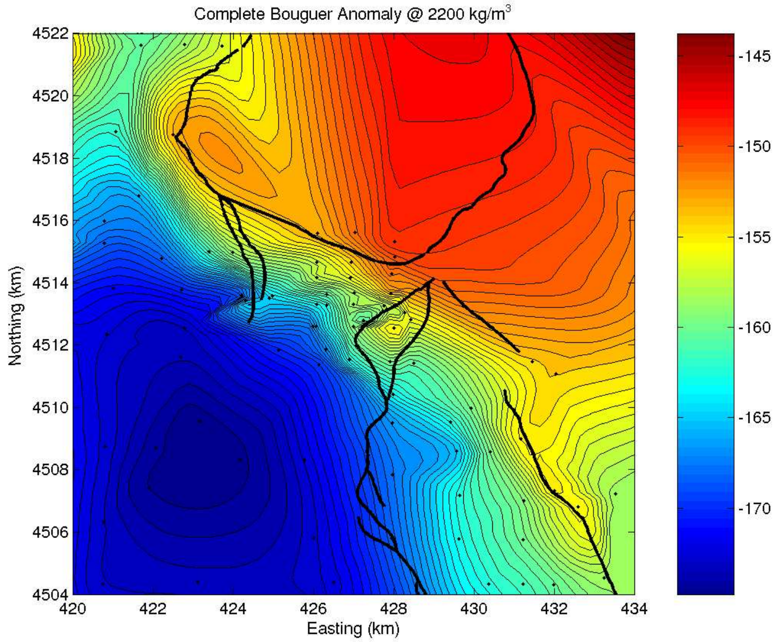

High Precision Gravity Measurements

Techniques, Software, & Algorithms

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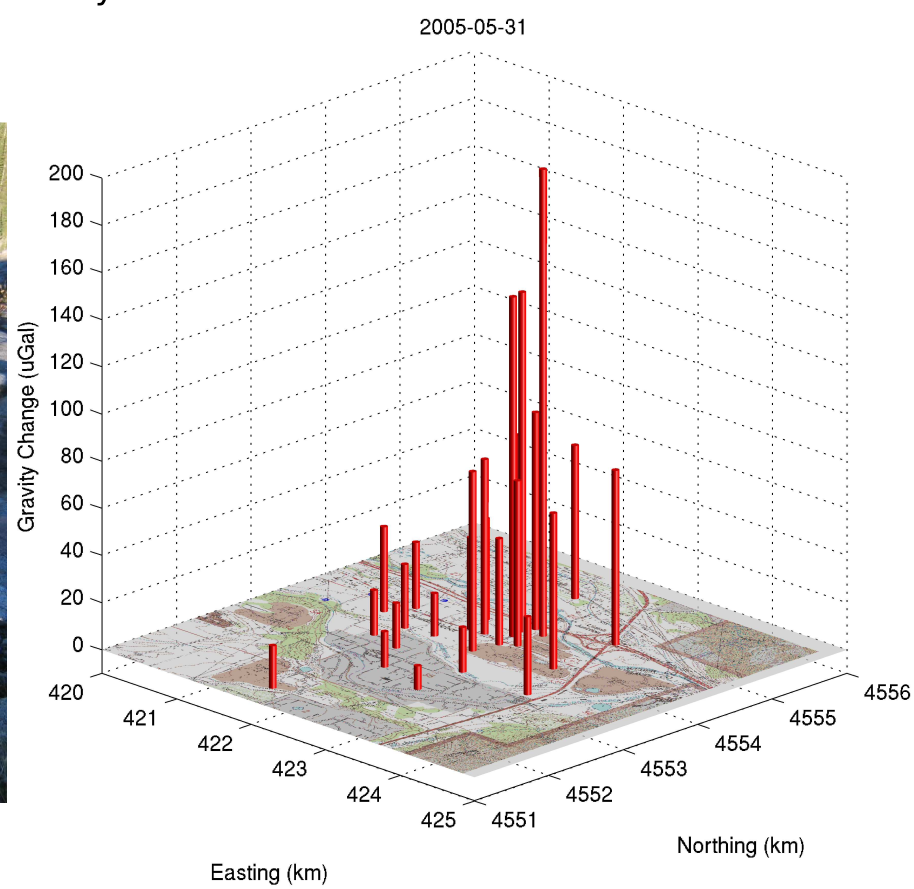

High Precision Gravity Measurements

Paul Gettings

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Contents

Chapter 1

Introduction

Repeated high-precision gravity measurements track changes in vertical position and mass under stations. If gravity changes due to vertical motion are removed, gravity changes reflect only mass changes under stations. These changes can provide insight into changes of geologic or engineering interest; for example, changes in storage of groundwater aquifers [*Pool and Eychaner*, 1995; *Pool*, 2008], natural seasonal mass changes [*Goodkind*, 1986; *Keysers et al.*, 2001], steam field changes under exploited geothemal resources [*Allis and Hunt*, 1986; *Arnet et al.*, 1997; *Sugihara*, 2001; *Nordquist et al.*, 2004; *Sugihara and Ishido*, 2008], or combined mass and elevation changes on volcanic or tectonic systems [*Jachens et al.*, 1981; *Arnet et al.*, 1997; *Battaglia et al.*, 1999; *Jousset et al.*, 2000; *Ballu et al.*, 2003; *Vigouroux et al.*, 2008]. Precision gravimetry can also be used for detailed investigation of geologic structures, although this has been little used historically. The applicability of gravity (change) data is controlled by the precision of the measurements, which determines the minimum position and mass changes resolvable.

Previously reported measurement techniques [*Whitcomb et al.*, 1980; *Jachens et al.*, 1981; *Dragert et al.*, 1981; *Allis and Hunt*, 1986; *Hunt and Kissling*, 1994; *Andres and Pederson*, 1993; *Arnet et al.*, 1997; *Battaglia et al.*, 1999; *Furuya et al.*, 2003; *Sasagawa et al.*, 2003; *Ferguson et al.*, 2007] generally use manually-recorded gravimeters, typically LaCoste & Romberg model "D" meters (1 μGal reported precision); *Whitcomb et al.* [1980] and *Furuya et al.* [2003] are notable exceptions, where multiple model "G" gravimeters ($\sim$10 μGal reported precision) were used to speed surveying over large areal and elevation extents. *Sasagawa et al.* [2003] and other sea-bottom monitoring projects use a 3-sensor gravimeter derived from Scintrex CG-3Ms to conduct highly automated ocean-bottom gravimetry. All techniques generally use multiple loops of one or more gravimeters to address instrument drift and tare concerns; *Sasagawa et al.* [2003] use a single loop of three sensors at once. The multiple occupations and/or gravimeters also allow for statistics (typically averaging or linear least-squares fitting) to be applied to reduce measurement errors. *Ferguson et al.* [2007] uses a CG-3M, but with a custom-built computer interface for logging and real-time analysis. The looping and analysis scheme of *Ferguson et al.* [2007] is very similar to those presented above for LaCoste & Romberg G meters, with low-order polynomial instrument drift functions (typically linear or cubic) fit from repeated station occupations.

In contrast, the techniques presented here are designed to allow for large networks to be rapidly measured using a single instrument, with minimal looping. This allows for maximal station counts for a project, while minimizing costs (instrument and field support). To achieve maximum return with minimal cost, the instrument operators are required to adhere to a relatively strict regimen for acquisition and processing of data.

The rest of this manual consists of chapter 2, on procedures for setting up, using, downloading, and analysing a CG-5 and its data; chapter 3 on the algorithms embodied in the analysis code, to help operators and project managers understand the restrictions and requirements presented in chapter 2; chapter 5 detailing differences if a project must be undertaken using a CG-3M or Aliod gravity meter rather than a CG-5; chapter 6 with additional processing techniques that are not used in the analysis package, but may be of use in some projects; and chapter 7 that reproduces the station occupation checklist from chapter 2 in a convenient form for carrying in the field.

Chapter 2

Acquiring Precision Gravity Data with a CG-5

2.1 Station Network Design & Repeat Schemes

Designing station networks always involves a trade-off between the number of stations and the time available to occupy the network. For the discussion here, we will assume that only one instrument is available, although the extension to multiple instruments is straight-forward.

2.1.1 Network Design

Station networks must be designed to capture the signal of interest. Given a restriction on the total number of stations that any project can occupy in its available time, this capture requirement will mean placing stations to maximize signal information with the minimum number of stations.

Station networks will typically cover either rectangular or circular regions, often with areas of high station density (near a source or sink of interest) and other areas with few stations (far from sources of interest). The dense station areas must be designed to capture (perferably on all sides) the signal of interest, and so should bracket the source of interest. Far-flung stations can generally be far more sparse, but should also surround the source(s) of interest to allow for regional/natural signal capture. Do not make the mistake of placing all stations on the target source, and neglecting nearby and far-flung stations; the resulting data set will be inadequate for most interpretation tasks.

Station spacing, in the densest regions, need not be less than the depth of the signal. Higher density will not reveal more information, as the nature of the gravity field is such that deep sources produce smooth, broad signals at the surface. Hence, keep the dense station spacing no tighter than half the depth of the source.

Far-flung stations should be as close as practical, but sufficiently far that the source will not influence the stations during the project lifetime. In hydrologic projects, this typically results in far-flung stations 2-8 km from the sources. For geothermal investigations, far-flung stations may be 30+ km from the production field. Do not choose all far-flung stations to be in different hydrologic and/or meteorologic regions than the sources, as the signals at such stations adds considerable complexity to interpretation.

Regular grids of stations are convenient for interpretation, but typically require too many stations to cover the region of interest to be practical. Thus, most projects will likely end up with networks that resemble collections of sparse rings and clusters. Irregular geometry generally does not greatly complicate interpretation, and increases the area that can be covered in a given time, or reduces the number of days required to measure the target signal.

Using the repeat occupation schemes presented in this manual, and assuming easy road transit between stations (1-5 min driving between stations), 11-15 unique stations can be occupied in one day, including time for commuting from the office/hotel to the field site. As an example, a project that can afford 1-3 days in the field for each campaign can have a network of 10-35 stations total. The stations per day rate is the critical factor in network design for any project, and determines the trade-off between number of stations and days in the field per campaign.

Summary

1. Networks need to cover sources of interest **and** far-flung regions for regional control. This requirement is relaxed to allow a network to only cover the source of interest if absolute gravity measurements are available during a project, as the absolute control can remove the need for far-flung/"stable" stations.

2. Projects need to first determine how many days per campaign are feasible, and then compute the maximum number of stations in the network.

3. Given a maximum number of stations, place stations in an irregular geometry to maximize the chances of capturing sources and regional/natural signals.

4. With the repeat schemes in this manual, 11-15 unique stations/day is the maximum that can be occupied.

5. Station spacing closer than about half the source depth is generally a waste of station occupations.

2.1.2 Station Repeat Schemes

Field data will have nonlinear instrument drifts due to transport effects, errors in Earth tide corrections, instrument tares, or other uncorrected noise. To measure and correct this nonlinear noise, it is necessary to have repeated occupations of stations in a single survey; by assuming gravity at a given station is static during a campaign, we can use repeated occupations to remove noise and improve our estimate of the true gravity field.

Choosing the scheme for repeating occupations of stations during a campaign is a critical part of project design, and is worth spending some time to get correct. The goal is a station occupation scheme (or schedule) that will allow at least two occupations of all stations in a network, 4-5 occupations of a local base station for each day of a campaign, and minimum transport time between stations.

To illustrate the general repeat schedule for a day of stations, assume a single day network of 11 stations, plus the office (called `O`). Name the stations by letters (`A-K`). Measurements taken at the office/hotel before moving in the morning, and after returning at night, will be used to tie multiple days together, hence station `O` is critical to all projects.

Measurements at station `O` must be taken before significant transport of the gravity meter; there is no way to determine instrument drift before the first measurement. Thus, ensure the gravity meter is stored overnight next to station `O` to allow a measurement without transport at the start of the next field day.

For any repeat scheme, it is highly recommended to write down the station order, in complete detail. Repeat schedules are complicated, and not easy to rebuild from scratch in the car!

Regional Networks

The general procedure to develop a station repeat scheme, given a regional network (one that covers a region, **not** a line), is to break the entire survey into chunks of 11-15 unique nearby stations for each day. A centrally-located station is chosen as the *local base*, which will be occupied at least 4 times in the day.

A general repeat scheme for 11 stations is:

```
O-A-B-C-D-E-A-F-G-H-I-J-K-A-B-C-D-E-F-A-G-H-I-J-K-A-O
```

27 occupations total, which would require ∼9 hours of measuring, typically.

Note that station `A` is occupied 5 times. If time is short, the **fourth** occupation (second to last occupation) could be omitted as each occupation after the first full loop of stations is closing repeat loops. In no case can the final measurements of `A` or `O` be omitted, as these loops are used to provide overall drift during the day and tie together multiple days.

For a network with 15 stations (`A-P`), use the repeats of `A` to ensure that there are not many hours between a repeat during the first full loop of all stations:

```
O-A-B-C-D-E-A-F-G-H-I-J-A-K-L-M-N-P-
  A-B-C-D-E-F-G-H-I-J-K-L-M-N-P-A-O
```

35 occupations total, which would require ∼12 hours of measuring, typically.

For such a large number of stations, station `A` must be occupied 5 times to create sufficient looping early in the day, before the loop closures during the second tour of the daily network. As with smaller networks, the last measurements of `A` and `O` are critical for tieing multiple campaign days together and tracking long-term meter drift during a campaign.

Linear Networks

The general procedure to develop a station repeat scheme, given a linear network (one that is a line), is to break the line into chunks of about 4 unique stations, and then stitch multiple chunks together into a day of 11-15 stations.

Because the network is a long line, efficient loops are best done by a modified ladder technique where a chunk of stations are measured from the start, then measure back to the start, then jump back to the end of the line.

For example, a day with 12 stations (`A-L`) plus the office (`O`), broken into 3 chunks of 4: `A-D`, `E-H`, and `I-L`

```
O-A-B-C-D-E-
             D-C-B-A-F-E-G-H-I-J-
                                  I-H-G-F-K-J-L-K-L-A-O
```

27 occupations total, which would typically require ∼9 hours.

Note the overlaps between chunks, which prevents any two chunks from being disconnected; the goal is to have every chunk have at least one station overlap with the next chunk, and every station has at least two occupations in the day.

The final measurements of stations `A` and `O` are critical in linear networks, for the same reasons as with regional networks.

2.1.3 Reference Stations

To handle instrument drift between surveys, one or more stations are assumed "stable," meaning no gravity change over time. The apparent gravity changes at the reference station(s) provide a correction to the measured gravity changes to compute gravity changes for interpretation. Any signals at the reference stations are superimposed (in an inverted manner) on all other gravity stations. In general, reference stations should be determined by the location of absolute gravity measurements during campaigns; gravity changes at reference sites are then directly measured, and the sites need not be stable.

In practice, many projects will need to use the far-flung stations as a set of reference stations, holding the average to zero. A suite of far-flung stations also provides a measure of the variability in natural signals, and will remove regional signals. Removing appropriate regional signals can be used to enhance the signal of interest. However, far-flung stations that are too distant, or in a different hydrologic or meteorologic region, will complicate interpretation.

2.1.4 Example Networks & Repeat Schemes

Here are two example networks and their repeat schemes. The first example is taken from an artificial recharge project based around infiltration of surface water into a deep aquifer using a small area of ponds. The second example is from Yellowstone National Park, where two lines of stations are being used to measure gravity change related to volcanic changes in the deep magma chamber; the large extent of the project and short field campaigns dictate the use of lines of stations, rather than a grid.

Weber River Aquifer Storage & Recovery

The Weber River ASR project was a multi-year infiltration experiment to determine the feasibility and limits of recharging the deep municipal-supply aquifer under the South Ogden urban area using surface water poured into 5 acres of infiltration ponds. As part of the overall project, the University of Utah used repeated high-precision gravity measurements on a network of 30 stations to track the infiltration and migration of the water. Figure 2.1 shows the network of stations used for the project. Stations were generally located on existing concrete structures; stations WRP01 (labelled 01 on the figure) and WRP28 were built using a 12" paving stone over a 12" deep hole filled with cement, with two 24"-long pieces of 3/8" rebar driven into the ground out of the poured cement. Stations WRP26 and WKRP were destroyed during the project by construction, but replaced with WRP30 and WKRD. Ideally, WRP30 and WKRD would have been occupied before the loss of WRP26 and WKRP, but this wasn't possible. Western stations were dropped early in the project to add more central stations once migration to the south, and not west, was observed. Thus, out of 30 stations located, no more than 25 needed to be occupied during any campaign.

To occupy the 25 stations of a campaign required two field days for gravity and two additional days for precision GPS. An example repeat schedule from actual field notes for the first day:

```
WBB115-WKRD-WRP05-WRP06-WRP07-WRP27-WRP08-WRP29-WKRD-
            WRP09-WRP02-WRP01-WRP11-WRP04-WRP28-WKRD-
            WRP05-WRP06-WRP07-WRP27-WRP08-WRP29-WKRD-
            WRP09-WRP02-WRP01-WRP11-WRP04-WRP28-WKRD-WBB115
```

And for the second day:

```
WBB115-WRP12-WRP10-WRP13-WRP16-WRP17-WRP18-WRP19-WRP12-
             WRP24-WRP20-WRP21-WRP22-WRP25-WRP30-WRP12-
             WRP10-WRP13-WRP16-WRP17-WRP18-WRP19-WRP12-
             WRP24-WRP20-WRP21-WRP22-WRP25-WRP30-WRP12-WBB115
```

Note the five occupations of WKRD or WRP12, and the overall loop between WBB115 for each day, which is the long-term storage location of the gravity meter.

