set up the options again.

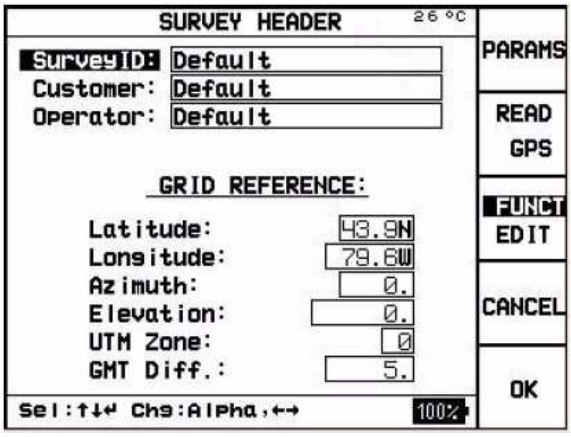
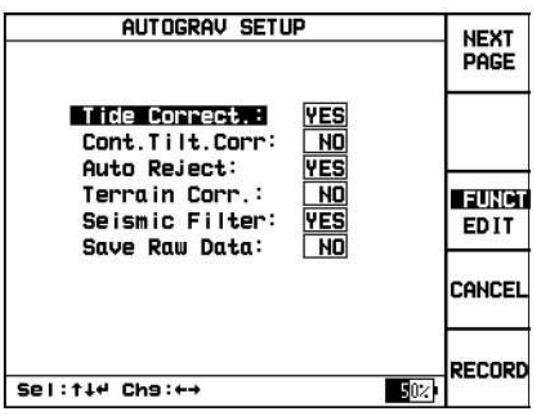
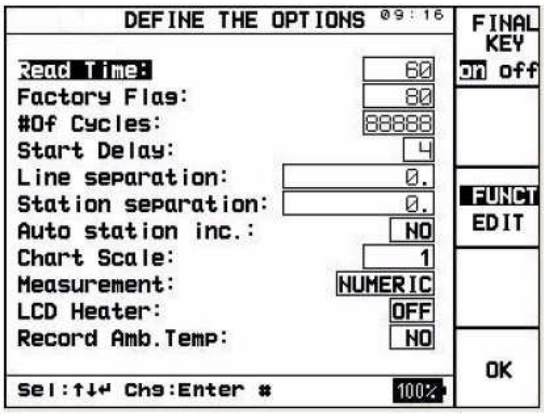


Figure 1.6: *Survey information screen*



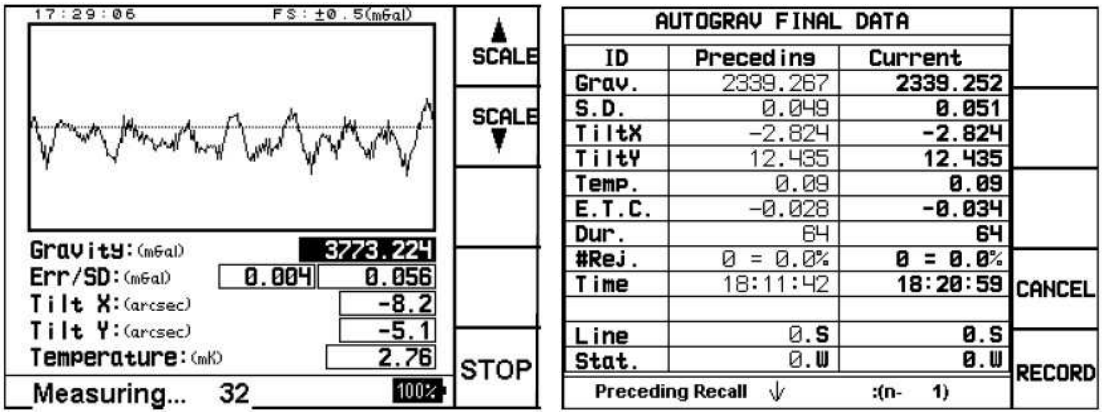
(a) Corrections setting screen



(b) Options setting screen

Figure 1.7: *Options screen*

In addition, also gradient measurements can be evaluated in this toolbox, which are the observations with different heights on one point. Therefore, for one point, it has a gradient itself.



(a) Measuring screen (b) Result screen

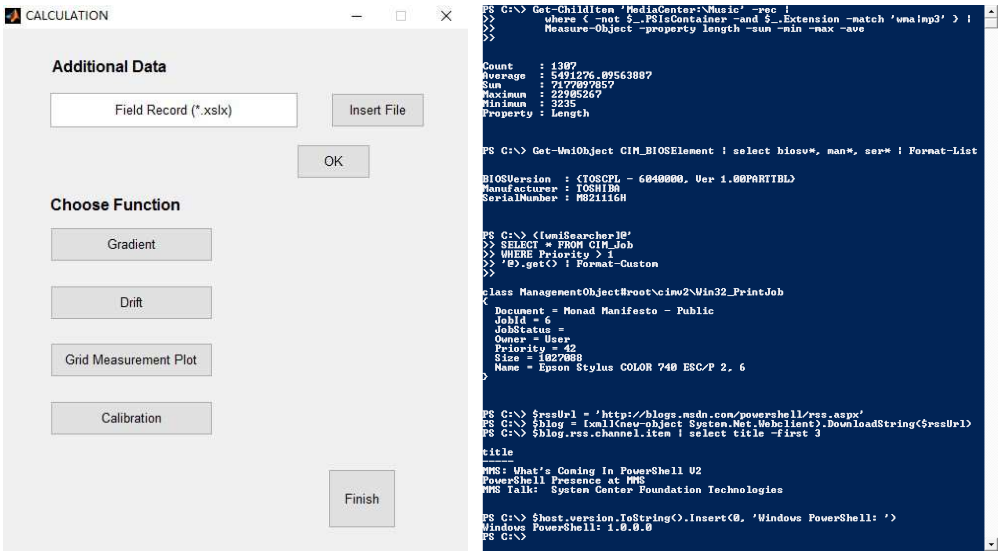
Figure 1.8: *Measuring and result screen*

Figure 1.9 is an example for gradient measurement, the instrument can be raised or lowered to change the instrument height.
Calibration factor can also be estimated to transform the voltage signal to gravity signal. For the purpose of calibration, user should measure the gravity on points that at least two of them with known absolute gravity values. Besides this, it is recommended to calibrate the drift first by measuring continuously on one point. As the calibration involves drift corrected measurement values, the accuracy of drift affects highly the calibration result.
It is also important to fill field book during the measurement for further data processing. After setting the instrument on a new point, the user should write down the station name and line name, measure the instrument height and air pressure. If the user has other information e.g. point height, free air gradient, horizontal coordinate, they should also be recorded.

Figure 1.9: *Gradient measurement on one point (picture from Ron Schlesinger)*

1.3 Graphical User Interface

To make this toolbox easy to operate, we apply graphical user interface. User interface is a junction between a client and a computer program, through which the client can interact with the program. Graphical user interface is a interface that allows a client to communicate by windows, icons and pop-up menus. There are also other types of user interfaces, figure 1.10 is the comparison between graphical user interface and also commonly used command line interface (use interacts with program by typing command strings), we can see that with graphical user interface, the user only need to click the button and the result would be obtained while the command line interface needs more knowledge in programming and is not easy to understand. Graphical user interface is the standard type for personal computer, as it has no requirement for user to understand the programming language or the calculation theory behind. Therefore, this gravimeter toolbox can be used by anyone who has the measurement data and no need to be familiar with programming or adjustment theory.



(a) Graphical user interface of the gravimeter toolbox

(b) Command line interface (Screenshot of Windows PowerShell 1.0, running on Windows Vista)

Figure 1.10: *User interface comparison*

1.4 Outline of This Work

This work starts with an operational manual of the toolbox, including the input data. Then Chapter 3 demonstrates the calculation method behind and in Chapter 4 examples are presented to display the obtained results.

Chapter 2

Operational Manual

This chapter is the operational manual for the gravimeter toolbox. It has two parts, the first part introduces the input data files that should be prepared in advance, and the second part is about how to operate the toolbox.

2.1 Preparation Files

The toolbox has five main functions: data selection, adjustment, gravity gradient computation, gravity visualization and calibration. To realize these functions, two files are needed:

1. Gravimeter data file in *.txt format (produced from gravimeter, figure 1.5),
2. Field record in *.xlsx format with specific content, based on field book (optional).

Here is an example of field record:

	A	B	C	D	E	F	G	H	I	J	K	L
1	PtID	Line	Point Type	Instrument Height [m]	pressure [mbar]	absGrav [mGal]	FAgrad [mGal/m]	DHHN [m]	stdDHHN [m]	X [m]	Y [m]	lattitude [degree]
2	100	1	0	0.474	999		-0.308	250				
3	801246	1	0	0.474	997	980812	-0.308	260.03				
4	801220	1	0	0.475	997	980811.5	-0.308	264.76				
5	286	1	2	0.247	994		-0.308	287.39		3405077	5305441	
6	286	2	2	0.214	994		-0.308	287.39		3405077	5305441	
7	286	3	2	1.378	994		-0.308	287.39		3405077	5305441	
8	286	4	2	0.214	994		-0.308	287.39		3405077	5305441	
9	286	5	2	1.378	994		-0.308	287.39		3405077	5305441	
10	286	6	2	0.214	994		-0.308	287.39		3405077	5305441	
11	286	7	2	1.378	994		-0.308	287.39		3405077	5305441	
12	59	1	0	0.422	994		-0.308	286.93		3405170	5305536	
13	281	1	0	0.364	994		-0.308	286.6		3405215	5305595	
14	59	2	0	0.422	994		-0.308	286.93		3405170	5305536	
15	14	1	0	0.187	994		-0.308	286.93		3405260	5305621	
16	281	2	0	0.367	994		-0.308	286.6		3405215	5305595	
17	13	1	0	-0.092	994		-0.308	287.92		3405254	5305633	
18	14	2	0	0.184	994		-0.308	286.93		3405260	5305621	
19	17	1	0	-0.144	994		-0.308	287.29		3405300	5305647	
20	13	2	0	-0.102	994		-0.308	287.92		3405254	5305633	

Figure 2.1: *Example of field record*

in which,

- PtID: Point identification (if identical points have different heights, they should have different 'Line' numbers),

- Line: Line number of the measurement, the same 'PtID' with different 'Line' indicates the movement of gravimeter, not continuously measuring,
- Point Type: 0 means common measurement, other positive integers specify the gradient measurement that on identical point but with different instrument height (the same 'PtID' with the same positive integer of 'Point Type'),
- dh [m]: The height from the top of the gravimeter to the ground,
- pressure [mbar]: Air pressure,
- absGrav [mGal]: Absolute gravity of the point (on the ground),
- FAgrad [mGal/m]: Free air gradient,
- DHHN [m]: Height of the point (on the ground) above sea level, height system does not matter,
- stdDHHN [m]: Standard deviation of 'DHHN', if nothing filled in, the default value is 0.02 m,
- X [m]: Horizontal coordinate of the point, used for gravity visualization (Gauss-Kruger coordinates are preferable, but also local coordinates are possible),
- Y [m]: Horizontal coordinate of the point, used for gravity visualization (Gauss-Kruger coordinates are preferable, but also local coordinates are possible),
- Latitude [degree]: Latitude of the point, used for visualization of Bouguer anomaly.

Remark 2.1: Field Record is not necessary. Every pair of 'PtID' and 'Line' in gravimeter data file should exist in field record only once! If for some column, there is no value accessible, just leave it empty or fill in NaN ('PtID', 'Line' and 'Point Type' should always have values). Do not change the column order!

2.2 Operating the Toolbox

The folder 'Gravimeter_Toolbox' consists of all files related to the gravimeter toolbox. Programs name in capital words are GUI files and others are functions used in these GUI. The main window is created by MAINWINDOW (figure 2.2), which is in the folder of 'Gravimeter_Toolbox', other sub windows and functions are all in the folder 'subfunctions'.
In MAINWINDOW window, there are two push buttons, which are 'DATA PREPROCESSING' and 'CALCULATION'. 'DATA PREPROCESSING' has two parts, it begins with data selection, deleting improper points first, then switching to computation part, to determine results e.g. drift, gradient, calibration. While 'CALCULATION' is directly the computation part. Next sections will introduce these two parts in detail.

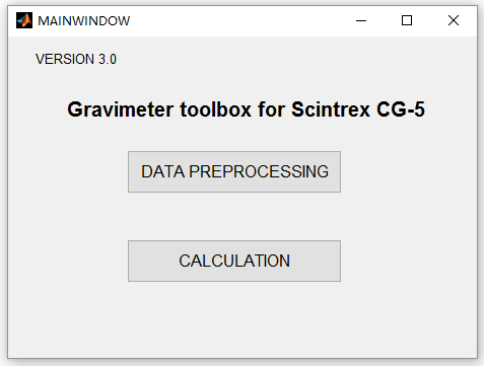


Figure 2.2: *Main window*

2.2.1 Data Preprocessing

This part is to delete inappropriate measurement data, which may be poor precision or apparently outlier.
The m-file DATA_PREPROCESS is the GUI file for data preprocessing. When the user clicks the button 'DATA PREPROCESSING' in MAINWINDOW window, the window below (figure 2.3) would be displayed.
Click 'Insert File' and insert the target gravimeter data file (*.txt) in the open file dialogue box, then the file name would be shown in this window. The path to this data file is recorded and other output files would be saved in the same folder.