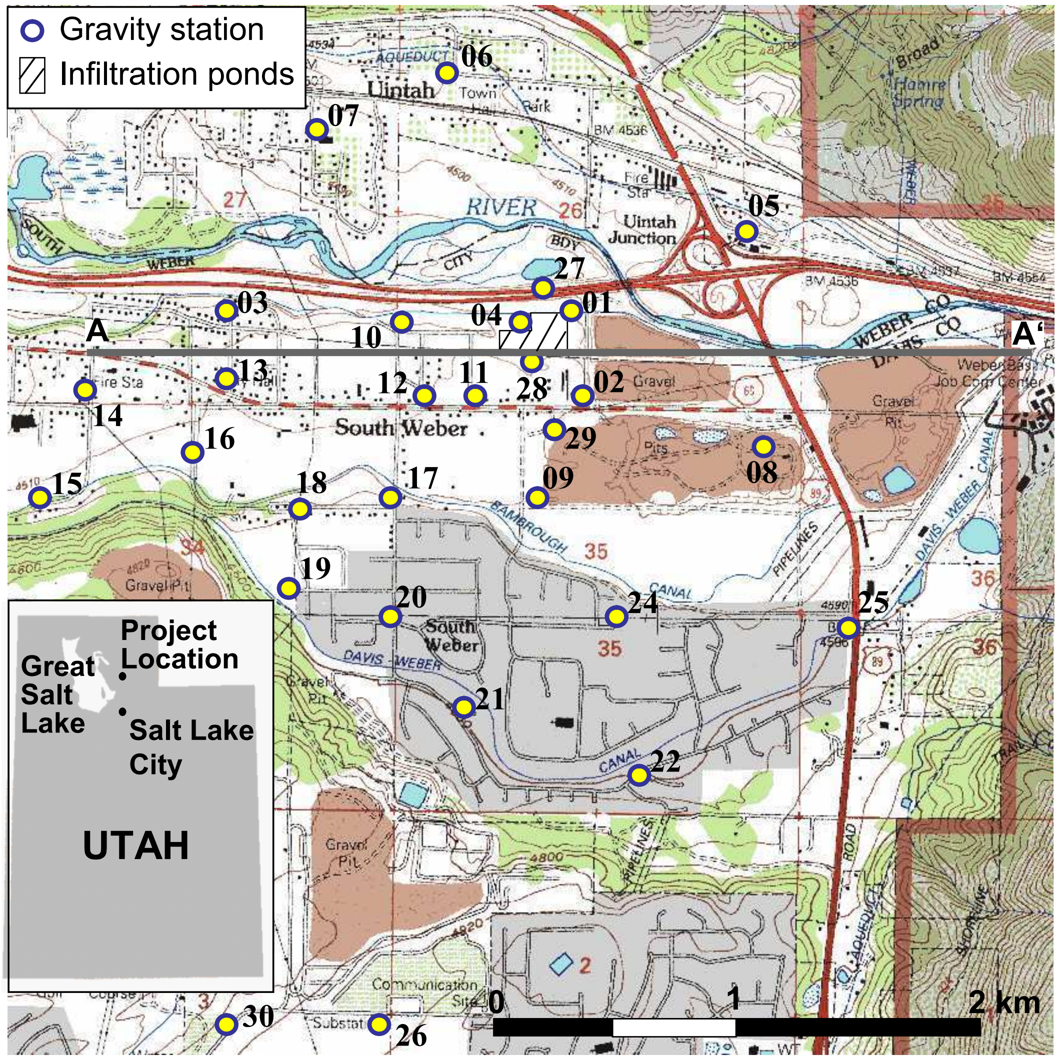

Figure 2.1: Station map for the Weber River Aquifer Storage & Recovery project gravity network. Station names have had a common "WRP" removed from the front for clarity. Note the tight station spacing at the source of interest (the infiltration ponds) and the far-field stations for natural background and instrument drift control. Stations WKRP and WKRD are ∼9 km east of WRP05.

Yellowstone National Park Caldera Lines

Yellowstone National Park, one of the world's best-studied hot spots, has recently been showing rapid uplift in certain portions of the park [*Chang et al.*, 2007]. To help determine the cause of the uplift (magma intrusion? pressure changes? hydrologic changes?), a new gravity monitoring program was begun on a couple of existing gravity networks which are located along roads crossing the main deformation zone. Figure 2.2 shows the stations of one such line, as an example of a linear network. In the case of the Yellowstone project, the stations were chosen by recovering all the old gravity benchmarks possible, to allow comparison with the measurements from the 1970's to 1990's. By using fixed benchmarks (e.g. NGS benchmarks on bedrock, etc.) with good field notes for exact meter positions, and assuming station 11mdc stable between campaigns, it is possible to tie together measurements over 30 years to look at long-term changes in the park!

Due to the linear nature of the network, campaigns use a ladder repeat schedule such as:

```
11mdc-13mdc-hollis-lc58-22mdc-y367-
  22mdc-lc58-hollis-11mdc-13mdc-24mdc-y367-
z367-kaygee-f11a-e11a2-arbee-27mdc-
  arbee-e11a2-f11a-kaygee-z367-24mdc-27mdc
```

This is for a single day; the plotted line takes two days to fully occupy, with the second following a similar repeat pattern to the first, starting with 11mdc and then da3c to k12 and back in segments. Note that at the end of the line (38mdc and k12), the repeat schedule flops back and forth to get 2 readings of each station without having to drive the entire line again:

```
...-cv8424-38mdc-k12-38mdc-k12-cv8424-cv8412-11mdc
```

This sort of trick allows for two occupations of all stations in the line, while minimizing driving without measurements.

2.2 Gravimeter Storage & Long-Term Drift Readings

In the experience gained so far, it is critical to store gravity meters in such a way that they are continously available for field work, and are given a chance to "age" as quickly as possible. Thus, relative gravity meters should be stored level, on wall power with an attached battery (in case of power failure), and reading/recording. The storage location must be stable, quiet, and secured since the meters will be left unattended for long periods.

The collected long-term drift data are valuable in checking the functioning of the meter, and in learning the expected daily drift rates for a meter. Since every meter is

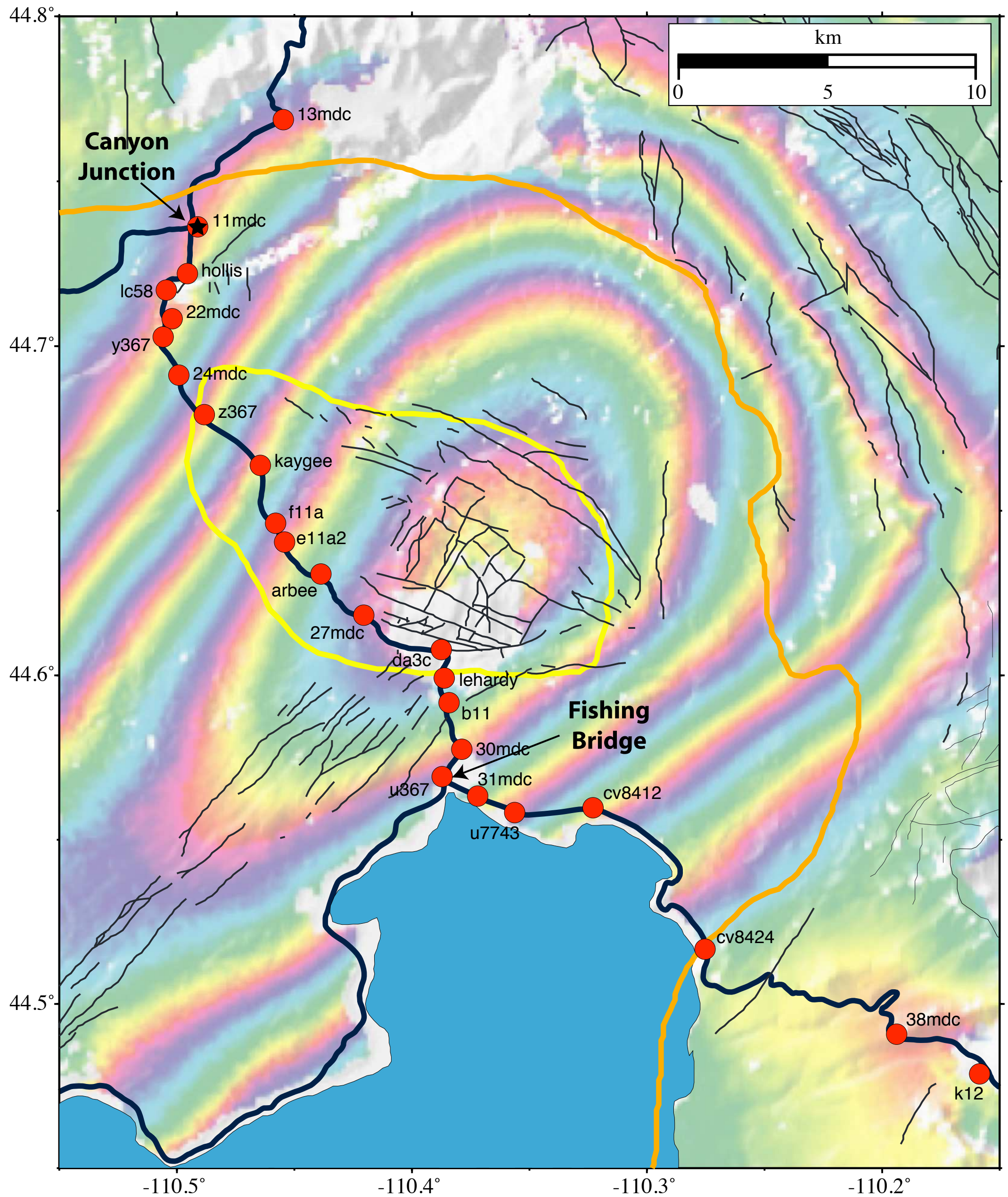

Figure 2.2: Station map of one of the Yellowstone gravity lines being used for investigation of the sources of Yellowstone's recent deformation. Note the linear nature of the station network, making the most efficient looping techniques ladders. Background is an InSAR image of deformation, with the 600 ka caldera outline in orange, and the main deformation zone in yellow. Station 11mdc, with the star, is used as a stable reference between campaigns.

unique, drift data for each meter is required. Also note that if the meter is recording up until a field campaign, there is no need to start or end a campaign day with occupations of the base, as the long-term data can be used instead. Add the long-term drift data to the field data after downloading, and save an untouched backup of the downloaded data.

The settings for long-term drift measurements are identical to those for field measurements (see section 2.4) except the `Read Time` should be increased to 180 or 240 s.

Download and check the drift rates for the meter every 1-4 weeks. This will also help catch impending temperature and tilt problems. A command-line utility (*cg5e_cmd.py*) has been included with the reduction software to parse CG-5 text data files and reformat into easily plotted files. Alternatively, load the CG-5 text file into *Excel* for plotting, or import the SGD-format data file into *Oasis montaj*.

It is recommended to store all the drift data for future reference, to help catch and interpret changes in the CG-5 drift rate, and to allow investigation of the long-term drift characteristics of the meter.

2.3 Gravimeter Transport

Transport of the gravity meter determines the success of projects. Rough transport will result in large apparent meter drifts, increased reading error, and possibly destruction of the sensor. After years of testing various transport schemes in vehicles and on foot, the following suggestions have been developed:

- Vehicle transport should be in a seat, with the seat belt used to strap the meter down under light compression. This helps keep the meter from tilting or bouncing on bumpy roads.
- The best seat for a gravity meter is the middle of the back seat in a four-door vehicle; this puts the meter closest to the geometric center of the vehicle, resulting in the least acceleration due to bumps and turns.
- If no backseat is available, put the meter in the passenger seat, and strap securely down.
- Don't let items hit the meter while in transport.
- Don't transport the meter on its side; keep it upright at all times.
- Typical car seats deal well with high-frequency vibration, such as from washboard roads. Thus, the real concern is sudden large bumps, such as from potholes or trenches when off-pavement.
- Slower travel with gentle ups and downs does not impact the gravity meter as much as sudden, sharp impacts. So, drive slowly over rough roads.

- Do not bump the meter into the car when putting it in, or taking it out, of the vehicle.
- Walking with the meter on a shoulder strap is worse than holding it in your hand, and trying to keep it stable. Don't let the meter bump against your leg when you walk; hold it away from your body.
- Backpacks are good for long-distance travel on foot, but vehicles are better if available.

2.4 Setting up the CG-5 Gravimeter

This manual will not explain how to run a CG-5; see the Scintrex Operator's Manual for the appropriate button sequences to push.

For precision gravity field measurements, set the instrument settings as follows:

- SURVEY HEADER menu
  - Station Designation system: **XYm** (but we will ignore the line number!)
  - Survey name: Appropriate to the project
  - Operator: Appropriate for the operator
  - Client: Ignored
  - Latitude: ignored, but set to the rough center of a project network if using the meter's Earth Tide Correction (ETC) for field comparisons.
  - Longitude: ignored, but set to the rough center of a project network if using the meter's Earth Tide Correction (ETC) for field comparisons.
  - Zone: ignored
  - GMT difference set correctly for the **clock on the meter**
- AUTOGRAV SETUP menu
  - Tide Correction: **YES** or **NO**; reduction programs will apply a more accurate tide correction, but field comparison of readings will be greatly aided by a rough ETC from the meter.
  - Continuous Tilt: **NO**
  - Auto Rejection: **YES**
  - Terrain Correction: **NO**
  - Seismic Filter: **NO**
  - Save Raw Data: **NO**

- DEFINE THE OPTIONS menu
  - Read Time: 30
  - Factory Flag: 80 (this apparently can't be less than the read time+20 or so ?)
  - # of cycles: 99998 (effectively infinite)
  - Start Delay: 1
  - Line Separation: 0 or 1; the line number will be ignored in processing, so don't worry about line separations or new lines.
  - Station Separation: 1
  - Auto station inc.: **NO**
  - Record Ambient Temp: **YES**

Note that the other settings can be set by operator preference or ignored.

2.5 Reading a Station

1. Remove the meter, in the transport case/bag, from the vehicle **without bumping it** and move to the station.
2. Setup tripod on station, centered on the station, with red-marked leg ("red leg") such that the meter will face the appropriate direction
   - Each station, when located for a project, must have a meter position and facing recorded so that every occupation will setup the meter in the same position and orientation.
   - To ease this, standard procedure is to orient the meter either with a cardinal direction (typically true north), or towards a nearby landmark (e.g. the fire hydrant next to a station, etc.)
3. Place the CG-5 on the tripod, with the upper left corner on the red leg.
4. Protect the meter from bad weather; the meter is "weather resistant", but some operators have had trouble with other meter types being damaged by weather.
   - Use an umbrella to protect the keypad and screen from rain and snow. Plastic bags can also be used, but are often hard to see through for meter setup and operation.
   - Wind is generally not a problem for a CG-5 on concrete or other stable ground; on dirt or other soft ground, wind will likely increase the standard deviations of readings by a factor of 3-50. Nearby trees will increase the standard deviation of stations, but within acceptable limits.

- The meter may be shielded from wind by the vehicle. Vehicles can be parked next to a station without affecting the readings, so long as the vehicle doesn't touch the gravimeter! Pick up and stow the meter before moving the vehicle.
- Other types of portable wind breaks or weather-proofing can be used, so long as they don't touch the gravimeter, and **cannot knock the meter off the tripod due to a wind gust!**

5. Level the instrument using a **bubble level** on the faceplate. This will get the instrument nearly level, which will speed the fine level adjustment, later.
6. Turn on the instrument using the `ON/OFF` button.
7. Increment the station ID (offset) by using the `NEXT STAT.` key (F4).
8. If the `NEXT STAT.` option is not available on the screen, return to the main screen (pressing `CANCEL` or `SETUP`), and then press the `MEASURE CLR` key. Then increment the station ID as above.
9. Press `MEASURE CLR` key to get to the level screen; `F5 (LEVEL)` will also work.
10. Level the meter to within ±5 arcsec in X and Y. This will cause a happy face icon to appear on the levelling screen.
11. Let the meter settle for a few seconds, to be sure the levels are stable and within 5 arcsec in both X and Y.
12. Press F5 to start the measurements; the screen will change to the numeric or graphic measuring screen, depending on which option the operator chose.
13. Watch for the first measurements; these should be reasonable numbers.
    - If the readings are near 0 or 7000 mGal, the meter may be broken. Watch the **standard deviation** (not standard error) of the readings for the first cycle; if less than 0.020 mGal, the meter is likely malfunctioning.
    - Generally projects will not cover regions with gravity changes of more than 100 mGal; changes larger than 100 mGal between stations may indicate a malfunctioning meter.
    - If all station readings consistently have measurements with standard deviations of less than 0.020 mGal, be wary of the meter. Most real field stations have standard deviations (for 30 s averages) of 0.030 mGal or larger. Exceptionally quiet stations will be 0.020 and less, but they are uncommon.

- If previous surveys are available, compare the current readings and standard deviations with previous values; large differences (> 1 mGal in reading, >50% in s.d.) may indicate problems.

14. After checking the first measurements, back away from the meter and start a 12-minute timer.

15. Record the station ID (offset), station name, and start time in the field book. If you forget this step, the data may not be usable in the office!

    - Compare the expected station ID from the field book with the instrument. If there is a question as to whether the station ID (offset) is correct in the instrument, skip station IDs. That is, if the field book indicates this station ID should be 10, but you can't remember if the instrument showed 9 or 10, skip to 11 or 12 at the next station.
    - The list of station IDs can have holes; there is no penalty to skip more than 1 between station IDs. It is better to have station IDs skipped (no station ID 10) than out of order (e.g. station ID 36 is between 9 and 10).

16. Stay **at least** 3 m away from the instrument while reading, and off the concrete pad or station monument with the instrument.

17. Watch for noise and safety concerns:

    - Anything that can cause vibrations should be watched: people near the meter, dogs sniffing the meter, trucks driving nearby, etc.
    - Protect the meter from impact, and tipping, but do **not** worry about people or cars travelling beside (and not touching!) the meter.
    - Pay particular attention near schools when children are present.
    - If necessary, stop the meter and pick it up to prevent impact or tipping of the meter. In extreme cases (e.g. charging bison), just grab the meter and run.

18. After at least 12 minutes, approach the meter and press the `STOP` button (`F5`). If possible, press the button while not standing on the concrete pad or monument.

19. Check the final reading to be sure it is still on-range (as when you started the instrument).

20. Note if the X or Y tilts are different by more than 10 arcsec from the start.

21. Turn off the display using the `ON/OFF` button.

22. Put the meter back into the bag, and clip the cover closed.

23. Replace the meter back into the transport location, and **DON'T FORGET THE TRIPOD**.

24. Record all notes regarding the station, including adverse weather, noise sources (pedestrians, trucks, etc.) in the field book.

25. Move to the next station and repeat.

2.6 Downloading the CG-5

As Scintrex provides comprehensive download instructions in their manual (starting on page 3-59), only additional notes will be presented here. So far, only the USB download has been made to work with the UGS and U of Utah laptops. The USB download setup using the Scintrex-supplied SCTUTIL program and Scintrex USB driver has been verified to work on Windows XP running natively on a laptop, and also as a virtual machine on a Macbook under VMWare Fusion.

SCTUTIL is available for free from Scintrex; look under the Support link at the bottom of the download page. Also get the Scintrex USB driver if setting up a download computer.

Install the SCTUTIL program according to the on-screen instructions or Scintrex's manual. Install the Scintrex USB driver as per its instructions.

Turn on the computer, and let it boot to the desktop. Make sure nothing else is running in the foreground; operators have reported problems with downloading if other programs are running along with SCTUTIL, and no problems if SCTUTIL is the only program on the task bar.

Connect the USB cable as per Scintrex's instructions; see page 3-60 in the CG-5 manual.

Run SCTUTIL and setup for a USB download, as per Scintrex's instructions.

Make sure to produce a text (.TXT) file of the data, as this is the only file type that can be processed with the reduction software!

2.7 Installing the Reduction Software

2.7.1 Installing the Python Software

From the CD, install *Python-2.5.4.msi* first. Then, install *numpy-1.3.0-win32-superpack-python2.5.exe*. Finally, install *scipy-0.7.0-win32-superpack-python2.5.exe*. All installers can be run from the CD by double-clicking the icon.

These installers will setup a working Python 2.5.4 installation, with Tkinter (a GUI builder). Be sure to select all the options when installing the Python package (all options are on by default). The *numpy* and *scipy* packages should be installed using the Python 2.5.4 installation you installed first.

Python versions other than 2.5.4 can be used if you acquire new versions of the *numpy* and *scipy* packages; as of April 2009, pre-built binary packages are only available for Python 2.5.

Installation of Python, *numpy*, and *scipy* should only take a few minutes total, and does not require a reboot.

2.7.2 Installing Micrograv

Extract the ZIP archive of the programs into a directory. Or, copy the *micrograv* folder from the CD to the hard disk.

2.8 Preparing to Reduce Gravity Data

Create a folder for the entire project if it doesn't exist. This folder should have a useful name, such as *WeberRiverASR*. Inside this folder (directory) will eventually be many other folders, one for each campaign. This allows for easy copying of all data and results, but reduces the chance of accidently overwriting data and results.

After downloading the data from the CG-5, create a new directory (folder) for this campaign within the project folder. Preferably, name the folder after the date(s) of the campaign, such as *2009-03* for a campaign in March 2009. All the following files will be placed in the campaign or project folders, to allow for results to be kept from all campaigns at once, without overwriting each other.

Copy the downloaded data, in text format, to the campaign folder. This makes a backup of the data file and makes it easier to import the file into the reduction software. The reduction software defaults to choosing data files with a `.dat` extension, so this extension is recommended for the text data files.

2.8.1 Preparing a "Name" File

Create a text file, using Notepad, Wordpad, or similar, that has the station number and station name, one per line. An example:

```
1 WBB115
2 WRP12
3 WRP17
4 WRP18
...
```

Save this file in the campaign folder. Call it something recognizable, such as "names".

2.8.2 Preparing a "Coordinates" File

To process the gravity data, we need to have accurate coordinates for each station. Thus, at least once for each project we need to build a file with station names, latitudes, longitudes, and elevations. The file also includes a field for elevation changes, if they are known. In general, the elevation change field will be left at 0.

Using a text editor (Wordpad using *Save as text*, Notepad, emacs, etc.), create a file with station name, latitude in decimal degrees (north positive), longitude in decimal degrees (east positive), elevation in meters, and elevation change in centimeters. An example:

```
# Coordinates from GPS and map interpolation
WKRP         41.141159  -111.808245 1459.990 0.0
WRP01 41.135807 -111.921265 1400 0.0
WRP02        41.132546  -111.921041 1362.037 0.0
WRP03 41.135875 -111.937339 1400 0.0
WRP04 41.135290 -111.923927 1400 0.0
WRP05        41.138707  -111.913560 1363.735 0.0
WRP06        41.144369  -111.927628 1360.311 0.0
WRP07        41.142176  -111.933948 1355.781 0.0
WRP08        41.130724  -111.912758 1343.950 0.0
WRP09        41.128914  -111.923269 1362.535 0.0
WRP10        41.135192  -111.929902 1354.874 0.0
WRP11        41.132578  -111.926417 1360.375 0.0
WRP12        41.132591  -111.928806 1359.063 0.0
```

Lines that start with # are ignored as comments. Fields must be separated by a space, but can be separated by many spaces or tabs. There must be all 5 fields on each line, in the order given above: name, lat, lon, elevation, elevation change. Do not add units or direction letters (e.g. N or E) to the fields.

Note that west longitudes are represented by negative longitudes, and southern latitudes are indicated by negative latitudes.

Give latitude and longitude coordinates to 6 decimal places if possible, and elevations to 3 decimal places (mm). Elevation changes, which are in cm, will rarely be known to better than 1 decimal place (mm).

This file should contain all stations ever used in a project, so it can be built once for a project and then used for each campaign.

Save this file into the **project** folder, not the campaign folders. The reduction software looks for a `.coord` extension on coordinate files by default, so it's easiest to use `.coord` as the extension on your coordinate files.

2.8.3 Preparing a "Skip" File

If there are stations or single occupations that should be skipped, due to bad or irrelevant data, place them in a text file in the campaign folder. Call the file something recognizable, such as *skips*.

The file can hold either a station ID or station name on each line. If a station name, **all** occupations of the station name will be skipped in processing. If a station ID, only that single occupation will be skipped.

An example:

```
64.
36.
WBB101A
```

This file will be used to instruct the reduction package to skip station IDs 64., 36., and all the occupations of station WBB101A regardless of ID.

Save this file in the campaign folder.

2.8.4 Making a Parameter File

Once the campaign folder has the name file, the project folder has a coordinate file, and the campaign folder has a skip file (if necessary), we are ready to make the **parameter file** which will hold all the information needed for the reduction program.

Two utilities are provided by the Micrograv package to make the parameter file from the 3 files noted above: *make_parm_file.py* (command-line) and *makeparameters.py* (graphical file choosers). *make_parm_file.py* is run from a command-line (*cmd* on a Windows PC, *Terminal* on a Mac); e.g. `make_parm_file.py names coordinates skips stations.par`.

makeparameters.py is more friendly, as it allows for choosing each of the files from dialog boxes. The order, as noted in the dialog box titles, is ID-name file, coordinate file, skip file (cancel if no skip file), and output file. The resulting parameter file is written to the output filename; name the parameter file with a `.par` extension, which is the default in the reduction software. After an info window noting success, the program dies. The program will fail if there are stations in the ID-name file without coordinates in the coordinate file.

Save the parameter file in the campaign folder; use an extension of `.par` as the reduction software expects this extension by default.

2.9 Reducing Precision Gravity Data

With the parameter file and raw data files, we are ready to reduce the data to single gravity values at each station. The program that will do all the heavy lifting is called *reduce.py*, and it can be run in two different modes: interactive with windows, or as a batch process that uses only files. Interactive mode is useful for the first reduction run of a campaign, as it allows immediate feedback and interactive setting of options. Batch mode is most useful for automated processing of results or re-running a reduction with the same parameters as before. Batch mode processing will not be discussed here; see section 2.11 for some notes on batch processing of gravity data.

- Run *reduce.py* (**in the campaign folder if possible**) and wait for the first dialog box to appear. Multiple windows appear when running the reduction; there is a status window which will have all the messages from the program about what it is doing, and any problems that are encountered. This information will also be written to a **log file** in the current directory, called *reduce.log*. If there are problems reducing data, start by reading through the text log file to see where the problem occurred.

- Unless the campaign was collected with a meter different than a CG-5, accept the default meter type of CG-5. *reduce.py* can also process data obtained with CG-3(M) meters and Aliod-equipped LaCoste & Romberg gravimeters; notes for using those meter types are included in chapter 5.

- Select the gravimeter data file, which is the text file obtained from SCTUTIL.

- Select the parameter file you created from the name file, coordinate file, and optional skip file.

- Check the Station Parameters window to make sure the station names, coordinates, and repeat occupations are correct according to the field notes, etc. The parameter window should look something like:

```
  ID  |    STATION NAME    |REPEAT|  LATITUDE  | LONGITUDE  | ELEVATION|  dZ
     2|WBB101A             |     8|  40.7651770|-111.8495850|  1436.300|  0.0
......|....................|     9|............|............|..........|
     3|LC11                |     5|  40.5975500|-111.8021860|  1477.104|  0.0
......|....................|     7|............|............|..........|
     4|LC12                |     6|  40.6024590|-111.8042980|  1475.164|  0.0
     5|LC11                | None |  40.5975500|-111.8021860|  1477.104|  0.0
     6|LC12                | None |  40.6024590|-111.8042980|  1475.164|  0.0
     7|LC11                | None |  40.5975500|-111.8021860|  1477.104|  0.0
     8|WBB101A             | None |  40.7651770|-111.8495850|  1436.300|  0.0
     9|WBB101A             | None |  40.7651770|-111.8495850|  1436.300|  0.0
```

  `ID` are the station IDs read from the parameter file that must match the station IDs in the data file. `STATION NAME` is taken from the parameter file, and should be checked against the field notes. `REPEAT` shows the station ID of the next repeat occupation of the station, if any. Note that stations with multiple repeats will have extra lines, one per additional repeat, with dots for all fields but the repeat. Check the station repeat list against the field notes, to help catch transcription errors. Also note that repeated occupations of a station are listed, but they do not have repeats listed, as the processing compares all repeats to the first occupation, not to the previous. `LATITUDE` and `LONGITUDE` are the supplied lat/lon coordinates, in decimal degrees. `ELEVATION` should be in meters above sea level, in a common datum for all stations; typically use WGS84 for easy import and comparison to GPS data. `dZ` is an elevation change of this station occupation; it is unique to each occupation to allow for elevation corrections when station occupations are on unstable ground, and different occupations could have slight elevation changes between them.

- When asked for the tare database file, select the previous output file to re-read tares entered from a previous reduction run. Otherwise, cancel the dialog, which will result in no tares being initially applied. The tare database file is almost always ignored.

- Select the reduction options; the defaults are typically correct unless there is a problem with the data or the data came from a meter other than a CG-5. For the first run for each campaign, the defaults are almost certainly correct; after inspecting the reduction log and results, re-run with different options if necessary. All the reduction options are detailed below, including when changes might be necessary. There is almost never a reason to turn off the non-linear instrument drift corrections, as residual instrument drift is the dominant noise source in gravity campaigns.

- Choose an appropriate reference type in the reduction options. The reference value will be entered in the `Reference gravity/station ID` box below the reference type options.

  For exploration surveys, choose the `fixed value` option and enter the difference between known absolute gravity at some station (e.g. 978032.674 mGal) and the measured gravity at the same station (e.g. 3827.654 mGal). The difference (-974205.020 mGal in this example) will be negative, as the reference value is subtracted from the measured gravity. Use of a fixed value reference may take two reduction runs: a first run with a zero reference value to determine the meter value at the absolute station, and then a second run with the appropriate difference.

  For repeat gravity projects, choose the `station ID` option, and enter a station ID in the box below. Choose some station as the reference for reduction of all campaigns. The choice of station is not critical, as any station will remove most of the meter drift between surveys, and further corrections to hold some station or set of stations stable will be applied to the reduced data during interpretation.

The average of the entered station ID and all its repeats will be used as the reference gravity value.

The reference gravity value will be put in the output file, as a comment, for future reference.

- If performing instrument drift corrections, the program will present 4 windows with plots. These are critical plots, and they should always be studied in detail to determine the quality of a campaign and the functioning of the instrument. See the next section (2.9.1) for details of interpreting the plots and assessing the campaign quality.

  It is generally best to save the plots using the `Save` button in the instruction window. The plots are all written at once, to fixed filenames of *dg_none.ps*, *dg_drift.ps*, *drift.ps*, and *repeats.ps* for the pre-drift arrow plot, post-drift arrow plot, drift function plot, and station repeat plot, respectively. The plots are saved as color Postscript (level 2) files, which should be directly printable on most modern printers, or viewable in various software on the reduction computer; Adobe Illustrator, Ghostview, and GIMP are known to work on Windows, and Preview will work on an OS X computer.

- If desired, the mouse can be used in the `Figure 2` window to add tares to the data. This will introduce a static gravity offset at a specified time to all station occupations after that time. To enter a tare, press the `Tare Entry` button, and follow the instructions. Existing tares can be edited by pressing the `Tare Edit` button and using the newly opened window to change the settings of each existing tare. The tares entered here will be saved to the output file, if written, in a format suitable for reading into *reduce.py* for the next reduction run.

  Note: the staircase drift function will automatically handle a tare in the data set by introducing a large offset at the appropriate time. Thus, tare entry is almost never used except in uncommon cases where station repeats are lacking, but a tare is known to have occurred. In general, **do not** enter tares into the data.

- When done with the instrument drift plots and (highly optional) tare entry, press the `Done` button in the instruction window to continue with reduction.

- Wait for the reduction process to complete, and choose an output file. Select a filename in the **campaign** folder.

- Assuming *reduce.py* claims the output file was written, the reduced gravity data will be in the specified output file, in text format. This file will be the basis of further analysis for interpretation, gravity change computations, etc.

2.9.1 Instrument Drift Plots & Tare Entry

There are four plots made by the instrument drift computations: a plot of gravity station repeats before any drift correction, a plot after drift correction with the staircase function, a plot of the staircase and polynomial drift functions, and a plot of the stations, repeats, and their time spans. Each of the four plots has a particular purpose, and all should be inspected for each reduction.

Drift Function Plot

The window `Figure 1` is a plot of the staircase and polynomial drift functions vs. time in hours. An example, taken from real field data, is shown in Figure 2.3. Functions are only computed at station occupations, and connected with straight lines, so non-linear polynomials may show aliasing effects in the plotting. The staircase function is plotted with a black line, with individual station occupations marked with a large black X. Polynomial functions of varying orders are shown as solid colored lines without points. Polynomial functions are shown for comparison, as the field data are corrected using the staircase function.

In general, there is no reason the instrument drift function should be smooth or continuous. However, most of the literature uses polynomial drift functions, so they are computed for comparison.

Pre-drift Arrow Plot

The window labelled `Figure 2` is the plot of gravity stations and their repeats before drift correction. Figure 2.4 shows an example plot saved from the reduction program. The plot shows each station and its repeats as a connected set of points, starting at the time of the first station in the repeat string. Gravity values are differenced to the reading at the first station in the string. Thus, each connected string of points starts at 0 relative gravity, and then shows the changes in gravity for each repeated occupation, in μGal.

Note that the gravity differences do not have error bars for clarity. Inspection of the pre-drift arrow plot can show possible changes in instrument drift rates, tares due to shocks, and significant Earth tide residuals. A good field day will have consistent slopes to all repeats. For CG-5 data, the instrument drift may be predominantly linear and possibly large; the drift rate of the instrument is dominantly linear, but the instrument's supplied drift rate may be incorrect for the current actual drift rate. Hence, field data may show linear drifts of 10s to 100s of μGal/day, either positive or negative. The example plot, in Figure 2.4, shows a consistent linear drift of $\sim$120 μGal/day; this is due to an old drift constant in the meter, and does not indicate poor data.

Random or sudden shifts in drifts for similar time intervals generally indicates shocks to the meter due to handling or transport. Sudden or sporadic changes in the

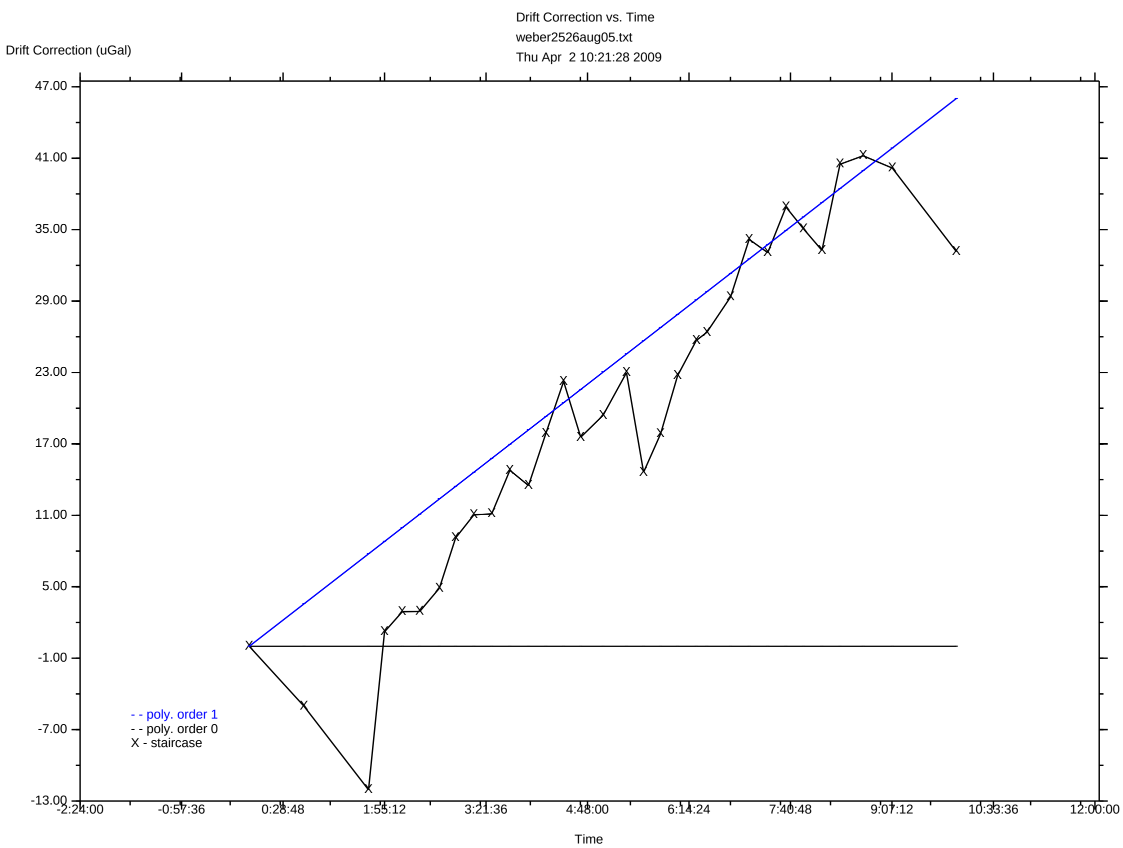

Figure 2.3: Example drift function plot, with all functions shown as solid lines. Station occupations are shown as black Xs for the staircase drift function. Polynomial functions are shown without points. Drift functions are required to start at 0 at the first repeated station. Polynomials are shown for comparison, but corrections are only taken from the staircase function.