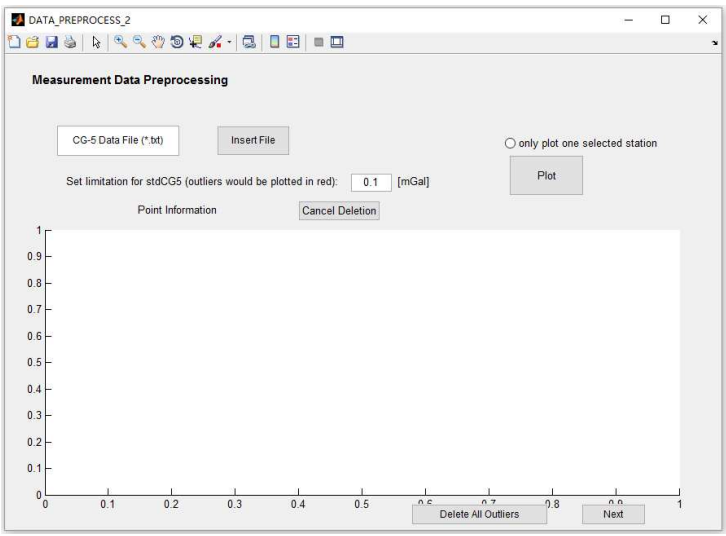


Figure 2.3: *DATA_PREPROCESS window*

The default standard deviation limitation for measurement is 0.1 mGal (set by experience), it can be altered by replacing the number by the keyboard. With the radio button above the 'Plot' button, the user can select whether he wants to plot one station instead of plotting all stations in the order of station name. If the user select the radio button, a question dialogue box (figure

2.4) appears to ask the station name.

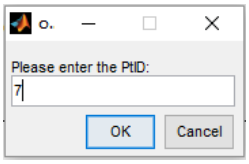


Figure 2.4: *Box for PtID*

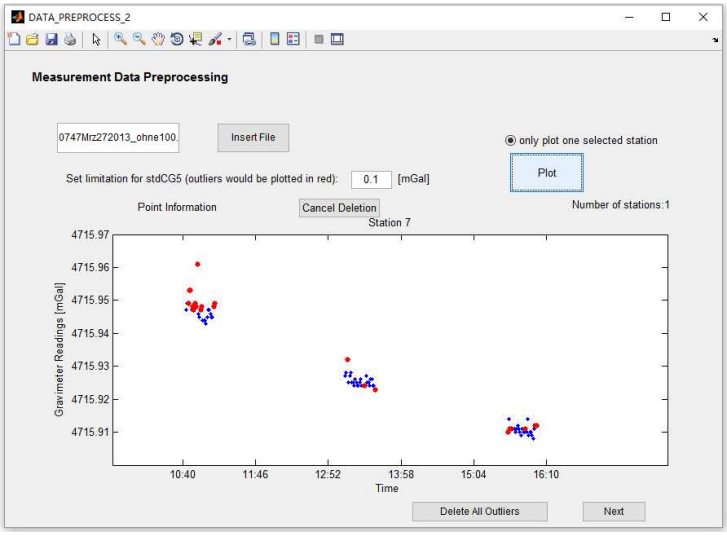


Figure 2.5: *DATA_PREPROCESS window with plotting*

Figure 2.5 shows the DATA_PREPROCESS window with plotting, in which the x-axis represents the time (hh:mm) of point measurement and y-axis is the gravimeter readings. The station number is shown above the image.
There are two ways to delete inappropriate points: clicking the specific point to delete one by one or clicking 'Delete All Outliers' to delete all points, whose standard deviations exceed the limitation. These 'outlier' points are highlighted in red, while other points are presented in blue. When using first way, the information of deleted point is shown in 'Point information' (display its standard deviation and measurement time). The deleted points are marked by black circles. It is also possible to cancel deletion, by clicking the point in black circle, then the deletion of this point is cancelled and the black circle vanishes, or clicking 'Cancel Deletion', then all deletions of current station are cancelled.
After the deletion, pushing 'Next' to check next station. If all stations have been preprocessed, the button 'Next' leads to DELETEDPOINT window, which shows the deleted points (figure 2.6). In the meantime, the output file is generated, saving the information of input measurement file name and detailed deleted point information ('PtID', 'Line', gravity readings, 'stdCG5', measurement time). Normally, the name of this output file is the name of input data file with '_output' at the end. If this file name exists, an input dialogue box requires the user to enter a new name.
In DELETEDPOINT window, the user can also choose to save a new data file without these deleted point by selecting the radio button. After clicking 'OK' button, the CALCULATION

window appears, which is the data computation part.

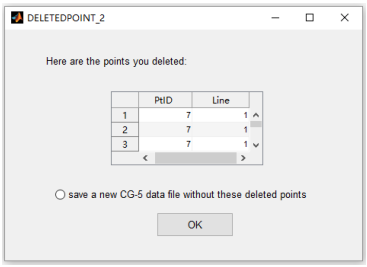


Figure 2.6: *DELETEDPOINT window*

2.2.2 Data Computation

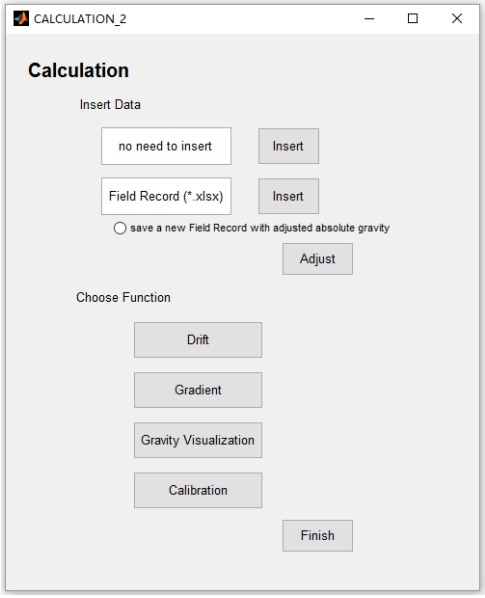


Figure 2.7: *CALCULATION window*

This part is the adjustment of measurement data, which can also be started from MAINWINDOW window without data preprocessing. Figure 2.7 is the CALCULATION window, where the user inserts data file and field record. If the toolbox is running from data preprocessing to this window, the text for CG-5 data file would show 'no need to insert', using the preprocessing data. If the inserted file record contains absolute gravity, the user can select a new field record with adjusted absolute gravity by the radio button above 'Adjust' button. If the inserted field record does not match with the measurement data file, WPTIDL window (figure 2.8, WPTIDL: wrong 'PtID' and 'Line') would inform user to check again. When clicking 'Adjust' in the CALCULATION window, the toolbox automatically adjusts the measurement data and the result of adjustment is saved in the output file.

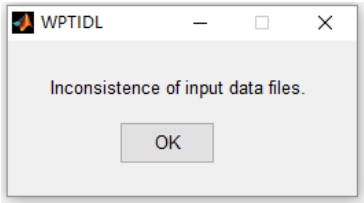


Figure 2.8: *WPTIDL window*

After the adjustment, the four functions in the CALCULATION window can be realized, which are gradient computation, drift estimation, gravity visualization and calibration. Among these, only drift estimation does not need extra data in field record, while gradient computation needs heights, gravity visualization needs horizontal coordinates and calibration needs reference absolute gravity.

When the user clicks 'Drift', a RESULT window (figure 2.9) appears. The text in the bottom indicates the estimated drift value and its precision, which are in the unit of [mGal] and [mGal/d] consistent with CG-5 data file. There are five figures in this window, which reflect the qualities of adjustment and observation data. The first figure is the measurement error after adjustment, which demonstrates the adjustment quality. The next four figures indicate the internal temperatures, standard deviations and two tilts of the measurement, which are the evaluations for the measurement situation. These figures are plotted with time sequence and different colors represent different stations. This RESULT window is also saved as a jpg file, in case that user needs these figures. The user can click 'OK' to close this window and return to CALCULATION window to choose other functions.

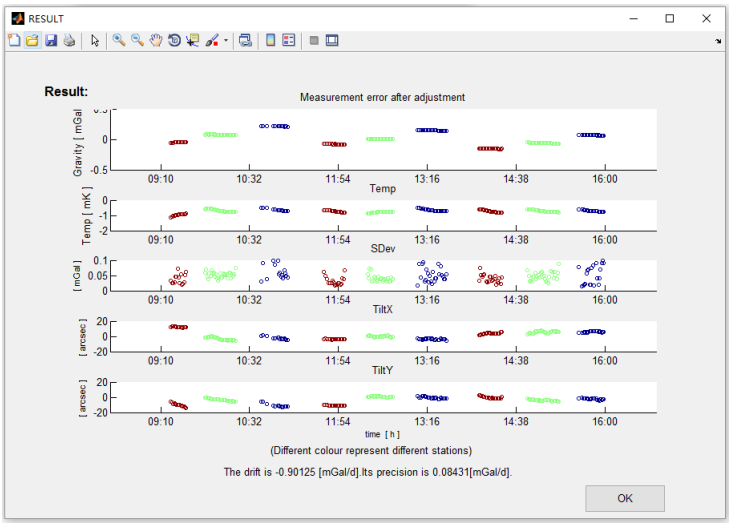


Figure 2.9: *Result window for drift*

Clicking 'Gradient' in the CALCULATION window, a question dialogue box (figure 2.10) appears to ask the gradient type: either the measurement includes gradient measurement points which have gradients themselves, or gradient between two points. Depending on the gradient type, an input dialogue box requires 'PtID' of the targeted point. Then the result is shown in

the 'RESULT' window (figure 2.11). The text in bottom is the gradient value and precision of selected points, which is also saved in output file. The two images above the text are the adjustment error and standard deviation of the selected points. The user can also click 'OK' to close this window.

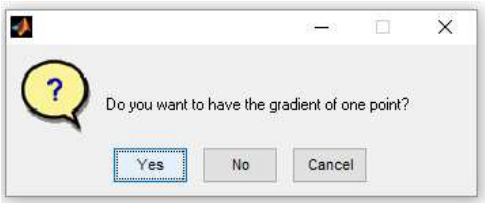


Figure 2.10: *Box for gradient type*

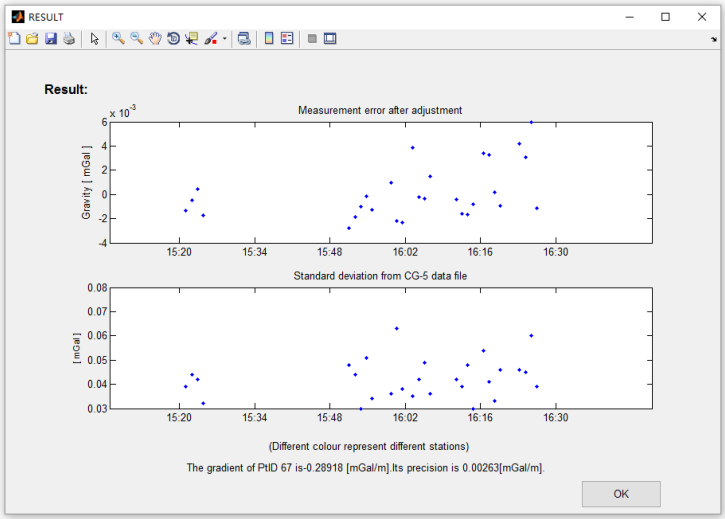


Figure 2.11: *Result window for gradient*

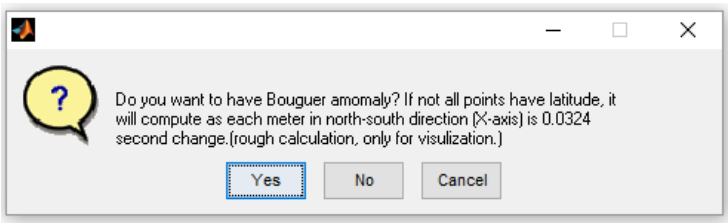


Figure 2.12: *Box for Bouguer anomalies*

After clicking 'Gravity Visualization', a question dialogue box (figure 2.12) appears to ask whether to visualize Bouguer anomaly if enough data are in the field record. The computation of Bouguer anomaly needs absolute gravity, heights, free air gradient and latitude, but the latitude is not necessary for all points. As the toolbox regards the X-coordinate in field record is in north-south direction (if not, field record needs latitudes for all points to compute), the unknown latitudes can be approximated. The detail calculation method is presented in chapter 3. The result figures will be saved as jpg files and different image types have different names

e.g. Bouguer anomalies with '*_bou', absolute gravity with '*_grav' and gravity differences with '*_gravdiff'.
If the user pushes 'Calibration', an information window (figure 2.13) will appear, which indicates the calibration method used in this function and require the user to choose the drift for the current computation. After setting the drift, 'RESULT' window appears to show the calibration factor and its precision, which is saved in the output file.

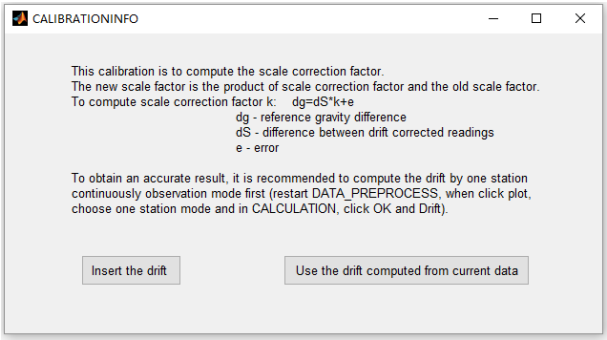


Figure 2.13: *CALIBRATIONINFO window*

After selecting all the functions, the user clicks 'Finish' and OUTPUTNOTE window (figure 2.14) appears to remind the user of output information.

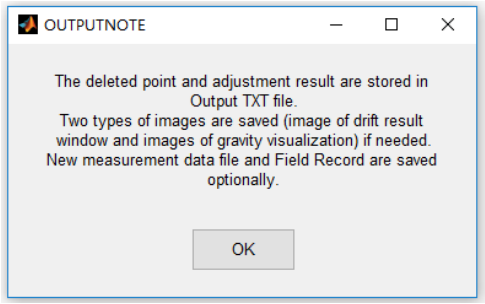


Figure 2.14: *OUTPUTNOTE window*

As is shown above, all these output files are saved in the same parent folder of the input gravimeter data file, so it is recommended to build a data folder that contains the gravimeter data file and then all result can be found there.
Remark 2.2.2: Whether user inputs a field record or not, the button 'OK' in 'CALCULATION' window needs to be pushed before other function buttons. Every step need some operation time, especially with a large amount of input data.

Chapter 3

Calculation Method of the Toolbox

This chapter illustrates the calculation method of the toolbox. There are five main functions in the toolbox, among these, the adjustment method, gradient computation method, calculation of Bouguer anomaly and calibration method would be explained in this chapter. As other parts are mainly about plotting, it would not be described here.

3.1 Adjustment Method

The adjustment method used in this toolbox is least squares adjustment. There are three cases: one station, multi-point with reference absolute gravity and multi-point without reference absolute gravity. Before these adjustments, data correction should be applied to ensure a high accuracy (not necessary for one station case).

3.1.1 Data Correction

As a gravimeter consists in elastic system, the measurements are influenced by many factors. The prominent factors are drift, gravimeter tilt, temperature, atmospheric pressure and tidal variation. Most of them are automatically corrected or compensated by Scintrex CG-5 gravimeter itself.

1. Influence of Drift
   The stress relaxation in the elastic system is inevitable, which is the main cause of drift. As it can be considered as a linear function of time, drift is estimated as an unknown variable in the adjustment (user can also set the drift in instruments).

2. Influence of Gravimeter Tilt
   The influence of gravimeter tilt on gravity measurement can be formulated as (Scintrex, 2008):

$$g_{(\theta_x,\theta_y)} = g_{(0,0)} - g(1 - \cos\theta_x \cos\theta_y), \tag{3.1}$$

   in which

   - $g_{(\theta_x,\theta_y)}$= gravimeter reading with tilt,

- $g_{(0,0)}$= gravimeter reading without tilt,
- g= gravity at the reading site,
- θ_x, θ_y= tilts of the gravity sensor in two horizontal axes.

The gravimeter saves θ_x and θ_y after levelling. With choosing the average sea level gravity $g_t = 980.6$ Gal, the gravimeter adds the tilt correction TIC to final reading:

$$\text{TIC} = g_t(1 - \cos\theta_x \cos\theta_y), \tag{3.2}$$

then the influence of tilt is reduced and the remaining worst error case is 0.002 mGal (Scintrex, 2008).

3. Influence of Temperature
The fused quartz mainspring is the most temperature sensitive component in the gravimeter. The higher the temperature, the stronger the spring. With a temperature control system in the gravimeter, the spring temperature varies within 0.5 mK under normal operating condition (Scintrex, 2008). This temperature change is compensated by TEC (Scintrex, 2008):

$$\text{TEC} = \text{TEMPCO} \times \text{TEMP}, \tag{3.3}$$

in which

- TEMPCO= instrument temperature coefficient in [mGal/mK], measuring during production,
- TEMP= spring temperature in [mK].

Besides TEC compensation, temperature causes a drift which is indistinguishable from gravity sensor drift and it will be also corrected by the linear drift correction.

4. Influences of Atmospheric Pressure
Although the sensors are sealed in a vacuum chamber, the air pressure still affects the measurement. The larger the air density, the stronger the attraction of air mass. To correct this effect, the toolbox applies the standard regression model (Scintrex, 2008):

$$\text{Corr}_{\text{air}} = -\alpha(p - p^n), \tag{3.4}$$

$$p^n = 1013.25\left(1 - \frac{0.0065H}{288.15}\right)^{5.2559}, \tag{3.5}$$

in which

- α= -0.0003 mGal/mbar, factor proposed by the International Association of Geodesy (IAG) in 1983
- p= the air pressure at the point, [mbar],
- p^n=normal air pressure, defined by DIN 5450 model,
- H= height above sea level, [m].

5. Influence of Tidal Variation
   Gravitational force varies with time and locations on Earth, which is mainly caused by the position differences between Earth, Sun and Moon. This tidal variation is corrected by Longman formula (Longmann, 1959). With the input of latitude, longitude, difference between gravimeter clock time and GMT, the tidal correction is automatically generated by the gravimeter and applied to measurements. It is important to enter these values correctly into the instrument. The gravimetric factor used here is 1.16 in the Longman formula (16% increase over the amplitude of gravimetric tides of the rigid Earth), which may cause an error about ± 3 μGal (Scintrex, 2008).

Besides these corrections, the readings from gravimeter also need instrument height correction to transform the measurement from the center of the instrument to the ground:

$$\mathrm{Corr}_h = -\mathrm{FA} \times (h - h^{ic}), \tag{3.6}$$

in which

- FA= free air gradient, [mGal/m],
- h= instrument height from ground to the top of the instrument, [m],
- h^{ic}=the height from center to the top of the instrument, 0.218 m.

Among all these corrections, air pressure correction and height correction need to be applied to measurement data before adjustment, drift is the result of adjustment, others are corrected or reduced automatically by gravimeter.

3.1.2 One Station Case

In the one station case, all measurements are continuously measured on one point (with the same instrument height) to determine the drift by adjustment. As it is all about one station, the drift of the gravimeter can be computed only with the automatic corrections of CG-5 in 3.1.1. The observation equation is:

$$g_i^m + c_i = g_j + d(t_i - t_0) + b + e_i, \tag{3.7}$$

in which

- $i = 0, 1, 2, \ldots, I - 1$. I is the number of all measurements,
- $j = 0, 1, 2, \ldots, J - 1$. J is the number of points, each point has multi measurements, J is the subset of I,
- g_i^m= gravimeter measurements,
- c_i=corrections, here are air pressure and height corrections,
- g_j= absolute gravity, represents the true value,
- d= drift,
- t_i= measurement time,

- b= bias,
- e_i= measurement error.

As it is one station case, c_i and g_i are almost identical for all measurements so we can subtract the first measurement in both sides:

$$g_i^m - g_0^m + c_i - c_0 = g_j - g_0 + d(t_i - t_0) + b - b + e_i - e_0, \tag{3.8}$$

leading to the adjustment equation:

$$g_i^m - g_0^m = d(t_i - t_0) + e_i - e_0. \tag{3.9}$$

With the abbreviations $\Delta g_i^m = g_i^m - g_0^m$ and $\Delta t_i = t_i - t_0$, the equation (3.9) simplifies to:

$$\Delta g_i^m = \Delta t_i d + \epsilon. \tag{3.10}$$

The standard deviation of g_i^m is represented by σ_i (from CG-5 data file), then the precision of Δg_i^m is $\sigma_{\Delta i} = \sqrt{\sigma_i^2 + \sigma_0^2}$ and the weight is set to be $p_i = \frac{1}{\sigma_{\Delta i}{}^2}$. To make the problem easy, here setting Δg_i^m uncorrelated. So the weight of the adjustment equation is:

$$\mathbf{P} = \begin{pmatrix} p_0 & 0 & \cdots & 0 \\ 0 & p_1 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & p_I \end{pmatrix}. \tag{3.11}$$

By least squares adjustment, the drift is estimated:

$$\hat{d} = (\Delta t_i^T \mathbf{P} \Delta t_i)^{-1} \Delta t_i^T \mathbf{P} \Delta g_i^m, \tag{3.12}$$

and its precision is:

$$\sigma_{\hat{d}} = \sqrt{\hat{\sigma_0}{}^2 (\Delta t_i^T \mathbf{P} \Delta t_i)^{-1}}, \tag{3.13}$$

with $\hat{\sigma_0}{}^2 = \frac{e^T \mathbf{P} e}{I-1}$ and $\hat{e} = \Delta g_i^m - \Delta t_i \hat{d}$.

3.1.3 Multi-Point Case with Reference Absolute Gravity

In this case, the measurements are performed on more than one point and the user has the reference absolute gravity of one or more points. There are several parameters estimated via least squares adjustment with constraints.
The equation of standard measurement is equation (3.7), here use $g_i^{m'}$ to replace the measurement after corrections, the equation would be:

$$g_i^{m'} = g_j + d(t_i - t_0) + b + e_i. \tag{3.14}$$

If the measurement contains gradient measurement type that measuring the same point with different instrument heights, the measurement equation would be:

$$g_i^{m'} = g_j + \mathrm{dh}_q \mathrm{grad}_p + d(t_i - t_0) + b + e_i, \tag{3.15}$$

in which

- $i = 0, 1, 2, \ldots, I-1$. I is the number of all measurements,
- $j = 0, 1, 2, \ldots, J-1$. J is the number of points, each point has multi measurements, J is the subset of I,
- $q = 0, 1, 2, \ldots, Q-1$. Q is the number of point measurements for gradient point (with different instrument heights for each gradient point),
- $p = 0, 1, 2, \ldots, P-1$. P is the number of points that with gradient measurement type, each gradient point has multi instrument heights, P is the subset of Q,
- dh_q = instrument height for gradient measurement type,
- grad_p = gradient of the point with gradient measurement type.

Here taking equation (3.15) as the general equation for this case. As g_i and b are both constants, they cannot be separated from adjustment, so reference absolute gravity is used as constraint to solve the problem.
From equation (3.15), the unknown parameter vector is $x = (g, \mathrm{grad}, d, b)^T$ and the constraint equation is:

$$g_l = g_l^r, \tag{3.16}$$

in which

- $l = 0, 1, 2, \ldots, L-1$, L is the number of points that have known absolute gravity in field record,
- g_l^r = reference absolute gravity.

Applying the formulation $\mathbf{D}^T x = C$ to the constraint equation, $\mathbf{D}^T$ would be a matrix that only contains 1 in related position and other elements are all 0.
The target function of this least squares adjustment is:

$$L_A(x, \lambda) = \frac{1}{2}(y - \mathbf{A}x)^T \mathbf{P}(y - \mathbf{A}x) + \lambda^T(\mathbf{D}^T x - C). \tag{3.17}$$

To make the problem simple, all measurements are set to be uncorrelated, so $\mathbf{P}$ is a diagonal matrix with diagonal elements $p_i = \frac{1}{\sigma_i{}^2}$.
The minimization of the target function leads to:

$$\begin{pmatrix} \mathbf{A}^T\mathbf{P}\mathbf{A} & \mathbf{D} \\ \mathbf{D}^T & 0 \end{pmatrix} \begin{pmatrix} \hat{x} \\ \hat{\lambda} \end{pmatrix} = \begin{pmatrix} \mathbf{A}^T\mathbf{P}y \\ C \end{pmatrix}, \tag{3.18}$$

from which, the adjustment result is obtained:

$$\begin{pmatrix} \hat{x} \\ \hat{\lambda} \end{pmatrix} = \begin{pmatrix} \mathbf{A}^T\mathbf{P}\mathbf{A} & \mathbf{D} \\ \mathbf{D}^T & 0 \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{A}^T\mathbf{P}y \\ C \end{pmatrix}, \tag{3.19}$$

and the precision of unknown is:

$$\sigma_{\hat{x}} = \sqrt{\sum_{\hat{x}}}, \tag{3.20}$$

which is computed from:

$$\begin{aligned}
\sum\nolimits_{y} &= \hat{\sigma_0}^2 \mathbf{P}^{-1} \\
\sum\nolimits_{\mathbf{A}^T\mathbf{P}y} &= \mathbf{A}^T\mathbf{P}\sum\nolimits_{y}(\mathbf{A}^T\mathbf{P})^T \\
\sum\nolimits_{(\hat{x},\hat{\lambda})^T} &= \begin{pmatrix} \mathbf{A}^T\mathbf{PA} & \mathbf{D} \\ \mathbf{D}^T & 0 \end{pmatrix}^{-1} \sum\nolimits_{(\mathbf{A}^T\mathbf{P}y,C)^T} \left(\begin{pmatrix} \mathbf{A}^T\mathbf{PA} & \mathbf{D} \\ \mathbf{D}^T & 0 \end{pmatrix}^{-1} \right)^T \\
\sigma_{\hat{x}} &= \sqrt{\sum\nolimits_{\hat{x}}}
\end{aligned}$$

From this adjustment, the result of estimated absolute gravity, estimated gradient of specific point (with gradient measurement type), estimated drift and bias can be achieved.
Remark 3.1.3: The measurements of points with gradient measurement do not need to apply instrument height correction.

3.1.4 Multi-Point Case without Reference Absolute Gravity

This case is similar to 3.1.3 but without reference absolute gravity. The equation system (3.15) has rank deficiency and cannot be adjusted directly. To solve this problem, the first point measurement (should not be a gradient measurement) is subtracted from all measurement equations:

$$g_i^{m'} - g_0^{m'} = g_j - g_0 + \mathrm{dh}_q \mathrm{grad}_p + d(t_i - t_0) + b - b + \epsilon_i. \tag{3.21}$$

Inserting the abbreviations $\Delta g_i^{m'} = g_i^{m'} - g_0^{m'}$ and $\Delta t_i = t_i - t_0$, the equation (3.24) changes to:

$$\Delta g_i^{m'} = \Delta g_j + \mathrm{dh}_q \mathrm{grad}_p + d\Delta t_i + \epsilon_i. \tag{3.22}$$

The weight of this case is similar to section 3.1.2 and with least squares adjustment, the result of estimated gravity difference, estimated gradient of specific point (with gradient measurement type) and estimated drift can be achieved.