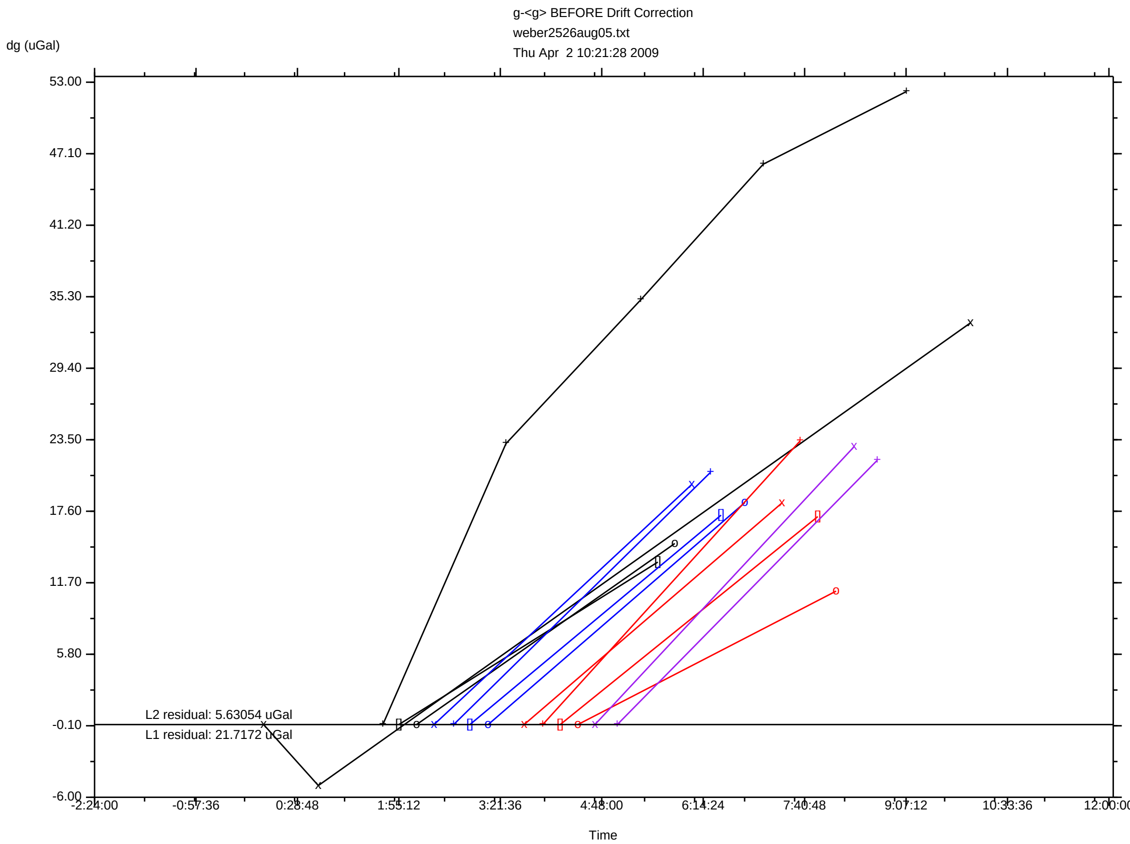

Figure 2.4: Example pre-drift station repeat arrow plot, with stations and repeats shown as connected strings of stations; markers and line color differentiate the strings. L1 and L2 show the L1 and L2 norms of the repeats; smaller numbers indicate smaller overall drift. All station strings start at 0 relative gravity, as gravity values are referenced to the first station in a string. Times are in hours since the first station in the data. Gravity differences represent instrument drift, residual Earth tides, etc.

slopes of the arrows can also indicate electronic or sensor errors in an instrument. Thus, good field data has consistent or **slowly** varying, even if large, slopes for repeats. Note that slow variation in slopes likely indicates a residual Earth-tide-like signal in the data, which may be due to errors in the Earth tide positions or GMT offsets.

Post-drift Arrow Plot

The window `Figure 3` reproduces the pre-drift arrow plot (window `Figure 2`), but after the staircase drift function is removed. Figure 2.5 shows an example using the same data as Figure 2.4. Note that the arrows now all lie along the zero line, and the residuals are 10^{-13} μGal or less. The non-zero (but tiny) residuals are due to the weighted fit of the drift function. If this plot shows a non-zero residual of more than 1-2 μGal, one of the occupations is likely quite poor, and should be inspected carefully.

Station Repeat Plot

The window `Figure 4` plots stations and their repeats vs. time; Figure 2.6 is an example plot for the same data as the other examples. This plot is similar to the arrow plots, but there is no gravity information shown. Instead, the plot shows a station, with the station ID, and then station IDs of the repeats as a connected string of occupations. The repeat strings are offset vertically for clarity. The plot visually depicts the looping schedule of the data, and also allows easy identification of particular stations in the arrow or drift plots for further inspection. Note that the lines connecting stations accurately represents the time interval covered by the loop, and thus what portion of the drift function will be influenced by the loop.

2.9.2 Reduction Options

Here is a description of each of the processing options available in *reduce.py* with notes on choosing values.

- **DATA INPUT** options
  - **Meter Type** - Set interactively at the beginning of the program run, or in the command file with the token `meter_type`. This option determines what format the raw data are in, and thus how to import data for processing. The default is "CG-5," and should only be changed if data were collected with a CG-3/CG-3M or Aliod.
- **PLOT DATA TIME-SERIES** options

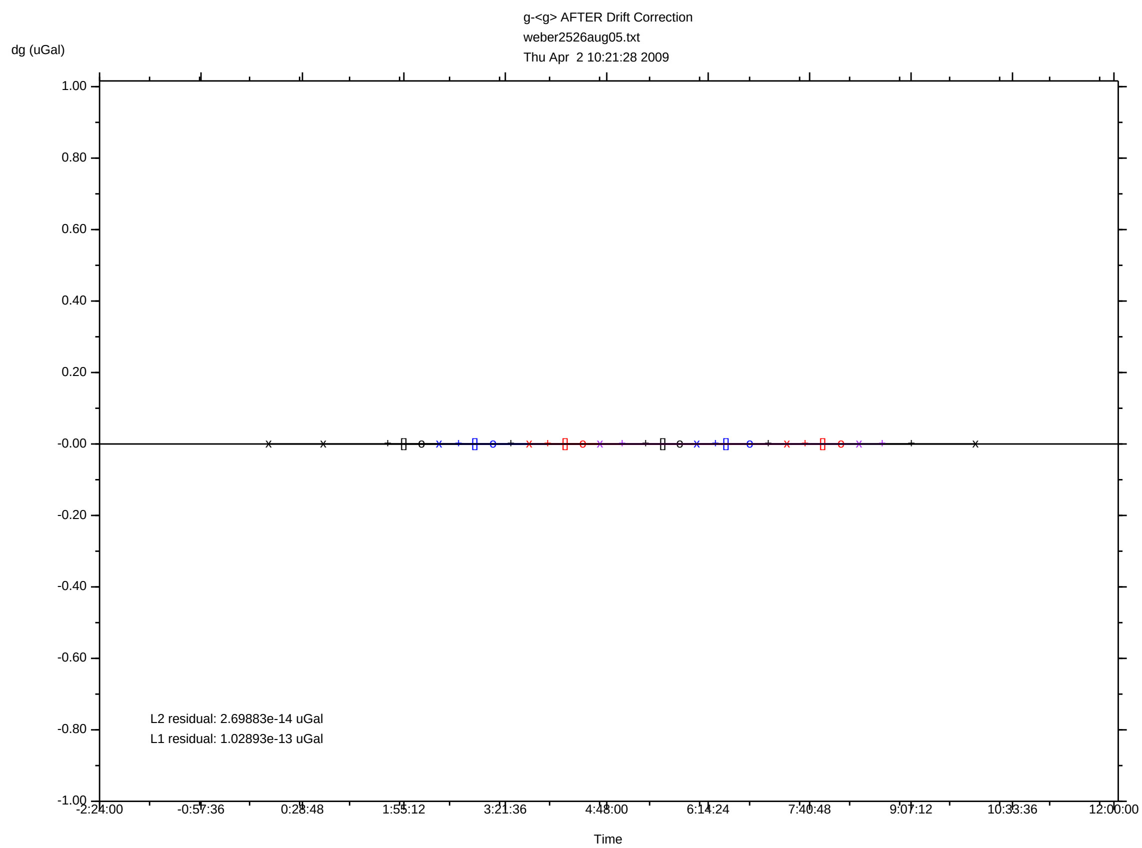

Figure 2.5: Example post-drift station repeat arrow plot, with stations and repeats shown as connected strings of stations. All strings start at 0 relative gravity, as gravity values are referenced to the first station in a string. Times are in hours since the first station in the data. The drift correction is taken from the staircase drift function, which typically results in zero differences after correction. Note the residuals in the range of 10^{-14} μGal.

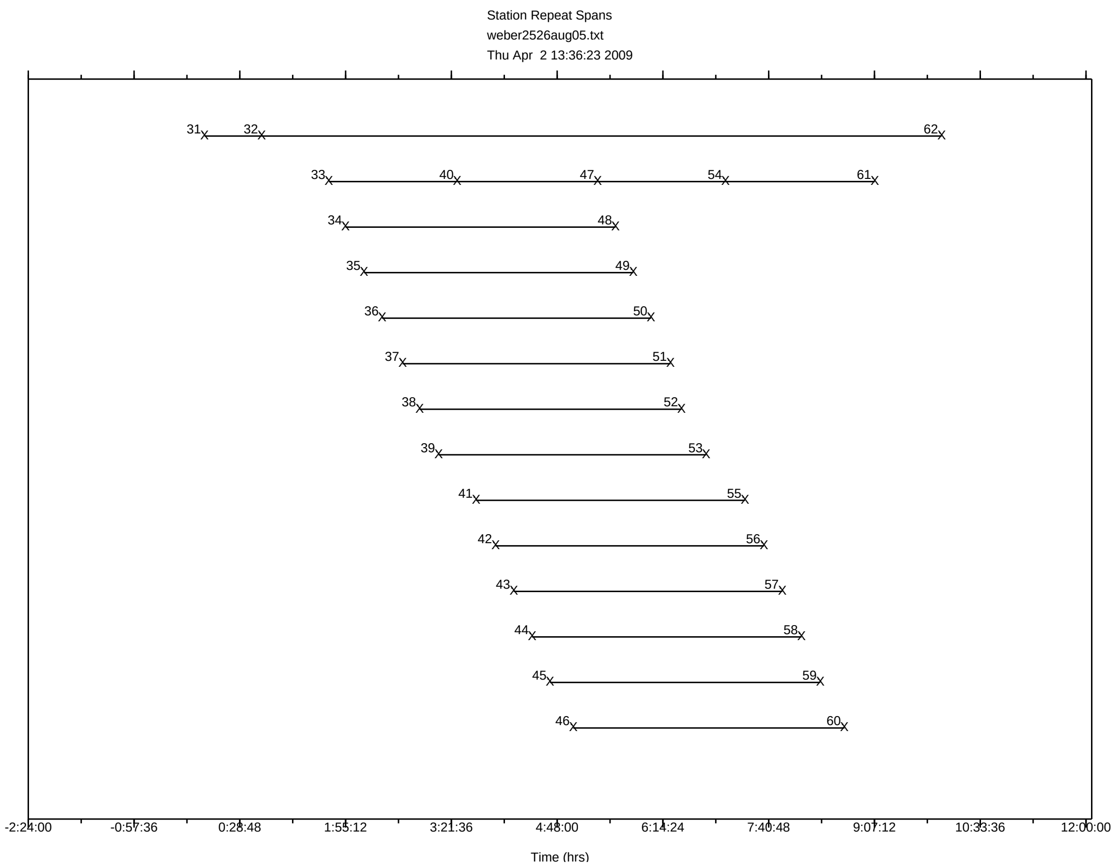

Figure 2.6: Example station repeat plot, with stations and repeats shown as connected strings of stations. Station occupations are labelled with the station ID from the data file. Connected stations are repeats of the first station. Vertical offset is for clarity only. The station labels allow this plot to be used as a map between the arrow and drift plots and the station IDs in the data file for quality checking or data inspection.

- **Plot uncorrected raw data** - If true, a simple data plotting utility will be launched to allow plotting of raw time-series, broken apart by station ID. All the station data is available for plotting, including gravity, standard error, tilts, temperature, etc. The data viewer is reasonably friendly to use, but is designed for working plots and not publication-quality graphics. This option is normally not used except if there are suspected problems with a time-series. It is generally easier to use the stand-alone program *cg5view.py* to look at raw data series.
- **Plot corrected time-series data** - If true, a simple plotting utility will be started after time-series corrections (Earth tide, etc.) but before time-series averaging/analysis. This allows plotting of the data series broken apart by station ID, but after the Earth tide and other time-series corrections. This option is not used, except in cases where a data series is considered suspect from inspection of a previous reduction run.

• **CORRECT RAW READINGS** options

- **Remove meter-applied Earth Tide correction?** - If true, any Earth tide correction applied by a CG-5 or CG-3 meter will be removed from the data series before any other processing is done. This option defaults to true, and should be left true unless the Earth tide correction in the data file is correct for all stations (which is extremely rare) or the Earth tide correction listed in the data file is not the correction that was applied (which has never yet happened).
- **Remove meter-applied linear drift?** - If true, a linear drift term subtracted by the meter will be restored to the raw data before time-series analysis. This option defaults to false, and is only used to check the overall drift rate of the instrument. If the meter-applied linear drift term is removed, the non-linear instrument drift corrections will incorporate the (large) linear drift, and will likely grow to very large values. Also note that removing the linear drift may cause station time-series to show linear trends in quality assurance, so be careful with the QA options, below.
- **Apply Tamura ETC w/parameter file lat/lon?** - If true (default), the Earth tide correction from *Tamura* [1987] using the latitude, longitude, and elevation from the parameter file will be applied to each reading before time-series analysis. **Do not set to true unless the meter-applied ETC is removed!**
- **Correct to fixed atmospheric pressure?** - If true, the code will ask for a file of atmospheric pressure vs. time and will interpolate a gravity correction for changing atmospheric pressure, relative to the supplied base pressure. This correction is so small, it is ignored unless some campaigns are being performed in the middle of hurricanes or typhoons.

- **Base Atmospheric Pressure (mbar)** - The reference pressure, if correcting for atmospheric pressure changes. Given in units of millibar.
- **Force ALL(!) GMT offsets to: (hrs E of GMT)** - If blank (default), the GMT offset encoded in the data file header will be used for computing the Earth tide corrections. If a number is entered here, **all** readings will use the entered value. Note that for areas west of GMT, the offset is negative. This may be a floating point number, if that will help remove residual Earth tide signals.
- **Correct for meter tilt (Aliod ONLY)?** - If true, convert the Aliod tilt measurements into a gravity correction. Aliod measurements are not automatically corrected for instrument tilt, which this corrects. If using a CG-5 or CG-3, **do not turn this option on!** The default is false, where it should stay.

- **STATION OCCUPATION CORRECTIONS** options
  - **Correct for elevation change listed in parameter file?** If true, convert the `dZ` entries in the parameter file to gravity corrections using the global vertical gradient of -3.086 μGal/cm. As most parameter files leave the `dZ` column at 0, this option defaults to off. In some cases, the local vertical gradient is significantly different from the global, in which case the corrections should be done after processing.
  - **Non-linear instrument drift corrections?** - If true (default), compute a non-linear instrument drift function from repeated station occupations, and remove from the occupation gravity values. This option should be left on.
  - **Use weighted fit for drift functions?** - If true (default), both staircase and polynomial drift functions will be found by a weighted inversion, using the occupation standard errors for the weights. This option should be turned off only if a particular occupation has a large standard error, but is somehow actually quite good anyway.
  - **Minimum order for polynomial drift functions** - Enter a number here that is the minimum order for the comparison polynomial drift functions. The default value is 0, which results in a zero line on the drift plot.
  - **Maximum order for polynomial drift functions** - Enter a number here that is the maximum order for the comparison polynomial drift functions. Typical maximums are 3-7 for a single day campaign.

- **TIME-SERIES PROCESSING** options
  - **Use Thiele extrapolation instead of weighted averages?** - If true, gravity time-series readings will be converted to an occupation gravity

value using a rational function extrapolation; see section 5.7 for the math behind the extrapolation.

The default is off, which is correct for CG-5 and CG-3 meters. Turn on for Aliod data.

- **Time-series data are samples, not averages?** - If true, raw data series are sets of individual samples, not sets of averages and standard deviations. The default is false, which is correct for CG-5 and CG-3 data. Set to true for Aliod data.
- **Sample decimation filter radius, in data points** - This number, default of 30, is the half-width of the window to use in despiking and decimating sample time-series before applying Thiele extrapolation. This setting only matters if analyzing sample time-series with Thiele extrapolation. In that case, the default window size is considered a good trade between despiking ability and computation time. Alter only after understanding the math behind the filtering; see section 5.5 and following.
- **Thiele extrapolation equality tolerance** - This setting has no meaning unless using Thiele extrapolation for time-series analysis. In that case, leave the tolerance at $1x10^{-7}$ unless you understand the math behind the Thiele extrapolation; see section 5.5 and following.
- **Skip how many minutes at beginning of time-series when using weighted averages?** - This setting determines how many minutes of data, counted from the reading times, are tossed from the beginning of an occupation to remove transient effects of transport and handling. For CG-3 and CG-5 meters, the default of 3 minutes is fine. Increase the value for meters with long-lived transport effects, but longer times will increase the standard error in occupation gravity values due to decreased readings in the averages. Decrease from the default for meters with extremely short transport relaxation times or projects with no transport noise (perhaps vertical gradient measurements).
- **Maximum # of readings for weighted averages? (-1 to use all)** - If set to a positive number, n, no more than n readings will be used in a weighted average, after removing readings prior to the skip-time set above. The default is -1, and it should rarely be changed. This setting applies to all stations, so remove problematic readings for a particular station by editing the data file.

• **TIME-SERIES QUALITY ASSURANCE** options

- **Correct tmperatures outside threshhold to running average?** - If true, temperature readings in each time-series that are outside a threshhold (see next option) will be replaced with a running window average of in-threshhold data points. The gravity reading will be updated using the new temperature correction and the data file temperature coefficient. This setting should only be used when data has been taken from a CG-3 or CG-5 meter with a malfunctioning temperature readout circuit which mostly works, but occasionally records incorrect temperatures. This option will almost always be left off, the default.