3.2 Gradient Computation Method

There are two types of gradient, one is the gradient of one point and the other is the gradient of two points. The first type of gradient is calculated from adjustment in section 3.1.3 and 3.1.4, so we presented here only the method to compute the second type of gradient.
The equation to calculate the gradient of two point P_1 and P_2 is:

$$\mathrm{grad} = \frac{g_1 - g_2}{h_1 - h_2}, \tag{3.23}$$

in which

- g_1 g_2= the absolute gravity of two points,
- h_1 h_2=the height of two point.

For the case of known reference absolute gravity in section 3.1.3, the estimated gravity of each point is computed and the gradient can be easily computed by equation (3.23). Assuming g_1 g_2 h_1 h_2 to be uncorrelated, the precision of this gradient is given by:

$$\sigma_{\text{grad}} = \mathbf{F} \begin{pmatrix} \sigma_{g_1{}^2} & 0 & 0 & 0 \\ 0 & \sigma_{g_2{}^2} & 0 & 0 \\ 0 & 0 & \sigma_{h_1{}^2} & 0 \\ 0 & 0 & 0 & \sigma_{h_2{}^2} \end{pmatrix} \mathbf{F}^T, \tag{3.24}$$

with $\mathbf{F} = (\frac{1}{h_1-h_2}, -\frac{1}{h_1-h_2}, -\frac{g_1-g_2}{(h_1-h_2)^2}, \frac{g_1-g_2}{(h_1-h_2)^2})$.
For the case of unknown absolute gravity in section 3.1.4, the gravity differences to first point are calculated. If one of the two points that needs to compute gradient is the first point, the specific gravity difference can replace $g_1 - g_2$ in equation (3.23) and the accuracy is according to formula (3.24). If both points are not the first point, their gravity difference should replace the absolute gravity and their gradient precision is similar to equation (3.24):

$$\sigma_{\text{grad}} = \mathbf{F} \begin{pmatrix} \sigma_{\Delta g^2} & 0 & 0 \\ 0 & \sigma_{h_1{}^2} & 0 \\ 0 & 0 & \sigma_{h_2{}^2} \end{pmatrix} \mathbf{F}^T, \tag{3.25}$$

with $\mathbf{F} = (\frac{1}{h_1-h_2}, -\frac{\Delta g}{(h_1-h_2)^2}, \frac{\Delta g}{(h_1-h_2)^2})$.
Remark 3.2: If the standard deviation of the height is not inserted into the field record, the default value is 0.02 m.

3.3 Computation of Simple Bouguer Anomaly

For gravity visualization, the user can choose to obtain a figure of Bouguer anomalies if the required data are in the field record. Bouguer anomaly is a gravity anomaly, which reflects the density contrast of the anomalous masses with respect to normal density (Blakely, 1996). It is the gravitational attraction remaining after correcting the measured vertical component of gravitational acceleration at a point for: (a) the theoretical gravity at that point; (b) the free-air correction; (c) the Bouguer correction; and (d) the terrain correction (Encyclopedia.com, 2017). In this toolbox, as we cannot obtain the terrain model for the real measurement site, we determines only the simple Bouguer anomalies, which ignores the shape of the topography, regard it as a homogeneous slab. Here is the equation of simple Bouguer anomalies:

$$\Delta g_{sb} = g_{obs} - g_0 - g_{fa} - g_{sb}, \tag{3.26}$$

in which,

- g_{obs} = gravity measurement,
- g_0 = theoretical gravity,
- g_{fa} = free air correction,
- g_{sb} = simple Bouguer correction.

The gravity observation here is the estimated absolute gravity, which is computed from section 3.1. Other values need to be calculated from the input data of field record.
Remark 3.3: To visualize Bouguer anomalies, the field record should be filled in point height, absolute gravity (at least one), latitude (if X-coordinate in south-north direction, we only need one latitude) and horizontal coordinate.

3.3.1 Theoretical Gravity

"Theoretical gravity is an approximation of the true effective or apparent gravity on Earth's surface by means of a mathematical model representing (a physically smoothed) Earth" (Hofmann-Wellenhof and Moritz, 2006).
The first international gravity formula, computing the theoretical gravity, was proposed in 1930 by the International Association of Geodesy:

$$g(\phi) = g_e(1 + A\sin^2\phi - B\sin^2 2\phi), \tag{3.27}$$

in which,

- $g(\phi)$ = gravity as a function of ellipsoidal latitude,
- g_e = the gravity at the equator,
- A, B = parameters that should be selected to produce a good global fit to true gravity (Hinze et al., 2013).

A more recent formula is the international gravity formula 1980 (IGF80), which is Somigliana equation:

$$g(\phi) = g^e\left(\frac{1 + k\sin^2\phi}{\sqrt{1 - e^2\sin^2\phi}}\right), \tag{3.28}$$

in which,

- k = formula constant $\frac{bg_e - ag_e}{ag_e}$, where a, b are the equatorial and polar semi-axes,
- g^e, g^p = defined gravity at the equator and poles,
- e = ellipsoidal eccentricity, $\sqrt{\frac{a^2-b^2}{a^2}}$.

Inserting the parameters of WGS80, we obtain the numerical expression:

$$g(\phi) = 9.7803267715\left(\frac{1 + 0.001931851353\sin^2\phi}{\sqrt{1 - 0.0066943800229\sin^2\phi}}\right). \tag{3.29}$$

A later refinement, based on the WGS84 ellipsoid, is the WGS84 ellipsoidal gravity formula (Hinze et al., 2013):

$$g(\phi) = 9.7803253359\left(\frac{1 + 0.00193185265241\sin^2\phi}{\sqrt{1 - 0.00669437999013\sin^2\phi}}\right), \tag{3.30}$$

which is the formula used in the toolbox.
Theoretical gravity is a function of latitude, but it is not easy to obtain the latitudes of each point without GPS measurement. With the assumption that the X-coordinate in the field record is in south-north direction, we can roughly calculate latitudes from one given latitude. Here we ignore ellipsoidal effects and use Haversine formula to determine the relationship between great-circle distance and latitude on a spherical Earth, which is not accurate, but sufficient for the purpose of visualization and small regions.
For any two points on a sphere, the Haversine of the central angle between them is given by:

$$\text{hav}\left(\frac{d}{r}\right) = \text{hav}(\phi_2 - \phi_1) + \cos\phi_1 \cos\phi_2 \text{hav}(\lambda_2 - \lambda_1), \tag{3.31}$$

in which,

- hav = Haversine function, $\text{hav}(\theta) = \sin^2(\theta/2)$,
- d = distance between two points, along a great circle of the sphere,
- ϕ_1, ϕ_2 = latitude of two points,
- $\lambda 1, \lambda 2$ = longitude of two points.

As we only consider the latitude difference and regard the longitude difference as 0, the equation (3.31) becomes:

$$\text{hav}\left(\frac{d}{r}\right) = \text{hav}(\Delta\phi), \tag{3.32}$$

where $\Delta\phi$ is the abbreviation of $\phi_2 - \phi_1$, in radian.
Using 6371 km as Earth radius, we can obtain the relationship between south-north distance and latitude difference is that: 1 m $\approx$ 1.56961×10^{-7} rad $\approx$ 8.9932×10^{-6} degree $\approx$ 0.0324 second.
Remark 3.3.1: If user does not have the latitude of all points and the horizontal coordinate in field record is a local coordinate system, which is not in the direction of south-north, then this method cannot be applied. When more than one latitude are in the field record, toolbox use the nearest latitude for calculation, which means it compares the X-coordinate distance differences and select the nearest known latitude to compute unknown latitudes.

3.3.2 Free-Air Correction

Free-air correction accounts for the difference in elevation between the observation point and sea level. It is the only elevation adjustment required if no mass exists between the point and sea level (Blakely, 1996). The equation is:

$$g_{fa} = -0.3086^{-5} h, \tag{3.33}$$

where h is the height above sea level, [m], and g_{fa} is in [m/s^2].

3.3.3 Simple Bouguer Correction

The simple Bouguer correction approximates all masses above sea level with a homogeneous, infinitely extended slab of thickness equal to the height of the observation point above sea level (Blakely, 1996). The attraction of an infinite slab is:

$$g_{sb} = 2\pi G\rho h, \tag{3.34}$$

in which,

- G = gravitational constant, $6.6740831 \times 10^{-11}$ $\mathrm{m^3kg^{-1}s^{-2}}$,
- h = thickness of the slab,
- ρ = density of the slab.

Inserting a typical crustal density of 2670 $\mathrm{kg/m^{-3}}$, the simple Bouguer correction becomes:

$$g_{sb} = 0.1119 \times 10^{-5} h, \tag{3.35}$$

in which h is in [m] and g_{sb} is in [$\mathrm{m/s^2}$].

3.4 Calibration Method

There are 2 calibration factors for Scintrex, GCAL1 and GCAL2, which transform the voltage readings to gravity readings. GCAL1 is responsible for the linear part and GCAL2 is used to model a small quadratic nonlinearity. Since 1991, GCAL2 has been reduced to zero by an electronic adjustment (Scintrex, 2008). So the calibration in the gravimeter toolbox is reduced to the determination of GCAL1.
The calibration method is from the CG-5 manual, it computes the scale calibration factor k instead of directly calculating CGAL1. The calibration equation is according to (Scintrex, 2008):

$$e_i = k\Delta S_i - \Delta g_i, \tag{3.36}$$

in which

- $i = 0, 1, 2, \ldots, n-1$. n is the number of measurements,
- e_i = measurement error,
- ΔS_i = drift corrected gravity reading difference between station i and reference station,
- Δg_i = gravity difference between station i and reference station, which should be given in high accuracy.

As the measurement should be applied drift corrections first, it is recommended to operate the one station case to obtain drift value. With at least 2 stations that have known absolute gravity, this calibration process can be done by least squares adjustment. To apply adjustment, the left part of the equation should be observations with errors and the design matrix should be almost error free, so the equation (3.29) is converted:

$$\Delta S_i = \Delta g_i \frac{1}{k} + \epsilon_i. \tag{3.37}$$

To ensure a higher accuracy, we linearise the unknown:

$$\Delta S_i - \Delta g_i \frac{1}{k_0} = -\Delta g_i \frac{1}{{k_0}^2} \Delta k + \epsilon_i. \tag{3.38}$$

The weight matrix of Δg_i is assumed to be diagonal matrix. The drift corrected gravity reading difference is computed from:

$$\Delta S_i = g_i^m + d(t_i - t_0) - g_0^m. \tag{3.39}$$

To simplify the process, the toolbox sets the first point as the reference point. The precision of ΔS_i is computed from the standard deviation of measurements σ_i, σ_0 and the precision of drift σ_d, which is $\sigma_{\Delta S_i} = \sqrt{\sigma_i^2 + \sigma_0^2 + \sigma_d^2 (t_i - t_0)^2}$. The weight of ΔS_i is $\frac{1}{{\sigma_{\Delta S_i}}^2}$.
The approximation value of k_0 is 1. With least squares adjustment, Δk can be computed, and the new factor is then $k_0' = k_0 + \Delta k$. Inserting k_0' and iterating until the tolerance $|\Delta k| < 10^{-10}$, then the scale calibration factor can be obtained.
The GCAL1 is calibrated by:

$$\text{GCAL1}_{\text{new}} = k \cdot \text{GCAL1}_{\text{old}}. \tag{3.40}$$

Chapter 4

Examples and Results

This chapter illustrates the application of the toolbox by 2 examples. The first one is a simple step measurement with three points and the second one includes gradient measurements.