- **Temperature correction threshhold for correction (mK)** - Enter the threshhold for correction. The absolute value of the temperatures is used for threshhold comparisons, so readings with temperatures outside + or -threshhold will be corrected. This option has no effect unless the previous setting is true.
- **Remove raw data with temperatures outside threshhold?** - If true, time-series readings with temperature values outside a threshhold will be dropped from the time-series. This may result in the complete removal of a station! The default is false, as the temperature readout circuits typically work. This option is a more harsh, but preferred, version of the temperature correction option. If possible, remove data rather than correct it, but some data sets may not be able to survive temperature removal without unacceptable loss of stations. In those cases, use the previous correction option instead of this one.
- **Temperature threshhold for removal (mK)** - Set this box to the threshhold, in mK, to remove data from the time-series. Note that both the correction and removal options can be true, and each has its own threshhold. Temperature correction is done after removal, which allows the use of the two options together. This option does not have any effect unless the previous option is true.
- **Reading s.d. warning threshhold (mGal)** - Time-series readings with standard deviations larger than this number will be flagged in the Quality Assurance portion of the reduction for checking. The default (0.050) is typically acceptable for most field data. Set the value larger for noisy campaigns, if the level of warning messages is distracting. This option only controls when warnings are printed for readings; it does not alter the time-series data in any way.
- **Occupation time-series detrend threshhold (uGal/hr)** - This option controls when an occupation time-series will be detrended using a linear fit to all but the first *skip time* minutes of data (see *Skip how many minutes at the beginning...* above for setting this time). Time-series with slopes larger than this value will be pivoted about the data point after *skip time* minutes to bring them to zero slope. This effectively removes trends due to varying tilt without introducing error from transport effects. The default (97.2) has been empirically chosen by inspecting a large number of CG-3 field stations with and without visually-apparent trends. Typical field data is

suitably handled with the default slope; set this number to >90 000 if using Aliod data! Otherwise, modify only if time-series inspection warrants it.

- **REFERENCE GRAVITY** options
  - **Reference station gravity values to**...
    - **fixed value** - If true, all stations will have a fixed value subtracted from the drift-corrected gravity value.
    - **station ID** - If true, the designated station and its repeats will be averaged to compute a reference gravity value, which will be subtracted from all stations. This is the default option, as repeat gravity surveys will need some station assumed fixed.
    - **abs. gravity station** - If true, the designated station and its repeats will be averaged to compute a gravity value which will then be differenced from the absolute gravity value entered. This difference will be subtracted from all stations, which will bring them all to absolute gravity readings based on the absolute gravity value for the chosen station ID.
  - **Reference gravity** - Enter the gravity value to subtract for a fixed value reference, or the absolute gravity value for the selected ID for an absolute gravity station reference in this box. Note that gravity values can be positive or negative, and are in mGal.
  - **Reference station ID** - Enter the station ID of the reference station for station and absolute gravity station reference options. Station IDs are strings, and must match the station ID of an occupation, not a station name! If the station ID cannot be found, the reference gravity will be set to 0!

2.9.3 Checking Reduced Data

Quality Check of Reduced Data

Reduced data should always be inspected using the instrument drift plots and reduction log file. Pay attention to the linear detrending in time-series quality assurance; detrended occupations are more suspect. Also, if computing instrument drift, compare the linear daily rates for stations and repeats. The rates will fluctuate even on good days, due to the extrapolation of short intervals to 24 hr periods. However, pairs with drift rates that are differing signs or more than 30 times different than all the other pairs are suspect.

The most useful plots for checking the reduction results is the pre-drift arrow plot. For a typical field day, this plot should show station pairs following one of 2 patterns: (1) small random drift at the 10-20 μGal level, or (2) predominantly linear drift over the entire day (parallel pairs) with random shifts at the 10-20 μGal level. Station pairs with radically different arrows than the others are suspect.

Before worrying about data, check the scale of the arrow plot; the plot is scaled to the maximum data range, and thus changes each time. Drifts less than 10 μGal are approaching instrument noise (2-5 μGal precision in each station) and should be ignored.

Drifts of milligals (1000s of μGal) generally indicate a naming problem; if the name-ID map file is incorrect, the constructed parameter file (with the repeat information) will claim that two different stations are repeats of one. This will cause an apparent drift of milligals. Hence, if such a giant drift is seen, use the *Station Repeat Span* plot to find the station IDs, and check the field notes to see if the repeats are correct. In one case, this check has led to noting that the field book was wrong! After finding what stations should be repeats, fix the name-ID map file and regenerate the parameter file, then re-run the reduction from scratch.

Other station pairs that are suspect need to be inspected individually. Use the program *cg5view.py*, included in the reduction package, to look at time-series data for each station. The program breaks apart the input data file by station ID, and then plots the various values (gravity, tilt, temp, meter ETC) for each station ID. Use the control window to find the stations under question, and compare the time series. Any current plot can be saved to a Postscript file using the `Save` button, if desired. Typically, it is best to run multiple copies of *cg5view.py*, so each one can be plotting a different station in the repeats.

Inspection of the raw time-series may help explain why a station pair shows a large drift. In some cases, station IDs were not changed between measurements, so one station ID has multiple occupations. In other cases, particular occupations are noticeably worse than others due to external factors such as traffic or weather.

In the case that multiple stations have been recorded to one station ID, the only fix is to edit the raw data file and change the station IDs. This should be done with a text editor (e.g. Notepad), not Excel or Word. Note that the reduction code doesn't care about order of station IDs when processing, so choose an unused number for the new station ID. In the field, when recording station IDs, always opt to skip IDs if there is a question as holes are even easier to ignore.

Troubleshooting Problematic Data

Name-ID map errors are fixed in the name-ID map, which is then used to regenerate the parameter file. Then restart the data reduction with the new parameter file.

Station occupations that have been combined into a single ID (by forgetting to increment the station ID before reading) can be fixed by changing the ID of one of the stations in the data file. Be very careful to maintain the format of the data file when editing. It is also best to save an untouched copy of the data before editing. Document the changes to the data file in your own notes.

Stations with poor-quality data can be dropped by adding their station ID to the `[SKIPS]` section of the parameter file and re-running the reduction. Repeat info, etc. will all be automatically updated after removing the skipped station in the reduction run. This is only really viable if there is a good occupation of the station, and a different occupation is clearly problematic (erratic gravity values, etc.). Always choose the best station time-series to keep, even if the kept station is the repeat of the first occupation.

If more than 10% of stations in the data file have problems due to intermittently faulty measurements, it is unlikely to be possible to simply skip stations and not lose all occupations of some stations or cripple the drift computations with few repeats. In this case, try fixing the data using the temperature correction/removal option (for faulty temperature readings) or the linear detrending (for faulty tilt measurements). Note that if the gravity readings are possibly faulty, skip the station(s) and redo the campaign if necessary.

Due to time constraints, it is not uncommon to have field data with no start or ending measurement at the gravimeter storage site. In this case, the data can be added to the data file by copying the lines from the bracketing long-term drift files. Ideally, the drift files should run right up to meter's transport to the field, and then start immediately upon return to storage. Add the data points and make sure they have unique station IDs, add the IDs to the name-ID map file, add the position of the storage location to the coordinate file, and regenerate the parameter file. Then re-run the reduction with the added data and check the drift based on the long-term data that brackets the field campaign. Note that enough data must be added to allow for losing at least one measurement at the beginning (due to the *skip time* option) and still produce a time-series; generally adding at least 10 measurements is best.

2.10 Reduced Gravity Data Output Format

Reduced data is output in an ASCII format, suitable for direct processing or import into Excel, etc. The format is fixed width, with spaces between fields. Comments start the line with "`#`"; they are for reference and generally not necessary for interpretation.

At the top of the file is a block of comments with the various settings of the reduction run. There is also a timestamp, to help determine if the output file is up-to-date.

Each station has a single line, with the following fields:

- Station name
- Station ID
- Final gravity (mGal)
- Gravity uncertainty (mGal) [2 standard errors]

- Date (year/month/day)
- Time (hours:minutes:seconds)
- Longitude (dec. degrees, E positive)
- Latitude (dec. degrees, N positive)
- Elevation (m)
- Δz (cm)
- Δz correction (mGal)
- Drift correction (mGal)
- Uncorrected gravity (mGal) [gravity after time-series corrections, QA, and analysis; no drift or elevation corrections]
- Unc. gravity uncertainty (mGal) [2 standard errors, from time-series analysis]

Due to the size of the fields, lines are 151 characters long.

2.11 Batch Processing of Gravity Data

reduce.py can be run interactively (the default), or as an automated batch process. In batch mode, the program gets input from a command file, which sets the processing parameters and data sources. The results are written to disk, as with interactive mode. The benefit is that a reduction run may be reproduced exactly using the command file prepared by *reduce.py* when it completes a run.

At the end of a reduction run, after writing output data to disk, *reduce.py* will write a command file in the current directory named `reduce.cmd`. This file contains all the settings and options that were chosen by the operator for the previous reduction run. Thus, the file can be used to reproduce the last reduction run without operator intervention.

Batch mode precludes the use of a mouse for interactive tare input, and will not allow for plotting of data. Batch mode will, by default, prepare Postscript versions of the drift and repeat plots in the current directory, just as if the `SAVE` button was pressed in the drift plot command window.

To run *reduce.py* in batch mode, use the command-line argument `-F` *command_file*, where *command_file* is a filename for the appropriate command file. To replicate the last run, from the same directory, use:

```
reduce.py -F reduce.cmd
```

A log file, `reduce.log`, will be created in the current directory, just as with interactive use. The command file `reduce.cmd` will be overwritten by *reduce.py*.

2.11.1 Command File Format

Command files are lines of key, value pairs. All entries are in plain text. Strings need not be quoted. All options have a default value, which may not be valid for a complete run (e.g. raw data file). The various options, with their meanings, are as follows:

- atm_file - Name of the atmospheric pressure file, if correcting to a base pressure. Can be `NONE` if not correcting to a base pressure.
- atmosphere - If `yes` or 1, correct for atmospheric pressure change.
- base_pressure - Base pressure value for corrections, in mBar.
- batch_drift_plot - If `yes` or 1, save a copy of drift and repeat plots in the current directory.
- detrend - List of station IDs to detrend; generally automatically generated. Separate IDs with commas.
- drift - If 1 or `yes`, remove the instrument-applied drift function.
- dz - If 1 or `yes`, compute a gravity correction from the elevation change column of the parameter file and the global free-air gradient of -0.3086 mGal/m.
- gmt_offset - If set to something other than "None", override the GMT offset of a data file with this value. All stations will have the GMT offset overridden!
- grav_samples - If `yes` or 1, raw data are samples, not averages.
- instrument_drift - If `yes` or 1, compute a non-linear staircase drift function from station repeat info.
- longman - If `yes` or 1, remove a meter-applied Longman ETC, if present.
- max_recs - Use no more than this number of records in processing average time series. If -1, use all records.
- meter_file - Filename of meter information file for Aliod data processing.
- meter_type - Type of raw data. Should be one of `CG-5`, `CG-3`, or `ALIOD`. Case doesn't matter.
- order - Maximum order to use for comparison polynomial drift functions.
- out_name - Output filename for processed gravity data. May have a full path.
- parm_file - Filename for parameter file. May have a full path.

- processed_view - If `yes` or 1, view corrected time-series. Requires a display for plotting.
- raw_file - Filename of raw data. May have a full path.
- raw_view - If `yes` or 1, view uncorrected time-series. Requires a display for plotting.
- ref_type - Type of gravity reference; 1 is fixed value, 2 is station ID, 3 is absolute station (set ID and value).
- ref_id - Station ID for reference, string - must match data file station ID.
- ref_val - Gravity reference value, in mGal
- sigma_threshhold - Threshhold for warning messages of reading s.d. in time-series quality checking.
- skip - Number of minutes to skip at the beginning of a station occupation when using weighted averages to analyze time-series.
- slope_threshhold - Threshhold, in mGal/day, for linear detrending in time-series quality checking.
- start_order - Starting polynomial order for comparison drift functions.
- tamura - If `yes` or 1, apply a Tamura ETC to the data.
- tare_file - Filename for tare information. May have a full path.
- temp_correct - If `yes` or 1, correct readings with temperatures outside the threshhold to a moving average of accepted temperatures.
- temp_correct_debug - If `yes` or 1, provide a printout of temperature corrections in the output file.
- temp_remove - If `yes` or 1, remove readings with temperatures outside a threshhold.
- temp_threshhold - Threshhold for temperature correction.
- temp_threshhold_drop - Threshhold for temperature filtering.
- thiele - If `yes` or 1, apply Thiele extrapolation to time-series, rather than weighted averages.
- thiele_filt_radius - Radius, in data points, for filtering time-series for spikes and decimation when using Thiele extrapolation.

- thiele_tolerance - Equality tolerance for Thiele extrapolation.
- tilt - If `yes` or 1, correct tilt errors using `xe` and `ye` entries. Does not currently work.
- tilt_corr - If `yes` or 1, correct for tilt using constants in the meter file. Useful only for Aliod data!
- weighted_drift - If 1 or `yes`, use weighted fits in drift function inversions.
- xe - Error in X tilt sensor; not currently used.
- ye - Error in Y tilt sensor; not currently used.

Chapter 3

High-Precision Gravity Data Theory & Algorithms

3.1 Station Occupation Time-series Length

When acquiring high-precision gravity data, we set the CG-5 to make many 30-s averages which we then analyze to produce a robust estimate of the true relative gravity at a station. Other techniques have used varying occupation times and reading cycles [e.g. *Sugihara*, 1999; *Sasagawa et al.*, 2003; *Ferguson et al.*, 2007]. The 30-s reading cycle was chosen by inspecting the instantaneous (running) average of five 60-s cycles of a CG-3M (which has the same sensor as the newer CG-5); one such cycle is plotted in Figure 3.1. The running average is recomputed with every sample, along with the standard deviation. No corrections are applied to these statistics during the reading cycle, but are applied to the final average. In all five inspected cases, the instantaneous average reaches a value within 1 μGal of the final value within the first 30 s. It is more valuable to have more stored readings of shorter time, to improve statistical certainty and allow for finer-grained quality control in processing. Read times less than 30 s tend to run into problems with excessive standard deviations due to the short sampling. There is also a built-in minimum 3 s delay between measurement cycles due to the CG-5 and -3 design. This delay becomes steadily more important at shorter read times, as more of the meter's occupation time is spent waiting rather than reading. Thus, we choose a 30 s read time as a balance.

3.2 Solid Earth Tide Corrections

Raw time-series data have a solid Earth tide correction applied using the precise coordinates of each station from the parameter file and the formulas of *Tamura* [1987]; the Longman correction computed by the meter, if present, is first removed.

Solid Earth tides, generated by the gravitational deformation of the Earth, can

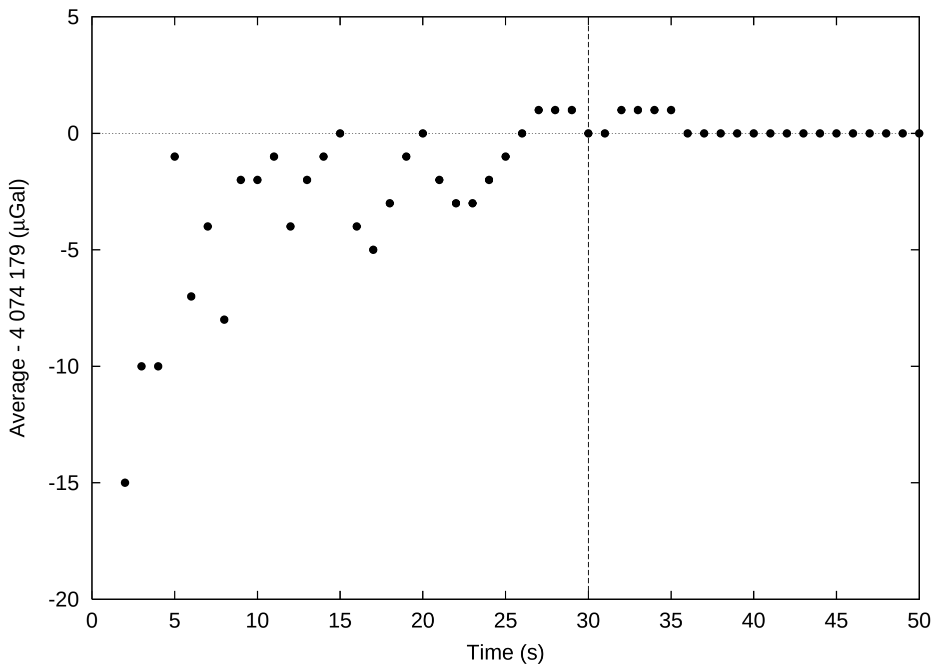

Figure 3.1: Instantaneous (running) average of gravity samples for one reading at a gravity station. Note the small change in the average after 30 s (vertical dotted line); variation is reduced to $\sim$1 μGal.

generate gravity signals with peak-to-trough amplitudes in excess of 0.2 mGal. Computation of the tide can be accomplished starting with observations of the astronomical motion of the planets and Sun, with a result that is accurate to several μGal [*Longman*, 1959]. *Tamura* [1987] fits the amplitudes of a harmonic function to a set of predicted Earth tide potentials. The resulting function, with its empirically-derived constants, is accurate to better than 0.06 μGal [*Wenzel*, 1996]. Either Earth tide algorithm is of sufficient accuracy for high-precision gravity at the several μGal level, but the reduction package uses the harmonic function. Both formulations require an assumed constant for the elastic response of the Earth to the applied stress. The constant has been hard-coded at the standard value of 1.16.

Using the harmonic Earth tide correction from *Tamura* [1987] and correct positions and time offset, there are residual periodic signals evident in long-term records of meters on a fixed location in Salt Lake City, possibly due to loading effects of the Great Salt Lake. Figure 3.2 shows an example residual over time. These data were taken on a single station where a CG-3 was not moved for weeks, removing the possibility that the signals are short-term instrument effects. Attempts were made to remove the residuals by varying the time offset from GMT, the station position used for computation, and the Earth's elastic response parameter. Regardless of the shifts employed, the residuals remained, with peak-to-trough amplitudes of $\sim$5 μGal.