4.1 Step Measurement

This example (*0747Mrz272013_ohne100*) has three measurement points and two of them have known absolute gravity values, one point also has a rough latitude.
Here are the two input data file:

```
/       CG-5 OPTIONS
/       Tide Correction:     YES
/       Cont. Tilt:           NO
/       Auto Rejection:       NO
/       Terrain Corr.:        NO
/       Seismic Filter:       NO
/       Raw Data:             NO
/------LINE-----STATION-----ALT.------GRAV.---SD.--TILTX--TILTY-TEMP---TIDE---DUR-REJ-----TIME----DEC. TIME+DATE--TERRAIN---DATE
 1.0000000  21.0000000   16.8944   4855.711 0.032   12.3   -5.6 -1.12 0.015  57   0 09:19:26     41330.38787    0.0000  2013/03/26
 1.0000000  21.0000000   16.8944   4855.710 0.025   12.9   -6.8 -1.08 0.016  57   0 09:20:29     41330.38860    0.0000  2013/03/26
 1.0000000  21.0000000   16.6502   4855.708 0.024   12.9   -8.7 -1.05 0.016  57   0 09:21:29     41330.38930    0.0000  2013/03/26
 1.0000000  21.0000000   16.4061   4855.705 0.027   13.0   -7.9 -1.02 0.016  57   0 09:22:29     41330.38999    0.0000  2013/03/26
 1.0000000  21.0000000   16.1619   4855.704 0.045   12.7   -8.7 -0.99 0.017  57   0 09:23:29     41330.39068    0.0000  2013/03/26
 1.0000000  21.0000000   16.1619   4855.702 0.045   12.4   -9.7 -0.97 0.017  57   0 09:24:29     41330.39138    0.0000  2013/03/26
 1.0000000  21.0000000   15.9178   4855.699 0.073   12.2   -9.8 -0.96 0.018  57   0 09:25:29     41330.39207    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.697 0.043   12.3  -10.5 -0.94 0.018  57   0 09:26:29     41330.39276    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.695 0.024   11.9  -10.4 -0.93 0.018  57   0 09:27:29     41330.39346    0.0000  2013/03/26
 1.0000000  21.0000000   15.4295   4855.694 0.054   12.3  -11.0 -0.92 0.019  57   0 09:28:29     41330.39415    0.0000  2013/03/26
 1.0000000  21.0000000   15.1854   4855.692 0.020   12.0  -11.5 -0.91 0.019  57   0 09:29:29     41330.39484    0.0000  2013/03/26
 1.0000000  21.0000000   14.9412   4855.691 0.022   11.5  -11.8 -0.91 0.020  57   0 09:30:29     41330.39554    0.0000  2013/03/26
 1.0000000  21.0000000   14.9412   4855.690 0.027   11.7  -12.2 -0.90 0.020  57   0 09:31:29     41330.39623    0.0000  2013/03/26
 1.0000000  21.0000000   14.6971   4855.690 0.052   12.3  -13.1 -0.90 0.020  57   0 09:32:29     41330.39692    0.0000  2013/03/26
 1.0000000  21.0000000   14.4530   4855.688 0.061   12.2  -13.9 -0.89 0.021  57   0 09:33:29     41330.39762    0.0000  2013/03/26
/ 1.0000000  21.0000000   13.7205   4855.679 0.070   12.3  -14.0 -0.89 0.021  24   0 09:34:30     41330.39832    0.0000  2013/03/26
 1.0000000  12.0000000   12.7440   4765.971 0.060   -1.6   -0.6 -0.58 0.027  57   0 09:50:46     41330.40960    0.0000  2013/03/26
 1.0000000  12.0000000   12.7440   4765.968 0.070   -1.7   -0.2 -0.56 0.027  57   0 09:51:49     41330.41033    0.0000  2013/03/26
 1.0000000  12.0000000   12.0116   4765.969 0.046   -1.9   -0.8 -0.55 0.027  57   0 09:52:49     41330.41102    0.0000  2013/03/26
 1.0000000  12.0000000   11.7674   4765.968 0.037   -0.8   -1.2 -0.54 0.028  57   0 09:53:49     41330.41171    0.0000  2013/03/26
 1.0000000  12.0000000   11.5233   4765.969 0.056   -0.2   -1.6 -0.55 0.028  57   0 09:54:49     41330.41241    0.0000  2013/03/26
 1.0000000  12.0000000   11.0350   4765.966 0.048   -0.6   -2.1 -0.56 0.028  57   0 09:55:49     41330.41310    0.0000  2013/03/26
 1.0000000  12.0000000   11.0350   4765.967 0.068    0.2   -2.7 -0.57 0.028  57   0 09:56:49     41330.41379    0.0000  2013/03/26
 1.0000000  12.0000000   10.5467   4765.966 0.058   -0.1   -2.6 -0.59 0.029  57   0 09:57:49     41330.41449    0.0000  2013/03/26
 1.0000000  12.0000000   10.3026   4765.966 0.059   -0.4   -2.6 -0.61 0.029  57   0 09:58:49     41330.41518    0.0000  2013/03/26
```

Figure 4.1: *Step measurement CG-5 data file (0747Mrz272013_ohne100.txt)*

	A	B	C	D	E	F	G	H	I	J	K	L
1	PtID	Line	Point Type	Instrument Height [m]	pressure [mbar]	absGrav [mGal]	FAgrad [mGal/m]	DHHN [m]	stdDHHN [m]	X [m]	Y [m]	lattitude [degree]
2	21	1	0	0.478	982	980886.1	-0.274	210.68		3435230	5387412	
3	12	1	0	0.478	929		-0.274	654.71		3438255	5386418	
4	7	1	0	0.478	901	980746.7	-0.324	890.02		3440513	5387100	54
5	21	2	0	0.478	982	980886.1	-0.274	210.68		3435230	5387412	
6	12	2	0	0.478	929		-0.274	654.71		3438255	5386418	
7	7	2	0	0.478	901	980746.7	-0.324	890.02		3440513	5387100	54
8	21	3	0	0.478	982	980886.1	-0.274	210.68		3435230	5387412	
9	12	3	0	0.478	929		-0.274	654.71		3438255	5386418	
10	7	3	0	0.478	902	980746.7	-0.324	890.02		3440513	5387100	54
11												

Figure 4.2: *Step measurement field record (FieldRec_20130327.xlsx)*

It should be remembered when the gravimeter moves, a new row in field record should be added and the 'PtID', 'Line' in field record should match with 'Station', 'Line' typed in gravimeter. The combination of 'PtID' and 'Line' should be unique. If user only needs drift, this field record is not necessary, otherwise it should be filled with enough information to obtain required result. The example field record above (figure 4.2) can compute all functions in the toolbox if needed.

With this two files correctly generated, the user can open the toolbox and start the process. Follow the steps in section 2.3, after the data selection, user could enter the CALCULATION window to choose next processing steps. Here in this example, measurements with standard deviation over 0.1 mGal are deleted (by setting limitation and the button 'Delete All Outliers'), and a new data file is created. Here are the output file till this step and a new CG-5 data file without deleted points:

```
Input Measurement File: C:\Users\SIYUN\Documents\MATLAB\Gravimeter_Toolbox_2.0\data\0747Mrz272013_ohne100.txt

Here are the information for deleted measurement points:
PtID  Line   Gravity measurement(mGal)  stdCG5(mGal)      Time
7     1          4715.9490            0.1310        26-Mar-2013 10:45:00
7     1          4715.9530            0.1370        26-Mar-2013 10:46:00
7     1          4715.9530            0.1160        26-Mar-2013 10:47:00
7     1          4715.9480            0.1650        26-Mar-2013 10:49:00
7     1          4715.9470            0.1080        26-Mar-2013 10:50:00
7     1          4715.9490            0.1530        26-Mar-2013 10:51:00
7     1          4715.9480            0.1040        26-Mar-2013 10:52:00
7     1          4715.9610            0.1580        26-Mar-2013 10:53:00
7     1          4715.9470            0.1940        26-Mar-2013 10:56:00
7     1          4715.9480            0.1010        26-Mar-2013 10:57:00
7     1          4715.9480            0.1270        26-Mar-2013 11:08:00
7     1          4715.9490            0.1940        26-Mar-2013 11:09:00
7     2          4715.9320            0.1650        26-Mar-2013 13:09:24
7     2          4715.9240            0.1090        26-Mar-2013 13:25:24
7     2          4715.9230            0.1390        26-Mar-2013 13:34:24
7     3          4715.9100            0.1690        26-Mar-2013 15:34:59
7     3          4715.9110            0.1760        26-Mar-2013 15:37:02
7     3          4715.9110            0.1160        26-Mar-2013 15:38:02
7     3          4715.9110            0.1010        26-Mar-2013 15:51:02
7     3          4715.9120            0.1500        26-Mar-2013 16:00:02
7     3          4715.9120            0.1610        26-Mar-2013 16:01:02
12     3          4765.9180            0.1270        26-Mar-2013 15:10:42
21     2          4855.6690            0.0860        26-Mar-2013 11:45:43
21     2          4855.6540            0.0710        26-Mar-2013 11:42:43
21     3          4855.6340            0.0300        26-Mar-2013 14:09:47
```

Figure 4.3: *Output file till data selection part*

```
// This is the new measurement data after point deletion.

/LINE-----STATION-----ALT.------GRAV.---SD.--TILTX--TILTY-TEMP---TIDE---DUR-REJ-----TIME----DEC.TIME+DATE--TERRAIN---DATE
1.000000 21.000000 16.8944   4855.711 0.032 12.3  -5.6  -1.12  0.015    57  0    09:19:26   735319.388495 0.0000 2013/03/26
1.000000 21.000000 16.8944   4855.710 0.025 12.9  -6.8  -1.08  0.016    57  0    09:20:29   735319.389225 0.0000 2013/03/26
1.000000 21.000000 16.6502   4855.708 0.024 12.9  -8.7  -1.05  0.016    57  0    09:21:29   735319.389919 0.0000 2013/03/26
1.000000 21.000000 16.4061   4855.705 0.027 13.0  -7.9  -1.02  0.016    57  0    09:22:29   735319.390613 0.0000 2013/03/26
1.000000 21.000000 16.1619   4855.704 0.045 12.7  -8.7  -0.99  0.017    57  0    09:23:29   735319.391308 0.0000 2013/03/26
1.000000 21.000000 16.1619   4855.702 0.045 12.4  -9.7  -0.97  0.017    57  0    09:24:29   735319.392002 0.0000 2013/03/26
1.000000 21.000000 15.9178   4855.699 0.073 12.2  -9.8  -0.96  0.018    57  0    09:25:29   735319.392697 0.0000 2013/03/26
1.000000 21.000000 15.4295   4855.697 0.043 12.3  -10.5  -0.94  0.018    57  0    09:26:29   735319.393391 0.0000 2013/03/26
1.000000 21.000000 15.4295   4855.695 0.024 11.9  -10.4  -0.93  0.018    57  0    09:27:29   735319.394086 0.0000 2013/03/26
1.000000 21.000000 15.4295   4855.694 0.054 12.3  -11.0  -0.92  0.019    57  0    09:28:29   735319.394780 0.0000 2013/03/26
1.000000 21.000000 15.1854   4855.692 0.020 12.0  -11.5  -0.91  0.019    57  0    09:29:29   735319.395475 0.0000 2013/03/26
1.000000 21.000000 14.9412   4855.691 0.022 11.5  -11.8  -0.91  0.020    57  0    09:30:29   735319.396169 0.0000 2013/03/26
1.000000 21.000000 14.9412   4855.690 0.027 11.7  -12.2  -0.90  0.020    57  0    09:31:29   735319.396863 0.0000 2013/03/26
1.000000 21.000000 14.6971   4855.690 0.052 12.3  -13.1  -0.90  0.020    57  0    09:32:29   735319.397558 0.0000 2013/03/26
1.000000 21.000000 14.4530   4855.688 0.061 12.2  -13.9  -0.89  0.021    57  0    09:33:29   735319.398252 0.0000 2013/03/26
1.000000 12.000000 12.7440   4765.971 0.060 -1.6  -0.6  -0.58  0.027    57  0    09:50:46   735319.410255 0.0000 2013/03/26
1.000000 12.000000 12.7440   4765.968 0.070 -1.7  -0.2  -0.56  0.027    57  0    09:51:49   735319.410984 0.0000 2013/03/26
1.000000 12.000000 12.0116   4765.969 0.046 -1.9  -0.8  -0.55  0.027    57  0    09:52:49   735319.411678 0.0000 2013/03/26
1.000000 12.000000 11.7674   4765.968 0.037 -0.8  -1.2  -0.54  0.028    57  0    09:53:49   735319.412373 0.0000 2013/03/26
1.000000 12.000000 11.5233   4765.969 0.056 -0.2  -1.6  -0.55  0.028    57  0    09:54:49   735319.413067 0.0000 2013/03/26
1.000000 12.000000 11.0350   4765.966 0.048 -0.6  -2.1  -0.56  0.028    57  0    09:55:49   735319.413762 0.0000 2013/03/26
1.000000 12.000000 11.0350   4765.967 0.068 0.2  -2.7  -0.57  0.028    57  0    09:56:49   735319.414456 0.0000 2013/03/26
1.000000 12.000000 10.5467   4765.966 0.058 -0.1  -2.6  -0.59  0.029    57  0    09:57:49   735319.415150 0.0000 2013/03/26
1.000000 12.000000 10.3026   4765.966 0.059 -0.4  -2.6  -0.61  0.029    57  0    09:58:49   735319.415845 0.0000 2013/03/26
1.000000 12.000000 10.0584   4765.965 0.046 -1.5  -2.8  -0.63  0.029    57  0    09:59:49   735319.416539 0.0000 2013/03/26
1.000000 12.000000 10.0584   4765.965 0.055 -1.7  -2.7  -0.64  0.029    57  0    10:00:49   735319.417234 0.0000 2013/03/26
1.000000 12.000000  9.8143   4765.966 0.040 -1.8  -2.7  -0.66  0.030    57  0    10:01:49   735319.417928 0.0000 2013/03/26
1.000000 12.000000  9.5702   4765.966 0.034 -2.4  -2.8  -0.68  0.030    57  0    10:02:49   735319.418623 0.0000 2013/03/26
1.000000 12.000000  9.3260   4765.966 0.042 -3.3  -3.1  -0.69  0.030    57  0    10:03:49   735319.419317 0.0000 2013/03/26
1.000000 12.000000  9.3260   4765.966 0.057 -3.9  -3.5  -0.70  0.030    57  0    10:04:49   735319.420012 0.0000 2013/03/26
1.000000 12.000000  9.0819   4765.967 0.044 -4.5  -3.2  -0.71  0.031    57  0    10:05:49   735319.420706 0.0000 2013/03/26
```

Figure 4.4: *Newly created CG-5 data file*

If user does not insert field record, only drift can be computed. When clicking other functions, a warning message appears.

Figure 4.5 is the result window for drift. The text above the 'OK' button is the drift value

and its precession. Above this text, the images reflect the result quality. First image displays the measurement error after adjustment, which indicates the measurement quality. Next four pictures are internal temperature of gravimeter, standard deviations and tilt in two directions, these values demonstrate the data quality of gravimeter.