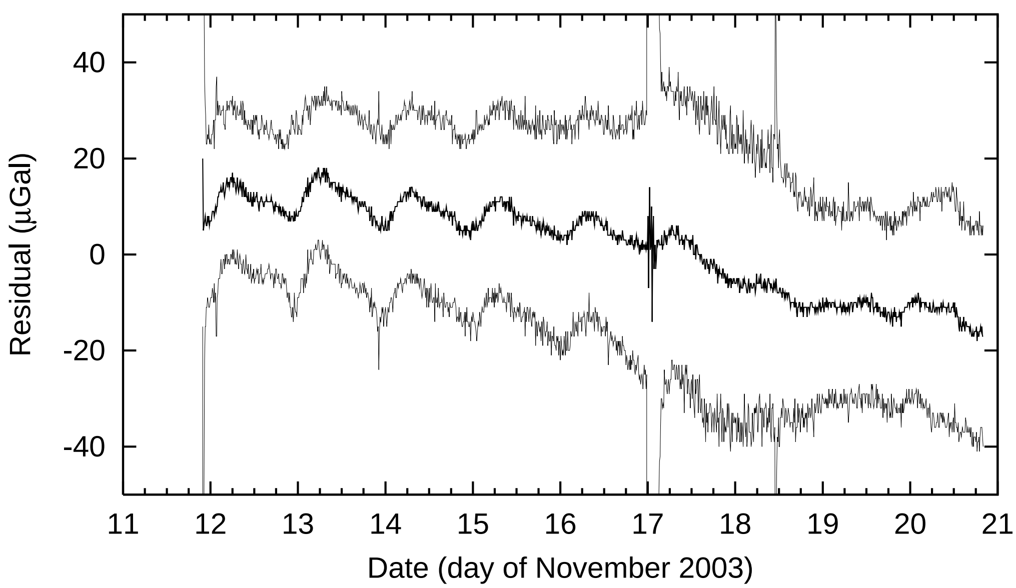

Figure 3.2: Residual gravity signal after removal of the overall average and Earth tide using *Tamura* [1987]. The heavy line is 540-second mean readings minus 4 687 480 μGal; light lines are residual mean plus or minus one standard deviation (σ). The large σ values (truncated at $\pm$50 μGal) indicate surface waves from a distant earthquake.

Applying a fast Fourier transform (FFT) to the time series gives an indication of

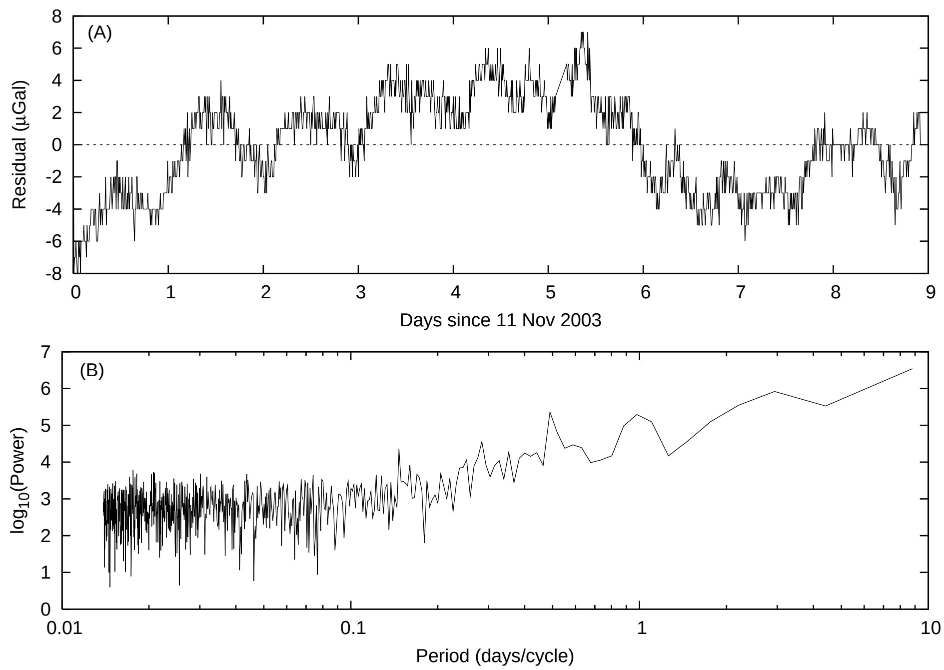

Figure 3.3: Investigation of dominant signal periods for Earth tide residual signals. (A) Residual gravity signal at a fixed site after removal of linear drift and Earth tides computed from [*Tamura*, 1987]. An additional -3 μGal/day drift has been removed compared to Figure 3.2. The sharp gravity changes during the large earthquake have been removed to focus on continuous signals, rather than the earthquake-induced surface waves. (B) Plot of the Fast Fourier Transform power spectrum of panel A as a function of period; the power is not normalized.

the dominant frequencies of the residual signals. Using the residual data shown in Figure 3.2, the results are shown in Figure 3.3. The data from Figure 3.2 have been detrended by an additional -3 μGal/day to remove residual linear drift. Examination of the FFT power spectrum in Figure 3.3B shows highly variable power at the short (sub-day) periods, with increasing power with increasing period. The short-period power is dominated by the longer periods, and represents noise in the residual time-series of Figure 3.3A. Part of the noise is certainly due to the 1 μGal precision of meter measurements; note the residual time-series shows large numbers of quickly oscillating values different by only 1 μGal. There are four prominent "peaks" in the power spectrum, at periods of 0.5, 1, 3, and 9 days/cycle. While attempts to remove the residual signals by varying the Earth tide parameters proved unsuccessful, the long periods of the residual signals allow nonlinear instrument drift functions to remove residual Earth tide signals present in field data.

3.3 Station Time-series Analysis

Each occupation of a station results in a set of readings over approximately 12-15 min. This length of time was chosen to allow for any short-term effects of instrument transport to dissipate while maximizing the number of stations observable in a single field day. A 12-15 min time series also gives enough data to average out small random noise, such as intermittent vehicle traffic. For typical field handling of the instrument, transient effects in the CG-3M decay within 3-5 min, and may take up to 12 min or more in an Aliod-equipped L&R. Figure 3.4 plots the time-series of a long site occupation to determine the relaxation characteristics of CG-3M 9711420. The light dashed lines indicate the envelope of one standard deviation (s.d.) of the measurements. Note the slightly elevated mean values (heavy line) in the first 3 min of measurement, and the near-zero means afterwards. There is no discernible trend in the data after the first 5 min; for a 15 min occupation, there would be at least 10 min of useful data after removing the first 3 to 5 min.

If particularly rough handling is suspected or known, 30 or 60 min occupations of a station are advisable. Figure 3.5 shows two time-series of CG-3M meter readings before and after an extreme shock where the meter was blown off the tripod by an exceptional wind gust. Error envelopes have been omitted for clarity in the plot, and both time-series have been differenced from the average reading of the "before" time series. The "after" time-series was taken immediately after the meter was restored to the tripod, 13 min after the extreme shock. Note the significant trends in the "after" time series for up to 20 min.

Although recorded for testing the elastic relaxation of the gravimeter spring, the time-series in Figure 3.4 is typical of normal stations. The initial trend or deviation in the readings is most likely due to elastic relaxation of the spring from small shocks in transport between stations. The trend is no longer noticeable after the first 3 min, so the initial readings are discarded for the purposes of averaging and analysis.

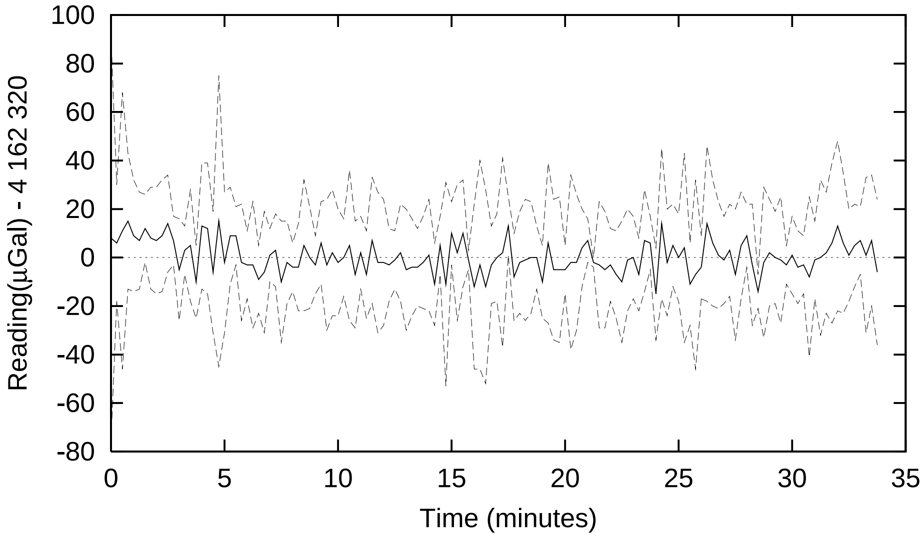

Figure 3.4: Time series of a long site occupation to test elastic relaxation properties of CG-3M gravimeter spring. Readings (heavy line) are shown with one standard deviation error envelope (light dashed lines), differenced from the average reading value. Note the elevated readings in the first three min, and the lack of noticeable trend after 5 min.

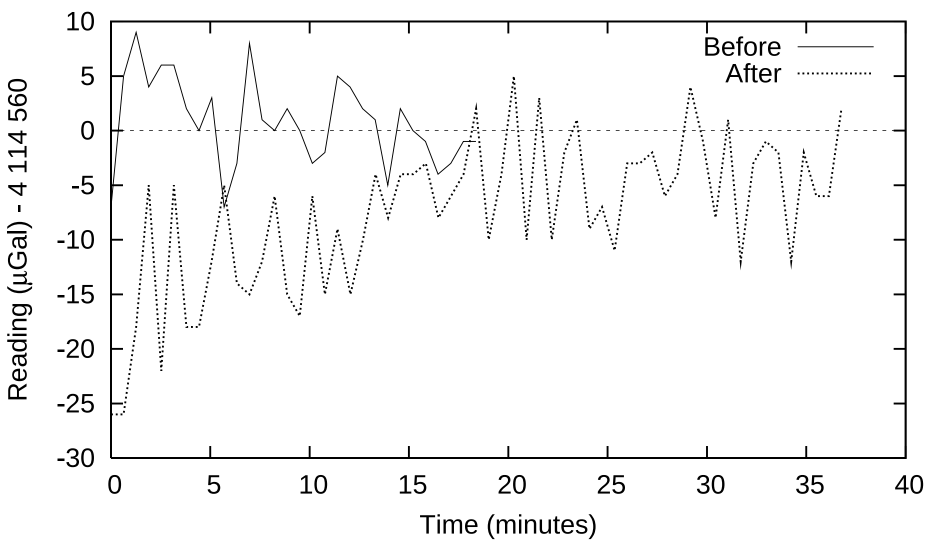

Figure 3.5: Time series before and after an extreme shock to the CG-3M meter. "Before" data taken from a station occupation previous to the severe shock. "After" data taken 13 min after shock at the same location. Error envelopes omitted for clarity.

Although discarded from analysis, the data are valuable for checking the response of the instrument to transport between stations; large trends in the first few minutes can indicate particularly rough transport, and hence the data warrant closer inspection than at other stations.

3.4 Automated Quality Assurance

As an automated check of station occupations, the processing package computes a linear fit to each time-series of readings. If the slope of the linear fit is larger than a defined threshhold, chosen empirically to be 97.2 μGal/hr (based on inspection of field stations with noticeable trends), then the time series is detrended with the fit slope. The procedure excludes the first few (typically 3) min of data, and performs a weighted fit using the inverse of reading standard deviations. This effectively pivots the time-series about the 3 min reading to have no overall trend in the final 9 to 12 min of data. Linear trends in a station occupation time-series are typically due to incorrectly set tilt correction constants, with time-varying tilt of the meter. Since earlier readings have smaller tilt, the linear fit removes the effect of changing tilt while maintaining other signals in the time-series.

3.5 Time-series Averaging

After linear detrending, the time-series is converted to a single value using a weighted average, where the weights (w_i) are taken to be the inverse square of the standard deviations (s.d.) of the readings (g_i). The formulas used to compute the average and two standard errors of the mean are:

$$\begin{aligned} \bar{g} &= \frac{\sum w_i g_i}{\sum w_i} \\ \bar{\sigma} &= 2\left(\frac{\sum w_i}{N}\right)^{-1/2} \end{aligned}$$

where overbars denote average values, w_i is the weight of the ith data point, g_i is the gravity value of the ith point, and N is the number of readings in the time-series.

The weighted average is a robust number, but it does include the possibility of unnecessarily down-weighting good data. The downweighting problem comes from the use of the s.d. as the weight; it has been noted in long-term drift records that some sources of noise, such as earthquakes, do not significantly change the mean reading, but strongly affect the s.d. For the case of earthquakes, the s.d. can vary by as much as an order of magnitude. When these data are used in the weighted average, it receives a small weight due to the large s.d., even though the reading value is still quite accurate.

Attempts to improve on the scheme of a weighted average of 15 min time-series included testing with both exponential function fitting and rational function extrapolation algorithms. It was hoped that by using an alternate algorithm, it would be possible to obtain a long-duration (15 min) result from a short (8-12 min) station occupation. Both schemes failed to produce results consistent with weighted averages in at least some real field data, and hence are not used with CG-5 data.

3.6 Post-Series Corrections

After reducing the station occupation time series to a single value, corrections for elevation change and instrument drift are applied.

3.6.1 Elevation Change Corrections

Station locations, while assumed to have static topography over a monitoring project lifetime, are quite likely to have varying elevations. Exploitation-induced elevation changes are known to occur in geothermal fields [*Allis and Hunt*, 1986], and seasonal elevation changes are seen in ground water reservoirs [*Merteens et al.*, 1998]. These changes are known to reach 5 cm per year, and may be larger in some systems. Given a typical vertical gravity gradient of -0.3086 mGal/m, elevation changes translate to a possible gravity effect of 15 μGal. Hence, it is desirable to have elevation control on all stations during a project, and the elevations should have an absolute accuracy of better than 3 cm.

After averaging the time-series, the station occupations are corrected for known elevation changes. The correction is computed from a constant global gradient of -3.086 μGal/cm. Local vertical gradients can vary from the typical free-air gradient [e.g., *Arnet et al.*, 1997], but this variation, while potentially exceeding 1 μGal/cm, is assumed to be small in most situations. Large changes in vertical gradient can always be handled using a post-reduction correction, or by mapping the gravity effect at the actual vertical gradient into an effective elevation change at the standard gradient. Moreover, a change of 1 μGal/cm in the vertical gradient, with subsidence of a few centimeters, causes an error still within the acceptable error bound of 5 μGal.

Measurements of the gradient using multiple heights at a fixed point suffer from the limited range of available heights [*Butler*, 1984], and extremely local terrain effects; for example, stations located on large cement blocks have measured vertical gradients significantly different from the free-air correction, but the measured gradients do not accurately reflect the gravity effect of ground subsidence. The cement block moves with the ground, and the actual gravity effect is closer to the free-air correction than the local gradient. Hence, for the relatively small elevation changes of concern in most monitoring projects, the global gradient of -3.086 μGal/cm is assumed.

To compensate for elevation changes, it is necessary to have elevation changes between surveys that are accurate to 3 cm vertically, and preferable to have accuracy of better than 1 cm vertically. Several methods are available to obtain this information, among them leveling and differential GPS. Leveling is the historical method, but is labor intensive and slow. Differential GPS is relatively quick and cheap, and can be sufficiently accurate.

3.6.2 Instrument Drift

Instrument drift corrections are inherently empirical calculations, although historically they have been handled by fitting simple theoretical functions to gravity differences. Unfortunately, no particular continuous function is necessarily the best choice for modeling gravimeter drift, making the choice of function part of the craft of gravity measurements. For exploration gravity, with acceptable accuracy of 100 μGal, linear drift models are often used for each campaign day. Previously reported high-precision techniques used large numbers of reoccupations and/or multiple gravity meters to help detect nonlinear instrument drift and tares [e.g. *Whitcomb et al.*, 1980; *Jachens et al.*, 1981; *Dragert et al.*, 1981; *Allis and Hunt*, 1986; *Hunt and Kissling*, 1994; *Andres and Pederson*, 1993; *Budetta and Carbone*, 1997; *Battaglia et al.*, 1999; *Sasagawa et al.*, 2003; *Ferguson et al.*, 2007], which were removed by fitting of low-order polynomial functions (sometimes with least-squares adjustment [e.g. *Jachens et al.*, 1981]). The maximum useful complexity in the drift function is set by the available drift information in the campaign, in the form of station reoccupations.

The fundamental assumption of all campaign drift functions is that the value of gravity should not change at a single station over the length of a single campaign. Under this assumption, repeated occupations of stations in a single campaign allows measurement and correction for instrument drift, regardless of cause.

Repeat schemes for a project should create many repeats of a daily local base (which may change each campaign day!) with 4 or more occupations throughout the day, particularly in the early loops. The extra repeats of a local base station allows a better representation of highly nonlinear drift curves with any drift function, but particularly the "staircase" function used in the reduction package. Early repeats of the local base station also allows identification of possible tares in the early part of the campaign day; such tares will be removed by the staircase drift function, but only if they can be correctly located within a loop.

It is important to note the first station in a campaign has zero drift by assumption; there is no information in the campaign data to indicate possible errors in the first station. For this reason, a very quiet station must always be used as the first occupation of a campaign, such as a location where the gravity meter has been undisturbed for at least 12 hours.