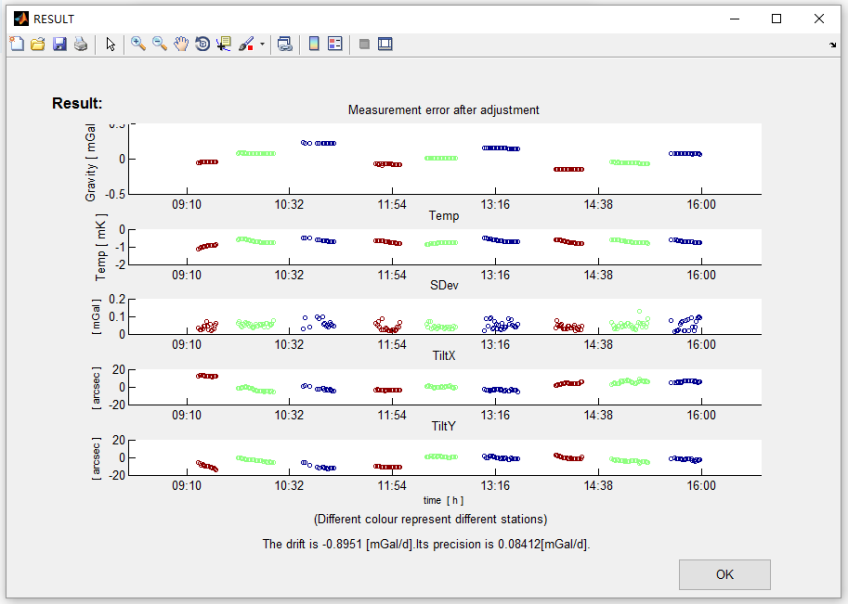
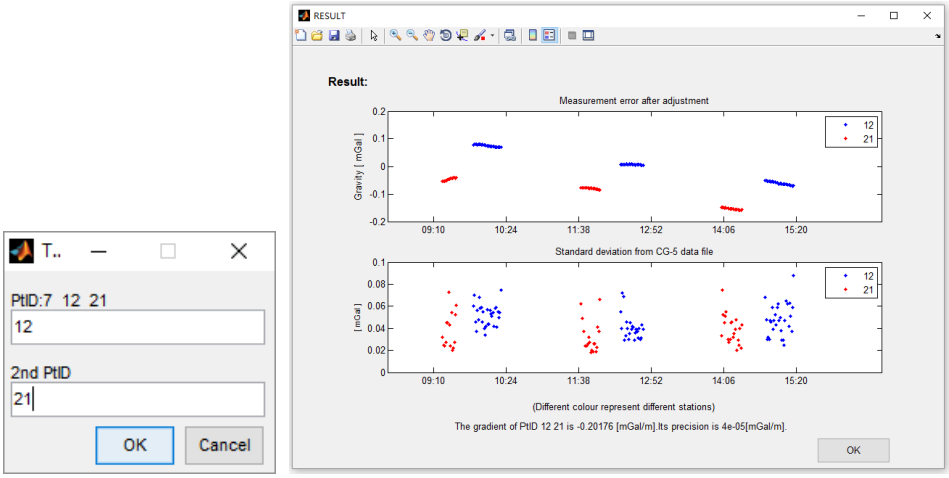


Figure 4.5: *Result window for drift*

If user inserts the field record with necessary information, other functions can be computed. With the field record in figure 4.2, we can calculate gradient, calibration and visualize Bouguer anomalies. Here we choose to achieve the gradient between 'PtID' 12 and 21, and the result window is:



(a) 'PtID' input (b) Result window for gradient

Figure 4.6: *Gradient computation in step measurement*

The result window for gradient and drift is similar, upper images reflecting data quality and a sentence showing the result. In this window, only measurements related to these two gradient points are displayed and the images are measurement errors and standard deviations.
For the 'Gravity Visualization', the toolbox would ask user whether wants to visualize Bouguer anomalies. Figure 4.7 is the image of simple Bouguer anomalies and figure 4.8 is the image of absolute gravity, the horizontal coordinates of these images are from field record. We can see that the color changing tendency of both images are similar, which are the values become smaller from left to right. While the colors distribute differently, the first image is divided by right-oriented line and the second image by left-oriented line, as Bouguer anomalies reflect density variation, not gravity distribution.

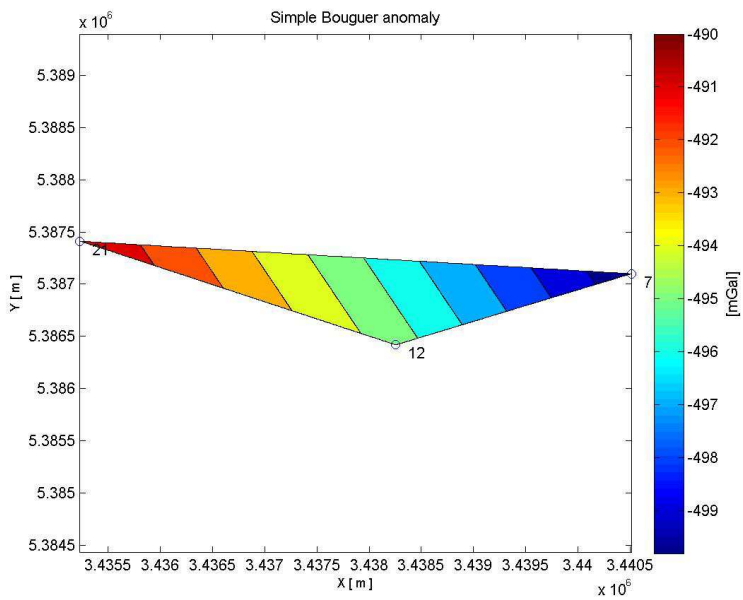


Figure 4.7: *Simple Bouguer anomalies for step measurement*

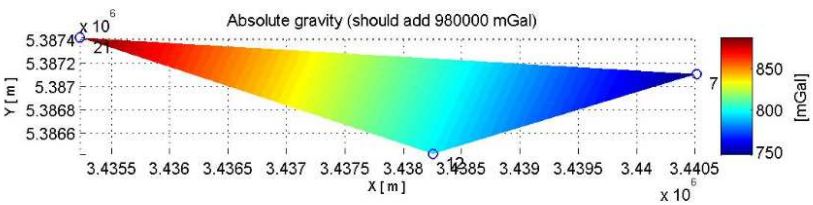


Figure 4.8: *Visualization of absolute gravity for step measurement*

If the field record does not contain absolute gravity, the toolbox would visualize gravity differences.
As our example is a step measurement work, not meant to do the calibration, we just use the adjusted drift to calculate the calibration factor. Figure 4.9 is the result window for calibration, the image shows the adjustment error, which has two colors as the adjustment only use given

absolute gravity points. The last sentence is the value of the factor and its precision.

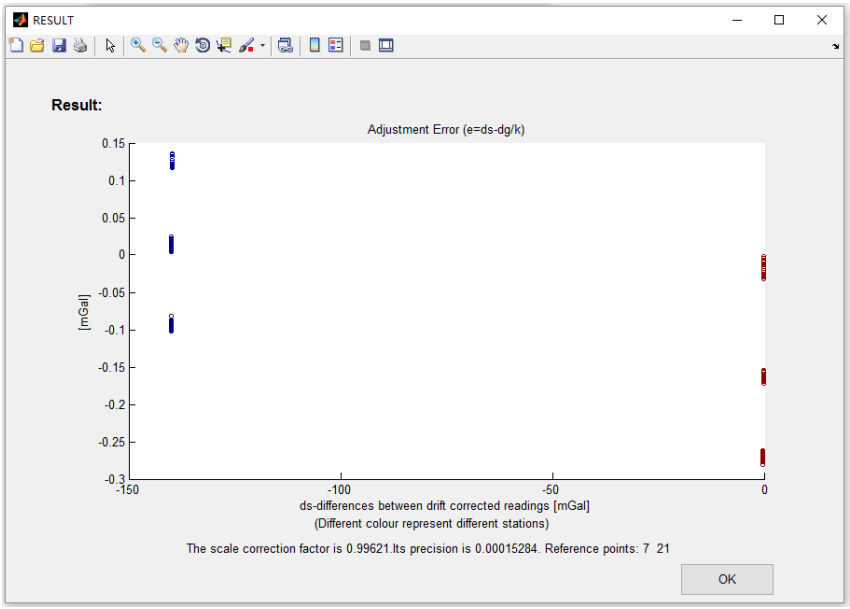


Figure 4.9: *Calibration result for step measurement*

There are several output files, their names are all related to the input CG-5 data file. If the input CG-5 file is *.txt, the output result file would be *_Output.txt (figure 4.10), the adjusted CG-5 data file would be *_Output_CG5data.txt, the new field record with the estimated absolute gravity would be *_Ouput_FieldRec.xlsx, the drift result window would be saved as *_Output_drift.jpg and the visualization image would be *_Output_grid.jpg. Besides the first output result file, others are optional depending on user's need.
From figure 4.10, we can see that almost all steps we have done in the gravimeter toolbox are saved in this file. It records the input file path, deleted points information, adjustment result, the gradient for selected points, the values related to simple Bouguer anomalies and the calibration factor.

```
Input Measurement File: C:\Users\SIYUN\Documents\MATLAB\Gravimeter_Toolbox_2.0\data\0747Mrz272013_ohne100.txt
|
Here are the information for deleted measurement points:
PtID  Line   Gravity measurement(mGal)  stdCG5(mGal)      Time
7     1          4715.9490          0.1310       26-Mar-2013 10:45:00
7     1          4715.9530          0.1370       26-Mar-2013 10:46:00
7     1          4715.9530          0.1160       26-Mar-2013 10:47:00
7     1          4715.9480          0.1650       26-Mar-2013 10:49:00
7     1          4715.9470          0.1080       26-Mar-2013 10:50:00
7     1          4715.9490          0.1530       26-Mar-2013 10:51:00
7     1          4715.9480          0.1040       26-Mar-2013 10:52:00
7     1          4715.9610          0.1580       26-Mar-2013 10:53:00
7     1          4715.9470          0.1940       26-Mar-2013 10:56:00
7     1          4715.9480          0.1010       26-Mar-2013 10:57:00
7     1          4715.9480          0.1270       26-Mar-2013 11:08:00
7     1          4715.9490          0.1940       26-Mar-2013 11:09:00
7     2          4715.9320          0.1650       26-Mar-2013 13:09:24
7     2          4715.9240          0.1090       26-Mar-2013 13:25:24
7     2          4715.9230          0.1390       26-Mar-2013 13:34:24
7     3          4715.9100          0.1690       26-Mar-2013 15:34:59
7     3          4715.9110          0.1760       26-Mar-2013 15:37:02
7     3          4715.9110          0.1160       26-Mar-2013 15:38:02
7     3          4715.9110          0.1010       26-Mar-2013 15:51:02
7     3          4715.9120          0.1500       26-Mar-2013 16:00:02
7     3          4715.9120          0.1610       26-Mar-2013 16:01:02
12    3           4765.9180          0.1270       26-Mar-2013 15:10:42
21    2           4855.6690          0.0860       26-Mar-2013 11:45:43
21    2           4855.6540          0.0710       26-Mar-2013 11:42:43
21    3           4855.6340          0.0300       26-Mar-2013 14:09:47


Input FieldRec: C:\Users\SIYUN\Documents\MATLAB\Gravimeter_Toolbox_2.0\data\FieldRec_20130327.xlsx

Here are the result of adjustment:
PtID   Gravity[mGal]   precision[mGal]   gradient[mGal/m]   gradient accuracy[mGal/m]
7     980746.7220          0.000000
12     980796.5560          0.015975
21     980886.1430          0.000000

drift:  -0.901254 [mGal/s]
precision of drift:  0.084311 [mGal/s]

bias:  -976030.415716 [mGal]
precision of bias:  0.015573 [mGal]

The gradient of PtID 12 and 21 is -0.20176 [mGal/m], and its precision is 4e-05 [mGal/m].

Here are the values for Bouguer anomalies:
PtID    lattitude(rough calculation)    theoritical gravity    FA correction    Bouguer correction    Bouguer anomalies [mGal]
7            54.000000                 981421.595297          -274.660172          99.593238          -499.806363
12            53.979682                 981419.843696          -202.043506          73.262049          -494.506215
21            53.952462                 981417.496487          -65.015848          23.575092          -489.912731


The scale correction factor is 0.99621.Its precision is 0.00015284. Reference points: 7  21
```

Figure 4.10: *Output result file for step measurement*

4.2 Measurement with Gradient Type

This example (*PA*) has 21 points, 4 of them have gradient type measurements. Here is the field record:

	A	B	C	D	E	F	G	H	I	J	K	L
1	PtID	Line	Point Type	Instrument Height [m]	pressure [mbar]	absGrav [mGal]	FAgrad [mGal/m]	DHHN [m]	stdDHHN [m]	X [m]	Y [m]	lattitude [degree]
2	100	1	0	0.474	999		-0.308	250				
3	801246	1	0	0.474	997	980812	-0.308	260.03				
4	801220	1	0	0.475	997	980811.5	-0.308	264.76				
5	286	1	1	0.247	994		-0.308	287.39		3405077	5305441	
6	286	2	1	0.214	994		-0.308	287.39		3405077	5305441	
7	286	3	1	1.378	994		-0.308	287.39		3405077	5305441	
8	286	4	1	0.214	994		-0.308	287.39		3405077	5305441	
9	286	5	1	1.378	994		-0.308	287.39		3405077	5305441	
10	286	6	1	0.214	994		-0.308	287.39		3405077	5305441	
11	286	7	1	1.378	994		-0.308	287.39		3405077	5305441	
12	59	1	0	0.422	994		-0.308	286.93		3405170	5305536	
13	281	1	0	0.364	994		-0.308	286.6		3405215	5305595	
14	59	2	0	0.422	994		-0.308	286.93		3405170	5305536	
15	14	1	0	0.187	994		-0.308	286.93		3405260	5305621	
16	281	2	0	0.367	994		-0.308	286.6		3405215	5305595	
17	13	1	0	-0.092	994		-0.308	287.92		3405254	5305633	
18	14	2	0	0.184	994		-0.308	286.93		3405260	5305621	
19	17	1	0	-0.144	994		-0.308	287.29		3405300	5305647	
20	13	2	0	-0.102	994		-0.308	287.92		3405254	5305633	
21	18	1	0	-0.142	994		-0.308	287.85		3405296	5305679	
22	17	2	0	-0.147	994		-0.308	287.29		3405300	5305647	
23	72	1	0	0.328	994		-0.308	286.52		3405276	5305696	
24	18	2	0	-0.125	994		-0.308	287.85		3405296	5305679	
25	5001	1	0	0.47	994		-0.308	295.94		3405356	5305766	
26	72	2	0	0.326	994		-0.308	286.52		3405276	5305696	
27	5001	2	0	0.472	994		-0.308	295.94		3405356	5305766	
28	325	1	2	0.18	994		-0.308	289.812		3405298	5305413	
29	325	2	2	1.34	994		-0.308	289.812		3405298	5305413	
30	325	3	2	0.18	994		-0.308	289.812		3405298	5305413	
31	325	4	2	1.34	994		-0.308	289.812		3405298	5305413	
32	325	5	2	0.18	994		-0.308	289.812		3405298	5305413	
33	325	6	2	1.34	994		-0.308	289.812		3405298	5305413	
34	325	7	2	0.18	994		-0.308	289.812		3405298	5305413	
35	299	1	0	0.285	993		-0.308	300.787		3405440	5304920	
36	325	8	3	0.226	994		-0.308	289.812		3405298	5305413	
37	299	2	0	0.283	992		-0.308	300.787		3405440	5304920	
38	79	1	0	0.413	994		-0.308	287.7		3405288	5305518	
39	43	1	3	0.174	994		-0.308	286.66		3405241	5305601	
40	79	2	0	0.414	994		-0.308	287.7		3405288	5305518	
41	41	1	0	0.191	994		-0.308	286.08		3405235	5305642	
42	43	2	3	0.136	994		-0.308	286.66		3405241	5305601	
43	43	3	3	1.296	994		-0.308	286.66		3405241	5305601	
44	43	4	3	0.136	994		-0.308	286.66		3405241	5305601	
45	43	5	3	1.296	994		-0.308	286.66		3405241	5305601	
46	43	6	3	0.136	994		-0.308	286.66		3405241	5305601	
47	43	7	3	1.296	994		-0.308	286.66		3405241	5305601	
48	67	1	4	0.393	994		-0.308	285.29		3405223	5305683	
49	41	2	0	0.203	994		-0.308	286.08		3405235	5305642	
50	6	1	0	0.378	994		-0.308	283.83		3405195	5305740	56
51	67	2	4	0.356	994		-0.308	285.29		3405223	5305683	
52	67	3	4	1.524	994		-0.308	285.29		3405223	5305683	
53	67	4	4	0.356	994		-0.308	285.29		3405223	5305683	
54	67	5	4	1.524	994		-0.308	285.29		3405223	5305683	
55	67	6	4	0.356	994		-0.308	285.29		3405223	5305683	
56	67	7	4	1.524	994		-0.308	285.29		3405223	5305683	
57	5000	1	0	0.472	994		-0.308	283.35		3405176	5305800	
58	6	2	0	0.377	994		-0.308	283.83		3405195	5305740	56
59	282	1	0	0.236	994		-0.308	282.191		3405144	5305880	
60	5000	2	0	0.472	994		-0.308	283.35		3405176	5305800	
61	282	2	0	0.236	994		-0.308	282.191		3405144	5305880	
62	801220	2	0	0.476	999	980811.5	-0.308	264.76		NaN	NaN	
63	801246	2	0	0.473	999	980812	-0.308	260.03		NaN	NaN	
64	100	2	0	0.474	999		-0.308	250		NaN	NaN	

Figure 4.11: *Field record for gradient type measurement*

Unlike the field record in figure 4.1, here the 'Point Type' has different values, not only 0, but also other integer numbers. 0 represents standard measurement type while other numbers indicate the points are measured with different instrument heights. The same 'PtID' has the

same 'Point Type' value and this value can be any positive integers (here the integer values are not important, they are only used to distinguish different gradient points). The number of these values depends on the number of gradient points.
It is worth to mention that the gravimeter can select the measurement for a specific point in data selection part. With this function, a user can have a new CG-5 data file that only includes measurements for one point if needed. This is the one station case in section 3.1.2, the drift can be calculated relatively with high accuracy as less error sources. This function is designed to compute a drift for calibration. The calibration adjusts the data after drift correction, so the accuracy of drift deeply affects the calibration result. If a point is measured continuously before and after the calibration measurement data, the drift of this point can be seen as the drift for all measurements. If we use the drift estimated from all measurements, it would already include the calibration error.
This measurement contains a station that continuously measured in the beginning and in the end, so we firstly select this station to plot (figure 4.12). All GUI windows in the toolbox can change size and for the windows with images, these images can also be zoomed in with the toolbar at the top of the windows. This function is helpful when too many measurement points in one image.
After the data selection part, we adjust the data directly without field record, as it is a one station case. The result is in figure 4.13. We can see that the second part observations contain distinctly larger adjustment errors, which indicates the measurement situation is poor and it is not suitable for calibration purpose. While as an example, we still insert this drift and its accuracy to compute the calibration factor for total measurements. Figure 4.14 presents the calibration result with given drift.

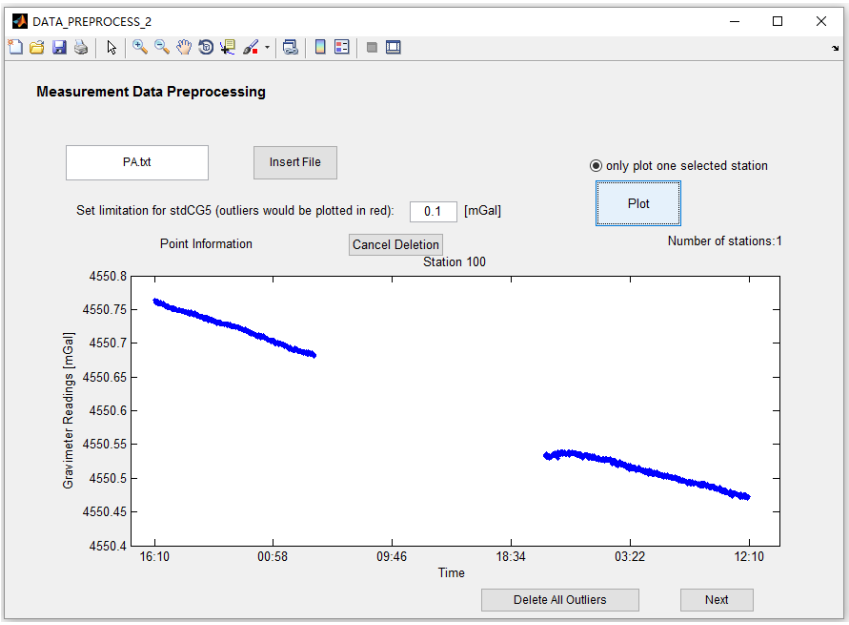


Figure 4.12: *One station plot*

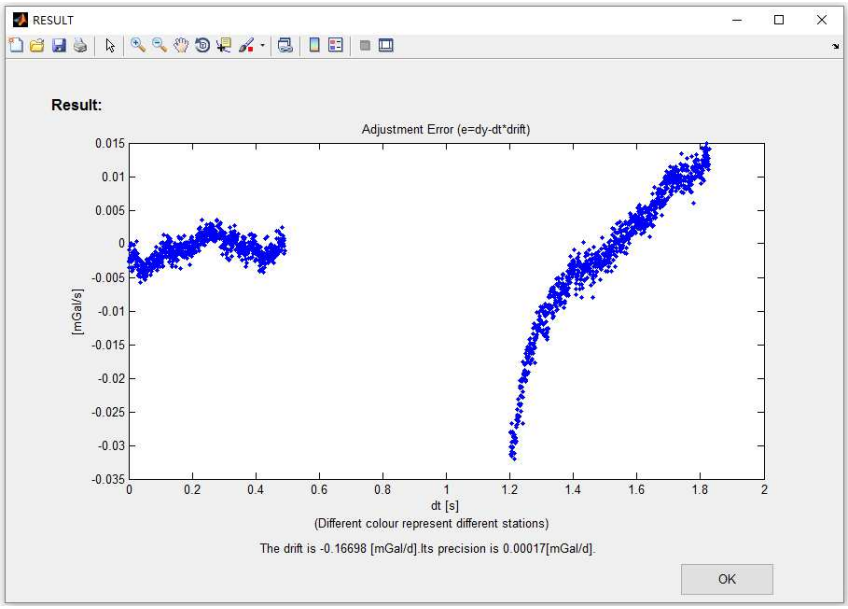


Figure 4.13: *Result window for one station*

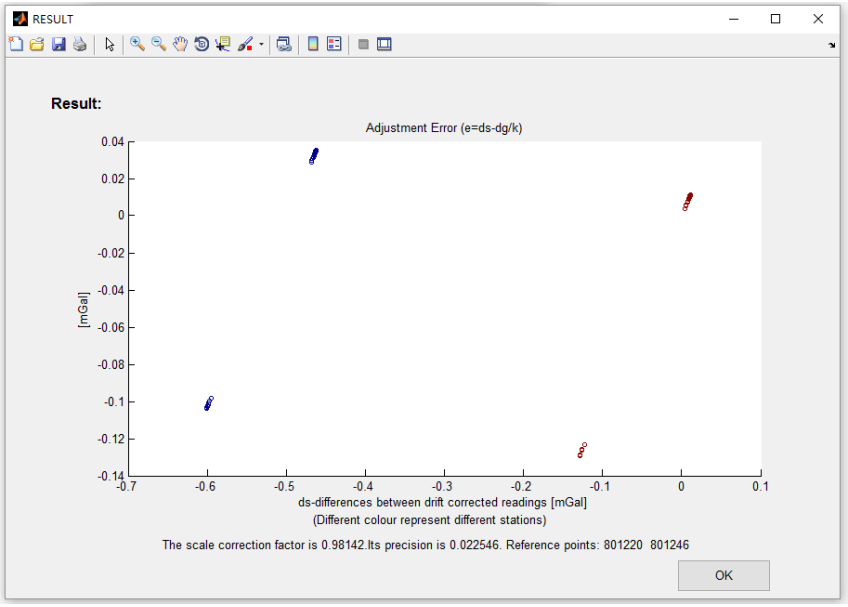


Figure 4.14: *Calibration result with inserted drift*

Figure 4.15 is the drift adjusted from total observations, which is -0.16462 mGal/d, different from one station case, -0.16698 mGal/d. The difference indicates the extra error source, e.g. calibration error, strongly influenced adjustment result.

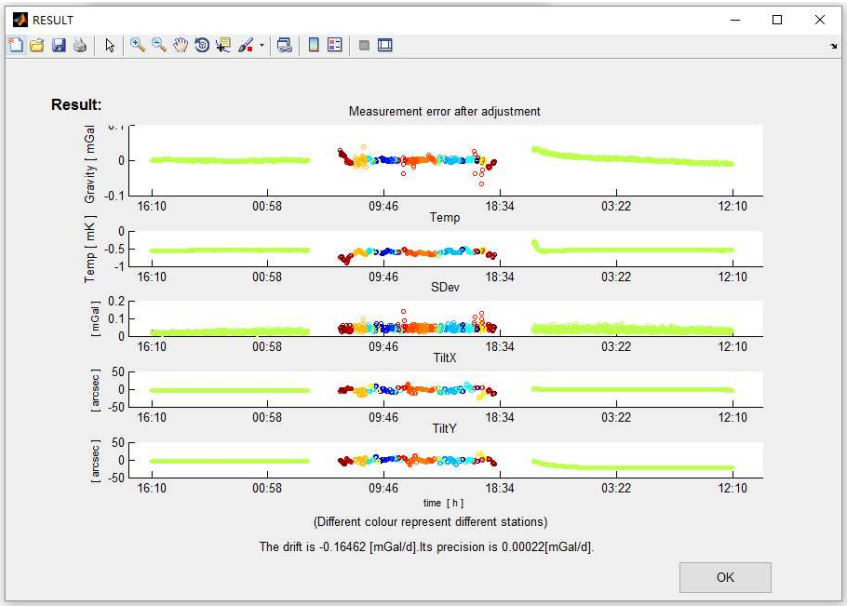
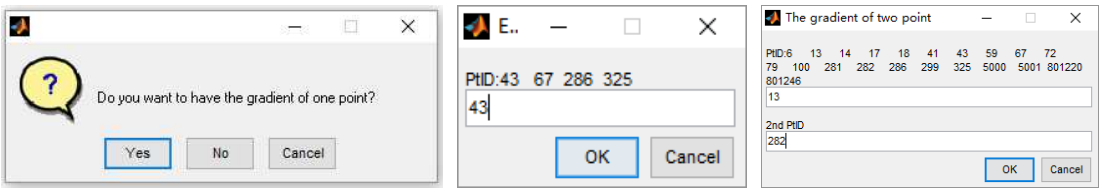


Figure 4.15: *Drift for total observations*

As this data has gradient type, when we click 'Gradient' in CALCULATION window, a question dialogue box would appear to ask whether the user want the gradient of one point or not. The user should type in 'PtID' and a result window (figure 4.17) would appear.