For processing campaigns of abritrary length and complexity, we have developed a drift function based on arbitrary offsets between stations; a chain of offsets forms a "staircase" function. By construction, the staircase function is nonlinear, discontinuous, handles arbitrary length campaigns, and does not assume an *a priori* functional

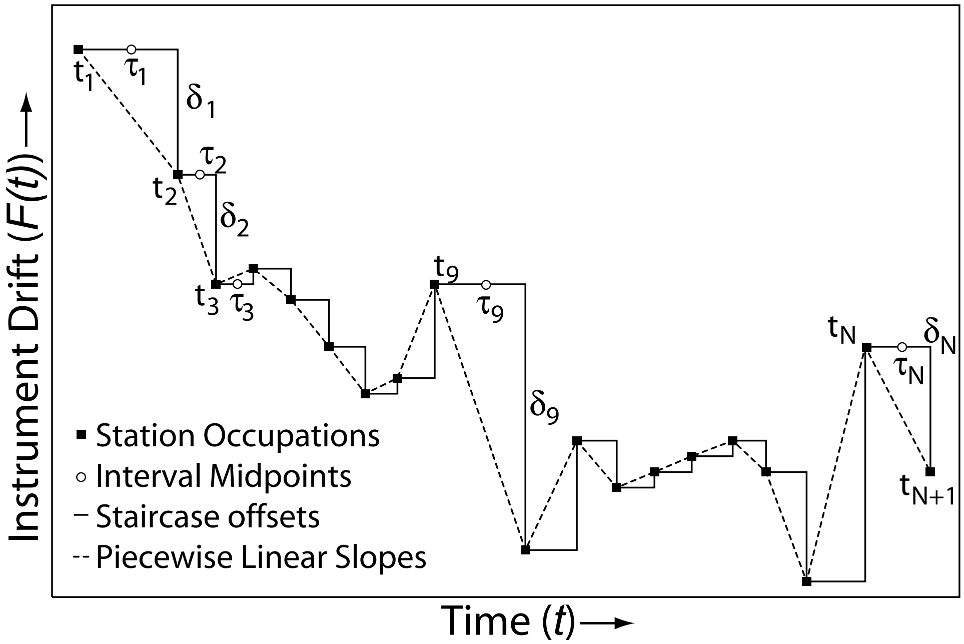

Figure 3.6: Schematic drift curve representation by the staircase drift function. Labels refer to the mathematical development in the text; δ_i is the drift for the ith interval, t_i the time of the ith occupation, and τ_i is the midpoint time of the ith interval.

form of the drift curve. A schematic staircase function is shown in Figure 3.6. The offsets between readings can be viewed as stair steps or linear trends; the drift function is only computed at station occupations, so the behavior of the function between station occupations is irrelevant. The stair step formulation simplifies the equations (developed below), but both views are equally correct. The staircase function produces effectively zero residuals for all campaigns and is therefore error-preserving.

3.7 Math of the Staircase Drift Function

We construct a staircase drift function as follows. First, we label all station occupations with a number, i, starting from 1. We define n as the total number of station occupations in the survey; thus, there are $N = n - 1$ intervals between ocupations. Let g_i be the gravity reading and t_i the time of the ith occupation. For every interval between two sequential occupations, we define τ_k as the midpoint time; note that there are N such times.

The drift function, $F(t)$, is defined as

$$F(t) = \sum_{k=1}^{N} C_k(t)\delta_k, \tag{3.1}$$

where $C_k(t)$ is the coefficient for the kth interval taken from the set $\{0, 1\}$, and δ_k is the drift for that interval. Note that the length of the interval is not used, nor are there any constraints on the change between sequential δ_k values. Thus, the function $F(t)$ is immediately applicable to surveys of arbitrary size and duration.

The value of $C_k(t)$ is found from

$$C_k(t) = \begin{cases} 0 & t < \tau_k \\ 1 & t \geq \tau_k \end{cases} \tag{3.2}$$

We label stations and repeat occupations with subscripts, so the first occupation of station A becomes A_0, the first repeat of station A becomes A_1, the second A_2, etc. Next, we construct a mapping, $\Gamma(\alpha_k) = i$, where α_k varies over all stations (α) and occupations of the station ($k = (0, 1, \ldots)$), and i represents the occupation number; this mapping is used below to build the drift observation equations.

A set of δ_k must be found such that the equation set

$$D_{\Gamma(\alpha_k)\Gamma(\alpha_{k+1})} = [g_{\Gamma(\alpha_{k+1})} - F(t_{\Gamma(\alpha_{k+1})})] - [g_{\Gamma(\alpha_k)} - F(t_{\Gamma(\alpha_k)})] \tag{3.3}$$

is minimized for all α_k (stations and repeated occupations).

This inversion problem is generally under-determined; there are $n - 1$ unknowns, and at most $n/2$ equations. Additional equations result from noting that the difference between stations should be constant over a campaign. Hence, we construct additional difference of differences equations:

$$D_{\Gamma(\alpha_k)\Gamma(\alpha_{k+1})\Gamma(\alpha_j)\Gamma(\alpha_{j+1})} = D_{\Gamma(\alpha_{k+1})\Gamma(\alpha_{j+1})} - D_{\Gamma(\alpha_k)\Gamma(\alpha_j)}, \tag{3.4}$$

where k and j can vary over all stations that have repeated occupations. To remove redundant equations, only differences that are forward in time are used; that is, only pairs of stations where the time of occupation $\Gamma(\alpha_j)$ is later than that of occupation $\Gamma(\alpha_k)$. Also note that if a station has multiple repeated occupations, these are used by forming the above equation once for each repeat with the original occupation. If the survey does not have enough repeated stations, the problem may still be under-determined even with the differences of differences. Results of an under-determined system may still be valid; in all work so far, inversion matrices have been nonsingular even with an under-determined problem.

Define M as the total number of equations; the number of equations for repeated occupations plus the number of equations for interstation differences. To solve the (most likely) over-determined minimization problem, it is convenient to recast it into a matrix form and add data weighting factors. The vectors $\hat{m}$ and $\hat{d}$ are defined by

$$\hat{m} = [\delta_1, \delta_2, \ldots, \delta_N]^T \tag{3.5}$$

$$\hat{d} = [D_{\Gamma(A_0)\Gamma(A_1)}, D_{\Gamma(B_0)\Gamma(B_1)}, \ldots, D_{\Gamma(A_0)\Gamma(A_1)\Gamma(B_0)\Gamma(B_1)}, \ldots]^T \tag{3.6}$$

and the $M \times N$ operator matrix $\hat{A}$ is defined by

$$\hat{A} = [A_{lm}], \tag{3.7}$$

where A_{lm} is chosen according to the following algorithm. If l is a row with an equation for a repeated occupation, then

$$A_{lm} = \begin{cases} 1 & t_i < t_m < t_{i'} \\ 0 & \text{otherwise} \end{cases} \tag{3.8}$$

where i is the occupation and i' the repeated occupation represented by the lth row.

If row l is a difference of differences equation, then

$$A_{lm} = \begin{cases} -1 & t_i < t_m < t_j \\ 0 & t_{i'} < t_m < t_j \\ 1 & t_{i'} < t_m < t_{j'} \\ 0 & \text{otherwise} \end{cases} \tag{3.9}$$

where i, i', j, and j' are the occupations and repeats represented by the lth row. Define the square $M \times M$ data weighting matrix by

$$\hat{W} = [W_{ll}] \tag{3.10}$$

where W_{ll} is computed by the following algorithm: If row l is a repeated occupation equation,

$$W_{ll} = \frac{1}{\sqrt{\sigma_i^2 + \sigma_{i'}^2}} \tag{3.11}$$

otherwise,

$$W_{ll} = \frac{1}{\sqrt{\sigma_i^2 + \sigma_{i'}^2 + \sigma_j^2 + \sigma_{j'}^2}}. \tag{3.12}$$

where i, i', j, and j' are the occupations and repeats represented by the lth row.

The matrix equation to be solved is

$$\hat{W}\hat{A}\hat{m} = \hat{W}\hat{d}. \tag{3.13}$$

As the operator is linear, the problem can be solved in a direct linear least-squares inversion, which can be written in matrix notation as

$$\hat{m} = (\hat{A}^T\hat{W}^2\hat{A})^{-1}\hat{A}^T\hat{W}^2\hat{d} = \hat{Q}^{-1}\hat{A}^2\hat{W}^2\hat{d}, \tag{3.14}$$

where $\hat{Q}$ is the diagonal matrix found from the singular value decomposition of $\hat{A}$.

Once $\hat{m}$ is found by equation 3.14, the drift for any station can be computed from a specialization of equation 3.1. As the drift function is always being computed on an interval boundary,

$$F(t_k) = F(k) = \sum_{i=1}^{k-1} \delta_i. \tag{3.15}$$

For stations that have no repeats, the inversion process (being a least-squares process) assigns a drift value that is a linear interpolation between the nearest repeated stations.

3.8 Reference Station

To handle instrument drift between surveys, one or more stations are assumed "stable," meaning no gravity change over time. The apparent gravity changes at the reference station(s) provide a correction to the measured gravity changes to compute actual change. Any signals at the reference stations are superimposed (in an inverted manner) on all other gravity stations. Since in the inter-mountain West, a known-stable site is generally not available, it is common to pick a set of reference stations, whose average will be held at zero. In general, reference stations should be determined by the location of absolute gravity measurements during campaigns; gravity changes at reference sites are then directly measured, and the sites need not be stable.

Chapter 4

Exploration Gravity with a CG-5

Exploration gravity projects can use the same software and general procedures as for precision gravity monitoring as described in Chapter 2, but there are some changes required by the large areas and allowed by the lower accuracy requirements.

This chapter will present the changes to the station repeat schedule and station occupation times that allow for large areas to be covered at acceptable accuracy.

4.1 Station Network Design

Unlike monitoring projects, the station network required for an exploration project will likely be sparse and relatively uniform. Networks will need to be designed with the end interpretative technique in mind, since acquiring sparse 2-D transects makes 3-D models nearly impossible, and grids are wasetful for a handful of 2-D transect models. Once the exploration area is known, the target must be identified in terms of size (lateral and thickness extent), depth of burial, and density contrast. These estimates need to be realistic enough to allow simple modeling to determine:

1. expected gravity signal at the surface, and therefore accuracy requirement; if accuracy of better than 0.05 mGal is needed, the exploration project will need to use the full monitoring-project techniques described in Chapter 2.

2. expected horizontal extent of signal, and therefore the station spacing needed to resolve it, which sets the number of stations to measure. Expect to only have time to put in a minimum number of stations at the maximum acceptable spacing.

3. vertical accuracy needed at stations, and thus the time-on-station for GPS measurements. This may require a second crew doing nothing but GPS, and a system for marking where gravity stations were placed!

4. how useful the existing gravity station database can be in the target area, and thus how many new stations will be needed, and where.

If stations must be reoccupied, such as 2 crews in the field - one for gravity and one for GPS, stations must be marked fairly exactly. Spray chalk and flagging will be helpful here. It is typically wasteful to install a true monument, as these stations will not be measured over many months or years. If doing combined gravity and GPS at once, stations need not be marked on the ground at all! With modern GPS receivers and processing, stations can be put at any convenient location, rather than requiring spot elevations or benchmarks. Thus, it is advantageous to perform GPS and gravity acquisition at once, and to mark the locations on a planning map for field reference, but not worry about marking the new stations for reoccupation. This also reduces the footprint of a gravity campaign to foot and tire prints!

4.2 Station Repeat Schemes

Since the acceptable accuracy of exploration projects is typically 0.05 mGal to 1 mGal, fewer repeat occupations are needed to correct for non-linear instrument drift. Thus, typical exploration projects can get away with 2-3 measurements on a local base per day, with no repeated stations during the day. This allows covering 15-30 stations per day, rather than the 10-15 of a gravity monitoring project. Note that the larger areas covered in exploration projects will reduce the station coverage, due to longer transport times.

4.3 Reference Stations

Unlike gravity monitoring, the primary job of the reference station in exploration projects is to provide a tie to an absolute gravity value from the relative gravity values measured by a CG-5 (or other) meter. Thus, all exploration projects must include at least one station with a known absolute gravity value, and preferably many. Also, the absolute gravity values should be as recent as possible, to track possible long-term changes in gravity at the reference sites.

If attempting to include existing gravity data in the exploration project (always a good idea), be sure to measure some of the old stations to check that the gravity values derived in the new survey tie to the old values, or construct a mapping (typically a static shift) to integrate new values into the existing database.

Existing gravity stations for the U.S. is available from the National Geospatial Intelligence Agency (formerly DMA) through the National Geodetic Survey of NOAA, the Pan-American Center for Earth Sciences (PACES) at the U of Texas-El Paso (`http:research.utep.eduDefault.aspx`), and individual workers with copies of the UTEP or NGS databases. The UTEP PACES database is more up-to-date than the 1999 NGS version and therefore includes more gravity data since the NGS version. Note that the PACES website can crash and require up to a day to restore, so be patient if attempting to grab large data coverages. Whatever database is used, it will likely have to be reformatted to be suitable for use in OASISMontaj, USGS processing flow, or whatever analysis system will be used.

4.4 Acquisition Time

Since the accuracy requirements for exploration stations is so relaxed compared to monitoring projects, the time on each station can be significantly reduced. In practice, a minimum station collection time of 5-6 min appears adequate for exploration projects with target accuracies of 0.05 mGal. The acquisition setup is identical as for monitoring projects, just cut the time in half.

Moreover, the lower accuracy allows the use of less-precise GPS systems, including averaging versions of hiking GPS receivers and the survey-grade receivers from Trimble, etc. that include ArcPad. Follow the directions of the receiver manufacturer for acquiring sufficient accuracy elevation values; this may require post-processing to a nearby geodetic-grade base station.

Recall that the typical free-air gradient is -0.3086 mGal/m, which means that an exploration project seeking 0.1 mGal accuracy must know the station elevations to 0.3 m or better (1 ft). This is achievable with a Trimble hand-held unit that is post-processed, according to Trimble. Other alternatives could be an L1-only unit set on the faceplate or a fixed-height tripod for an L1/L2 unit recording for only 5-10 minutes, perhaps in a kinematic or real-time kinematic mode. Regardless, the trade-off between time-on-station and vertical accuracy will typically be solved by accepting less vertical accuracy to keep the time-on-station to 10-15 min or less; otherwise the coverage of extensive exploration areas at reasonable station spacing requires more field time than available.

4.5 Processing

Data processing is unchanged from monitoring projects, and the use of the high-precision software allows improved exploration results compared to many older schemes. However, the processing does not stop with the reduction from raw data file to relative gravity values.

Relative gravity values need to be differenced to a known gravity value to get an actual observed gravity value at each station. This is most easily accomplished by referencing to a station and then adding the known absolute gravity value at that station to all.

4.5.1 Anomaly Computations

As you will no doubt recall from your geophysics course work, the most common interprative anomaly for gravity is the Complete Bouguer Anomaly, which requires terrain, Bouguer, and free-air corrections to the theoretical gravity at each station. The most recent paper on the standards for computing these corrections and the basic theoretical gravity values is *Hinze et al.*. Note that there are several different possibilities for the typical processing flow, including OASISMontaj, the USGS potential field package, and a U of Utah package building on the micrograv package introduced in Chapter 2.

Chapter 5

Using Other Gravimeters

5.1 CG-3M Gravity Data Acquisition

Like the CG-5, the CG-3M automatically stores measurements so each occupation of a station results in a time-series of readings. The instrument sensor of a CG-3M is identical to the sensor of a CG-5, although the control consoles are quite different. Data collection with a CG-3M is very similar to use of a CG-5; the station occupation procedure is unchanged. Set the read time to 31, and the cycle time to 38. Set the `Cal after` setting to 10. Set `Mode` to Cycling, `Auto-repeat` to off, `Auto-record` to on. Turn off `Seismic filter` and `Cont. Tilt. Corr.`. Turn on `Auto Reject` and Tide Correct, and enter appropriate lat and lon for the center of the project. Set `GMT Diff` to the appropriate hours for the gravimeter's time; **the GMT offset in the meter has opposite sign to normal convention - west of GMT is positive!**

Download of a CG-3M can be accomplished by any computer with a serial port. See the Scintrex manual for details. Once downloaded, process the CG-3M data like CG-5 data. However, note that the CG-3M stores station IDs as numbers with a "." after them, so be sure to add the period in the ID-name file when making a parameter file.

5.2 Long-term Drift Records of an Aliod

Due to the limited storage space of the handheld computer logging the Aliod output, and the design flaw that loses all data if the memory fills, we use a laptop to log data directly from the Aliod. This means the data file format is different from the standard GravLog output, but is well documented in the code for *aliod-monitor*. *aliod-monitor* is only know to work on Unix-based systems, but should be easily portable to other architectures.

5.3 Aliod Field Data Acquisition

An Aliod-equipped L&R meter stores a significantly different data stream, although the field technique is nearly identical. As with the CG-5, stations are occupied for 12-15 minutes of continuous recording. Unlike the CG-5, recorded data are the 1 Hz samples, with no averaging or corrections. Use of the GravLog program on the iQue palmtop computer for logging allows continuous recording at 1 Hz, once the station number has been entered.

Since Earth tide corrections will be applied later based on precise positions, the GravLog Earth tide computations are ignored, so it is not necessary to input lat/lon into GravLog. Also note that the timestamps for data samples are taken from the iQue clock, which needs to be set to a known GMT offset, and accurate to within 1 minute or better.

Station names in GravLog are constructed from a prefix (5 characters), 4-digit zero-padded number, and an optional suffix. Do not use a suffix, and ignore the prefix - the processing program will remove the prefix when parsing the data file. Station numbers, originally zero-padded, are reformatted to simple numbers with no padding or decimal point when read by the processing package. Hence, when constructing the reduction input/parameter files, use integers (e.g. “1”, “2”) rather than decimals (“1.”, “2.”) as for the CG-3M.

5.3.1 Station Occupation Length

Based on existing testing with real field conditions in October 2007, stations should be occupied for a minimum of 10 min, with a good standard being a minimum of 12 min. It is clear in some cases that elastic relaxation (transport & unclamping) effects may still cause noticeable trending after 10-12 min of measurements. However, given a standard field day with 35 occupations, lengthening occupations to 15 min adds 2 hrs to the field day, which may well be too long for accurate work. Hence, a compromise time of 12 minutes is adopted as with the CG-5.

An example raw station timeseries, with filtering and extrapolation results, is shown in Figure 5.1; the filtering and extrapolation procedure will be covered in greater detail later. The raw time series shows a distinct non-linear trend characteristic of elastic relaxation after unclamping. Due to the clamp holding the beam at the extreme low end of the range, the relaxation trends are always from lower gravity readings to higher. Note the large spike between 660 and 680 s. This spike, of $\sim$2 mGal scale, is likely due to a near-meter disturbance (jogger running by the meter). Filtering is used to remove such spikes and decimate the data stream for numerical precision reasons before extrapolating to an infinite-time asymptote.