(a) Gradient type selection (b) Input 'PtID' for 1 point (c) Input 'PtID' for 2 points

Figure 4.16: *Choose gradient type and type in 'PtID'*

This measurement can visualize simple Bouguer anomalies (figure 4.18) and absolute gravity (figure 4.19). If we delete the absolute gravity in field record, we can also obtain the visualization of gravity differences (figure 4.20). We can see that the color distribution of absolute gravity image and gravity difference image is similar, as they both demonstrate gravity variation in this area. While the image of simple Bouguer anomalies is distinct with others, as it visualizes the density differences.

The output file of this process includes a text file recording all steps, 4 images in jpg format (drift result window, simple Bouguer anomalies visualization, absolute gravity visualization and gravity differences visualization) and a new field record (figure 4.21). This field record changes 2 columns, fulfilling 'absGrav' with adjusted absolute gravity and replace 'FAgrad' with one point gradient for gradient measurement points. Other contents are identical to the

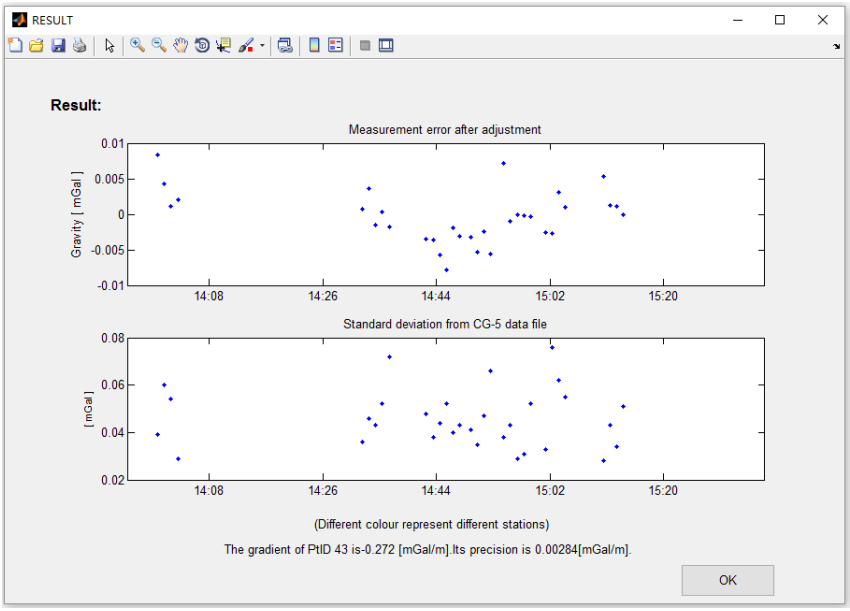


Figure 4.17: *Result window for one point gradient*

input field record.

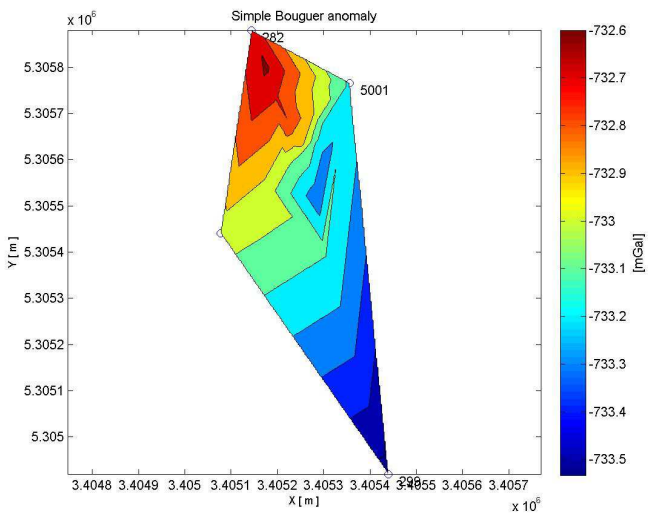


Figure 4.18: *Simple Bouguer anomaly visualization for gradient measurement*

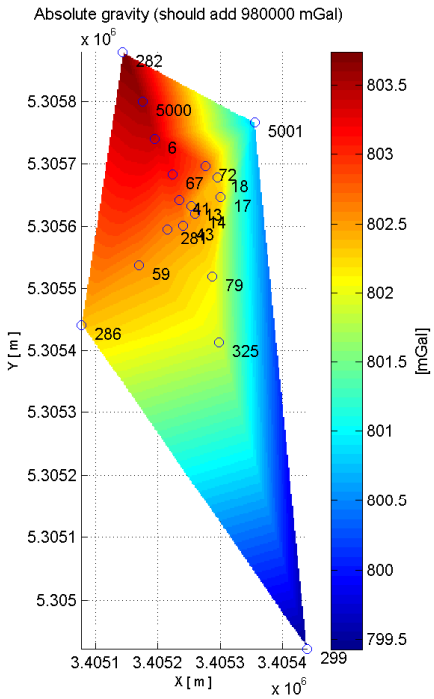


Figure 4.19: *Absolute gravity visualization for gradient measurement*

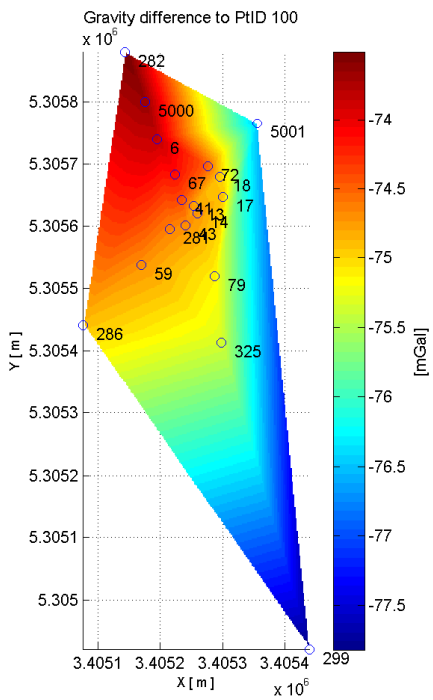


Figure 4.20: *Gravity difference visualization for gradient measurement*

	A	B	C	D	E	F	G	H	I	J	K	L
1	PtID	Line	PointType	dh	pressure	absGrav	FAgrad	DHHN	stdDHHN	X	Y	Latitude
2	100	1	0	0.474	999	980877.3	-0.308	250				
3	801246	1	0	0.474	997	980812	-0.308	260.03				
4	801220	1	0	0.475	997	980811.5	-0.308	264.76				
5	286	1	1	0.247	994	980802.4	-0.2638	287.39		3405077	5305441	
6	286	2	1	0.214	994	980802.4	-0.2638	287.39		3405077	5305441	
7	286	3	1	1.378	994	980802.4	-0.2638	287.39		3405077	5305441	
8	286	4	1	0.214	994	980802.4	-0.2638	287.39		3405077	5305441	
9	286	5	1	1.378	994	980802.4	-0.2638	287.39		3405077	5305441	
10	286	6	1	0.214	994	980802.4	-0.2638	287.39		3405077	5305441	
11	286	7	1	1.378	994	980802.4	-0.2638	287.39		3405077	5305441	
12	59	1	0	0.422	994	980802.5	-0.308	286.93		3405170	5305536	
13	281	1	0	0.364	994	980802.6	-0.308	286.6		3405215	5305595	
14	59	2	0	0.422	994	980802.5	-0.308	286.93		3405170	5305536	
15	14	1	0	0.187	994	980802.5	-0.308	286.93		3405260	5305621	
16	281	2	0	0.367	994	980802.6	-0.308	286.6		3405215	5305595	
17	13	1	0	-0.092	994	980802.5	-0.308	287.92		3405254	5305633	
18	14	2	0	0.184	994	980802.5	-0.308	286.93		3405260	5305621	
19	17	1	0	-0.144	994	980802.3	-0.308	287.29		3405300	5305647	
20	13	2	0	-0.102	994	980802.5	-0.308	287.92		3405254	5305633	
21	18	1	0	-0.142	994	980802.3	-0.308	287.85		3405296	5305679	
22	17	2	0	-0.147	994	980802.3	-0.308	287.29		3405300	5305647	
23	72	1	0	0.328	994	980802.7	-0.308	286.52		3405276	5305696	
24	18	2	0	-0.125	994	980802.3	-0.308	287.85		3405296	5305679	
25	5001	1	0	0.47	994	980800.7	-0.308	295.94		3405356	5305766	
26	72	2	0	0.326	994	980802.7	-0.308	286.52		3405276	5305696	
27	5001	2	0	0.472	994	980800.7	-0.308	295.94		3405356	5305766	
28	325	1	2	0.18	994	980801.9	-0.27176	289.812		3405298	5305413	
29	325	2	2	1.34	994	980801.9	-0.27176	289.812		3405298	5305413	
30	325	3	2	0.18	994	980801.9	-0.27176	289.812		3405298	5305413	
31	325	4	2	1.34	994	980801.9	-0.27176	289.812		3405298	5305413	
32	325	5	2	0.18	994	980801.9	-0.27176	289.812		3405298	5305413	
33	325	6	2	1.34	994	980801.9	-0.27176	289.812		3405298	5305413	
34	325	7	2	0.18	994	980801.9	-0.27176	289.812		3405298	5305413	
35	299	1	0	0.285	993	980799.4	-0.308	300.787		3405440	5304920	
36	325	8	3	0.226	994	980801.9	-0.27176	289.812		3405298	5305413	
37	299	2	0	0.283	992	980799.4	-0.308	300.787		3405440	5304920	
38	79	1	0	0.413	994	980802.1	-0.308	287.7		3405288	5305518	
39	43	1	3	0.174	994	980802.6	-0.272	286.66		3405241	5305601	
40	79	2	0	0.414	994	980802.1	-0.308	287.7		3405288	5305518	
41	41	1	0	0.191	994	980802.8	-0.308	286.08		3405235	5305642	
42	43	2	3	0.136	994	980802.6	-0.272	286.66		3405241	5305601	
43	43	3	3	1.296	994	980802.6	-0.272	286.66		3405241	5305601	
44	43	4	3	0.136	994	980802.6	-0.272	286.66		3405241	5305601	
45	43	5	3	1.296	994	980802.6	-0.272	286.66		3405241	5305601	
46	43	6	3	0.136	994	980802.6	-0.272	286.66		3405241	5305601	
47	43	7	3	1.296	994	980802.6	-0.272	286.66		3405241	5305601	
48	67	1	4	0.393	994	980803.1	-0.28918	285.29		3405223	5305683	
49	41	2	0	0.203	994	980802.8	-0.308	286.08		3405235	5305642	
50	6	1	0	0.378	994	980803.4	-0.308	283.83		3405195	5305740	56
51	67	2	4	0.356	994	980803.1	-0.28918	285.29		3405223	5305683	
52	67	3	4	1.524	994	980803.1	-0.28918	285.29		3405223	5305683	
53	67	4	4	0.356	994	980803.1	-0.28918	285.29		3405223	5305683	
54	67	5	4	1.524	994	980803.1	-0.28918	285.29		3405223	5305683	
55	67	6	4	0.356	994	980803.1	-0.28918	285.29		3405223	5305683	
56	67	7	4	1.524	994	980803.1	-0.28918	285.29		3405223	5305683	
57	5000	1	0	0.472	994	980803.6	-0.308	283.35		3405176	5305800	
58	6	2	0	0.377	994	980803.4	-0.308	283.83		3405195	5305740	56
59	282	1	0	0.236	994	980803.7	-0.308	282.191		3405144	5305880	
60	5000	2	0	0.472	994	980803.6	-0.308	283.35		3405176	5305800	
61	282	2	0	0.236	994	980803.7	-0.308	282.191		3405144	5305880	
62	801220	2	0	0.476	999	980811.5	-0.308	264.76				
63	801246	2	0	0.473	999	980812	-0.308	260.03				
64	100	2	0	0.474	999	980877.3	-0.308	250				

Figure 4.21: *New field record for step measurement*

Chapter 5

Conclusion and Outlook

This gravimeter toolbox combines and extends several functions for processing Scintrex data with GUI. A user can easily achieve the result of adjustment, gradient, gravity visualizations and calibration factor. It can also be used for data selection and saving. These functions are suitable for most applications, which is the aim of the toolbox. With graphical user interface, even the user without any knowledge of programming can operate the toolbox and obtain needed result.

There are two problems in this toolbox, which may need further improvement. The first one is in the data selection part. Once a station has been checked and the window moves to next one, user cannot check or change it again. This means that once the station is checked and the user clicks 'Next', this station can not be displayed to operate again. As the DATA_PREPROCESS window has already too many buttons, here we did not design a table for station selection to recheck the station. Another problem is about the operating speed. If there is a large number of input data, the toolbox would be slow, especially for adjustment part. Depending on the computer capacity, MATLAB can not operate and warn 'out of memory' if too much data. In most cases, these two problems do not occur.

Besides the functions in the toolbox, other functions can also be further programmed to obtain specific results. For example, linking different measurement data together by reference points.

In conclusion, the gravimeter toolbox offers basic functions for gravimeter data process, which can be operated by any users.

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