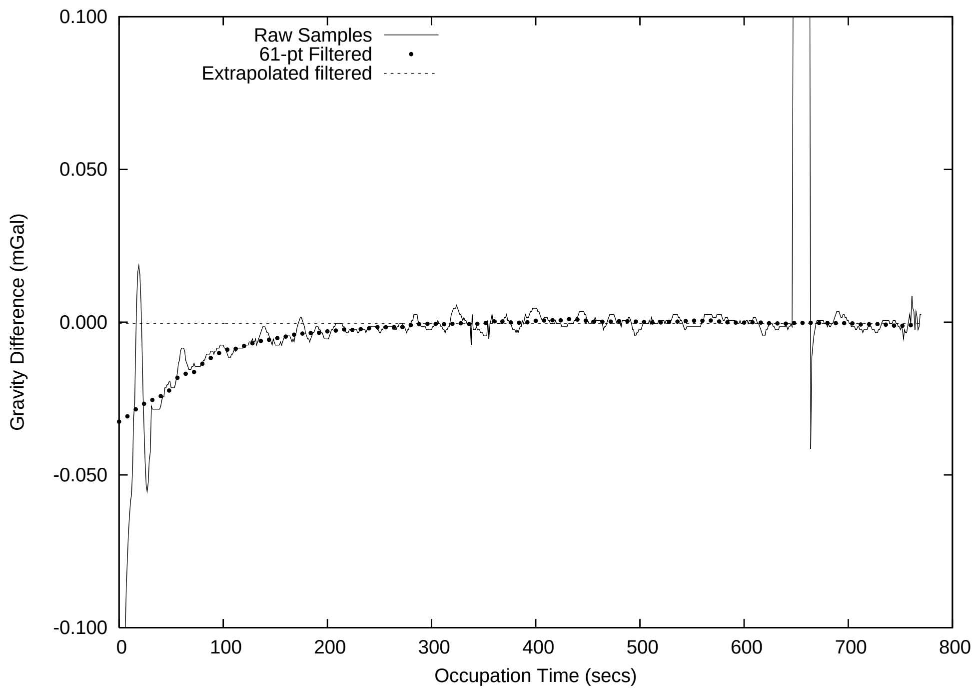

Figure 5.1: Raw, filtered, and extrapolated time series for station occupation 20 of 9 Oct 2007. The raw time series exhibits most of the common traits in Aliod-collected station data - rise from lower readings to higher, spikes from near-meter disturbances, and 30-60 s signals from environmental noise. Filtered time series uses an 8 s offset between points, with a 61-point centered window. Thiele extrapolation of the filtered series results in the constant value shown.

5.3.2 Temperature Compensation

The Aliod-equipped meter provides a coarse (0.1 C) temperature readout of the meter temperature for each measurement. According to the L&R literature, the temperature dependance of the metal zero-length spring is significantly less than that of the fused-quartz fiber in a CG-5 or -3. Hence, the relatively coarse temperature readings are used as a check of meter operation, not a source for compensation.

There is no data to indicate that a meter with apparently good voltage and temperature has significant temperature effects in the range of desireable field conditions (-10 to 30 C). Without a better temperature readout circuit, there is not enough precision in the Aliod data stream to produce a useful temperature correction to the data; instead, temperature measurements are useful only as a coarse quality control measure for removing/skipping data.

5.3.3 Voltage Fluctuations

With good batteries (typically 7-7.5 Ah), the meter and electronics should get at least 8 hours of measurements before needing a change. Battery changes, unlike the CG-3M, cannot be done without losing power for a second or so. This does not let the meter cool significantly, nor does it cause loss of constants in the electronics. Swapping batteries at 10.5-11 V is recommended. Note that bad batteries will typically show good voltages for 4 hrs or so, and then drop from 11-11.5 V to 8-10 V in 5-10 min; this is an indication that the battery needs to be tossed and replaced with a new one.

Current data from readings with bad batteries where voltages dropped to <10 V show no gravity reading change with dropping voltage. Regardless, readings with voltages <10.5 V should be checked for consistency with previous, high voltage readings.

5.3.4 Tilt Corrections

Aliod-equipped meters provide a stream of cross and long level measurements, in counter units. Unlike the CG-3M, these have not been converted to a displacement from maximum gravity in arc-sec. The counter range is reported by L&R to be between [0, 65535]. There is a procedure in the Aliod manual for adjusting the levels to maximum gravity using the front display; this does not guarantee a maximum gravity counter value of 32767 or so.

Without testing to see how the gravity value changes depending on the deviation from "zero" (maximum gravity/nulled level galvo), we cannot apply a tilt correction to readings. To produce the necessary numbers, we need to know how many counter values are represented by 1 division on the galvo, and how much this affects the gravity reading. This is essentially determining the cross- and long-level sensitivities and zero errors as for the x,y tilt meters on the CG-3M; however, the equations and procedures of the CG-3M manual can't be used unmodified!

A theoretical correction to the gravity values, given a tilt in cross- and long-level directions, can be derived from a coordinate rotation. Define ψ as the angle (in radians) to be rotated about the x axis, and θ as the angle (in radians) to be rotated about the y axis. Since we only measure a vertical component, rotations about the z axis are irrelevant and set to 0. Note that the angles ψ and θ are the angles we measure with the levels in the meter.

Now, compute a rotation from a theoretical, untilted frame to the tilted frame. By Euler's rotation theorem, we can compute a single rotation matrix A from the individual rotations about x, y, and z axes (B, C, D matrices) from $A = BCD$. Since there is no rotation about the z axis, $D = I$, and the resulting matrix is $A = BC$. B and C are defined as,

$$B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{bmatrix}$$

$$C = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$

Hence,

$$A = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ \sin\psi\sin\theta & \cos\psi & \sin\psi\cos\theta \\ \cos\psi\sin\theta & -\sin\psi & \cos\psi\cos\theta \end{bmatrix}$$

Application of this rotation matrix to an unrotated frame yields the rotated (measured) gravity value, g',

$$g' = g\cos\psi\cos\theta$$

since only the vertical component of the gravity field is measured. Hence, an unrotated gravity value can be computed from the measured angles and gravity values as

$$g = \frac{g'}{\cos\psi\cos\theta}$$

This is significantly different from the development of a tilt correction in the Scintrex manual, which is of unknown origin.

All that remains to implement a tilt correction for Aliod data is the mapping from level counter value to radians from local vertical. This will also require knowledge of the "zero" tilt counter value in the cross- and long-level directions. All of which must be empirically derived for each meter, and then stored in the meter info file.

5.4 Aliod Time-series Analysis

Aliod time series are significantly different from the CG-5 data, and require a significantly different processing approach. Aliod-generated data show much longer relaxation times, typically in the 5-10 minute range. Although this leaves little (or no)

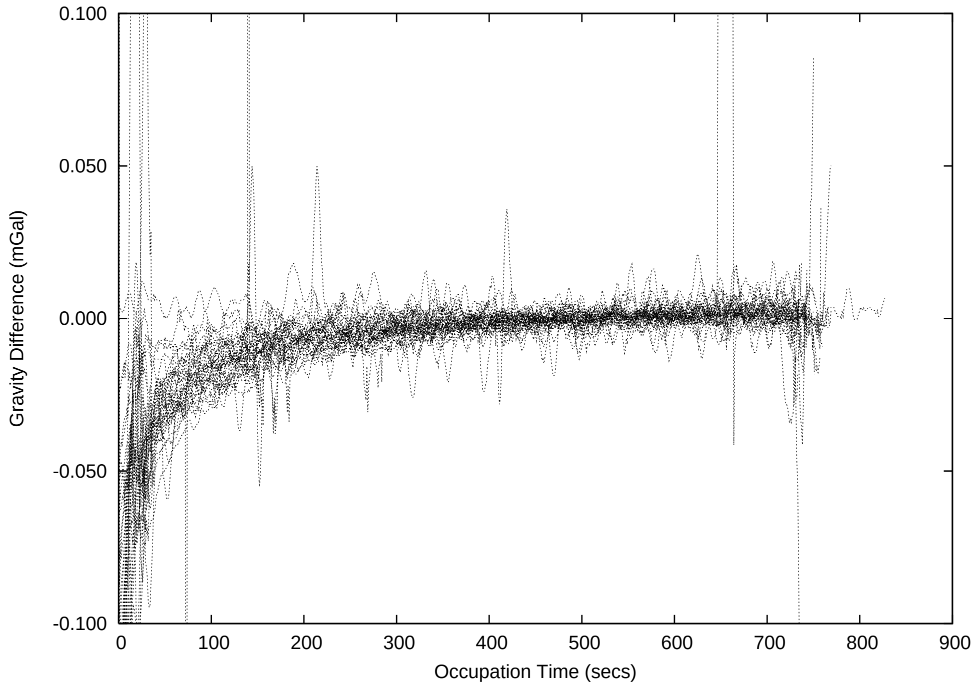

Figure 5.2: Time series of 35 stations from 9 Oct 2007, without filtering. All stations are shown relative to their despiked station average. Gravity range held at [-0.100, 0.100] mGal to enhance detail. Note the strong trends in the first 300 sec due to elastic relaxation (unclamping), except for one station that was taken after the meter was left unclamped overnight. Large spikes are also visible, which may be >2 mGal in size; these are removed by the despiking filter.

data in a 12 min occupation for using a simple average, extrapolation techniques allow useful, accurate gravity determinations from a 12 min occupation. Figure 5.2 plots the raw time series of 35 stations from 9 Oct 2007, relative to their despiked averages. The stations show significant trends in the first 300 sec, with some stations having visible trends to 700+ sec. One station, which was taken after leaving the meter unclamped overnight, shows no consistent trend, reinforcing the conclusion that the trends are due to transport and (mostly) unclamping. Note that the large spikes in many stations are due to near-meter disturbances, and the spikes may be >2 mGal in magnitude. The despiking filter detailed below was applied before averaging, to center all stations near zero.

Note that due to the longer relaxation time of the Aliod meter, linear detrending, as with CG-5 or CG-3M data, is not advisable for those data; early time readings are more likely incorrect due to elastic relaxation from unclamping, and hence detrending tends to severely underestimate the gravity reading at a site, possibly by as much as 0.1 mGal. When processing Aliod data, disable detrending by setting the threshold to >90000 μGal/hr.

Raw gravity sample series are first corrected for Earth tides using the *Tamura*

[1987] formulation. Samples are then filtered for spikes and decimated to a maximum of 100 points covering the time span of the station occupation. The filtered, decimated series is then extrapolated to infinite time for the station reading.

5.5 Despiking Filter

The raw time series is first despiked using a multiple-pass despiking filter. For each point in the series, a centered window (truncated to series length) of (typically) 61 points is used to find the local average (S_i) and standard deviation (σ_i). Then, all points where $|s_i - S_i| > N\sigma_i$ are replaced with S_i; the multiplier N is found from interpolation of Chauvenet's table for data rejection using the actual width of the window for the point i. This procedure (find S_i, σ_i, replace s_i where $|s_i - S_i| > N\sigma_i$) is repeated until no points are replaced, up to 5000 times. The resulting series is used as the despiked series for further filtering and extrapolation.

Note that the ability of the despiking filter to remove spikes is strongly dependant on the choice of window size; small windows will leave residual spikes, and very large windows take long times to compute. By inspecting the test data, spikes are at most 15-30 seconds wide. Thus, a 61 point window (30 points on either side) was chosen to gain maximum despiking with minimum computation time.

5.6 Series Decimation

Due to the finite precision of a computer, and the need to use the (e^j, S_j) series for extrapolation, it is impractical to use a sequence of more than ~500 points ($exp(500)$ is at the limit of a double-precision float). Thus, the 700+ point series from a 12 min occupation must be reduced in size. Moreover, Thiele extrapolation is quite sensitive to trends in the end of the provided series. To minimize short-term trends in the series, and decimate the data to a maximum of 100 points, the despiked time series is filtered as follows:

The despiked time series, typically 720-800 points long, is decimated to at most 100 points by computing an offset of

$$O = \mathrm{ceil}(N/100)$$

where N is the number of points in the original series. A moving average filter, with a 61-point centered window, then starts at the first point and marches through the despiked series moving O points each time. Windows are truncated at series boundaries, so beginning and ending points are averaged over a window of 31-60 points. Note that the window is much larger than O, so neighboring filtered points have significant overlap in their windows; this leads to a smoother filtered series, which is desireable.

The result of the moving average filter is a series of at most 100 points which is quite smooth, and fairly resistant to trends at the end of the time series.

5.7 Thiele Extrapolation of Filtered Series

The despiked, decimated, filtered time series is then used as the input to a Thiele extrapolation to estimate the infinite-time gravity reading.

Thiele extrapolation [*Stenger*, 1993] is a procedure for estimating the value of a function at infinity given some number of points at finite values. It uses a constructed rational function (computed as a "ρ-table") to represent the function at known points, and the value of the rational function is found at infinity. Since the algorithm needs only a set of known points, it can be applied to series of data as well as analytic functions.

For the Thiele algorithm to be accurate, it is necessary and sufficient for the sequence to have a limit at infinity, and for the sequence to approach that limit "sufficiently" fast. Here, "sufficiently" rapid convergence is achieved if

$$S - S_j = O(e^{-j\alpha}) \text{ as } (j \to \inf) \tag{5.1}$$

or

$$S - S_j = O(\frac{1}{Cj^\alpha}) \text{ as } (j \to \inf) \tag{5.2}$$

where S is the sequence value at infinity, S_j is the sequence value for some j, $O()$ indicates the order operator, and C and α are constants. For the case of exponential convergence (equation 5.1), it is necessary to apply the Thiele algorithm to the sequence (e^j, S_j); algebraic convergence uses the sequence (j, S_j). Based on the results of the exponential function inversion testing, it is apparent that station time series do converge at a rate of $O(e^{-j\alpha})$ and hence the algorithm can be accurately applied.

Note that algebraic convergence is only sufficient if a sequence is **monotonic**. As gravity time series are never monotonic, algebraic convergence is not sufficient, and only exponential convergence can be used. In practice, attempts using an algebraic sequence result in divide-by-zero errors, as the non-monotonic nature of the sequence causes entries in the ρ-table to be opposite in sign, equal in magnitude, which results in a divide by zero. Also note that since the sequence (e^j, S_j) has to be used, there is a limit of ~500 points in a sequence, as e^{500} approaches the limit of a double-precision float, and overflow errors occur.

While the sequence to be extrapolated must converge within an exponential envelope, the sequence cannot have any repeated elements; that is, if $S_j = S_{j+1}$ for any j, the algorithm will result in a divide-by-zero when constructing the rational function table. To prevent this, the filtered gravity sequence is examined, and adjacent repeated values are removed. To prevent divide-by-zero due to adjacent, nearly-equal values becoming equal in finite precision results, the equality test is relaxed to remove adjacent points that are within a specified tolerance (defaulting to 10^{-7}). This

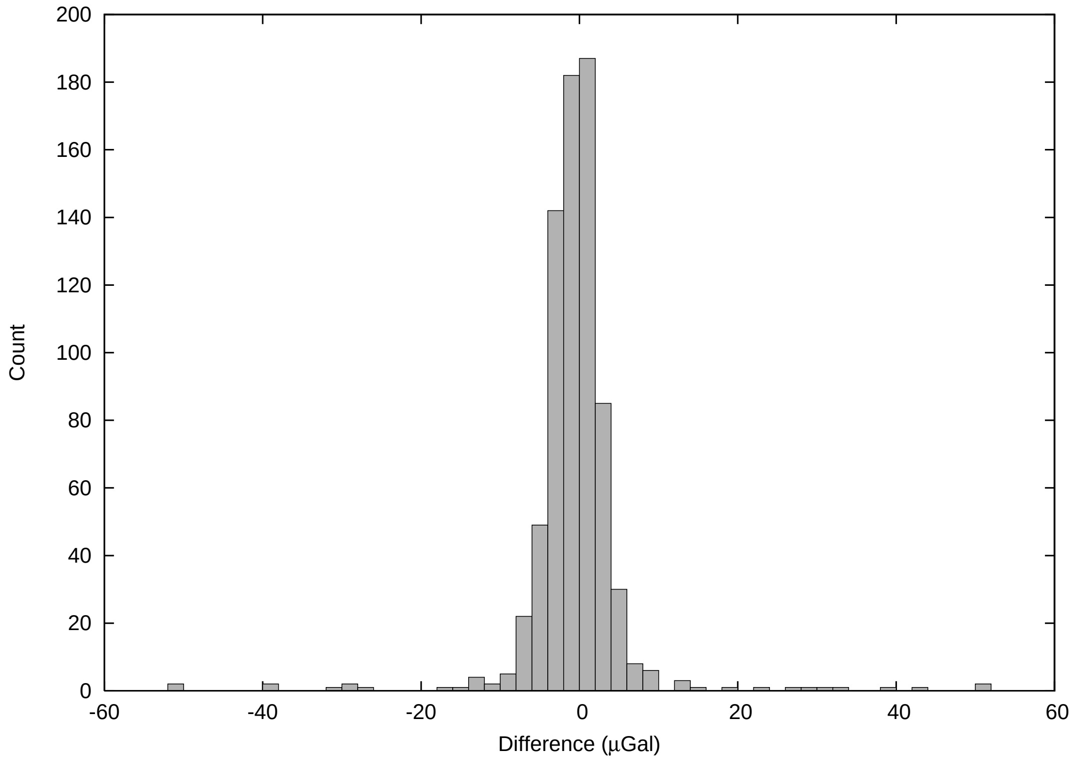

Figure 5.3: Histogram of differences between Thiele extrapolation result and weighted average for full time series. Of the 746 time series, 100 have a difference >5 μGal. Note the strong central peak and greater number of negative differences; extrapolation is more often underestimating the gravity compared to a weighted average.

particular case is commonly encountered in a raw time series filtered to at most 100 points, where the window offset is small (e.g. 5 points) with a relatively large window (e.g. 61 points) - the averaging of two points nearby can result in averages that are strictly different, but at the limits of machine precision; the construction of the rational function then creates a difference less than machine precision, and a divide-by-zero results.

Testing the algorithm with a data set of 746 CG-3M station time series yields results close to weighted averages in most cases. The difference between the result of the Thiele algorithm and the weighted average is shown in Figure 5.3. A total of 100 series have differences greater than 5 μGal, or about 13%. Only 30 series (4%) have a difference greater than 10 μGal. Moreover, the extrapolation algorithm remained finite for all stations, even those with consistent trends. Trends which cause a large difference (>10 μGal) in the extrapolation result compared to an average generally exceed the 97 μGal/hr detrending threshhold typically used.

Extrapolation is more likely to underestimate the gravity value than overestimate; the distribution in Figure 5.3 is weighted towards the negative numbers. Figure

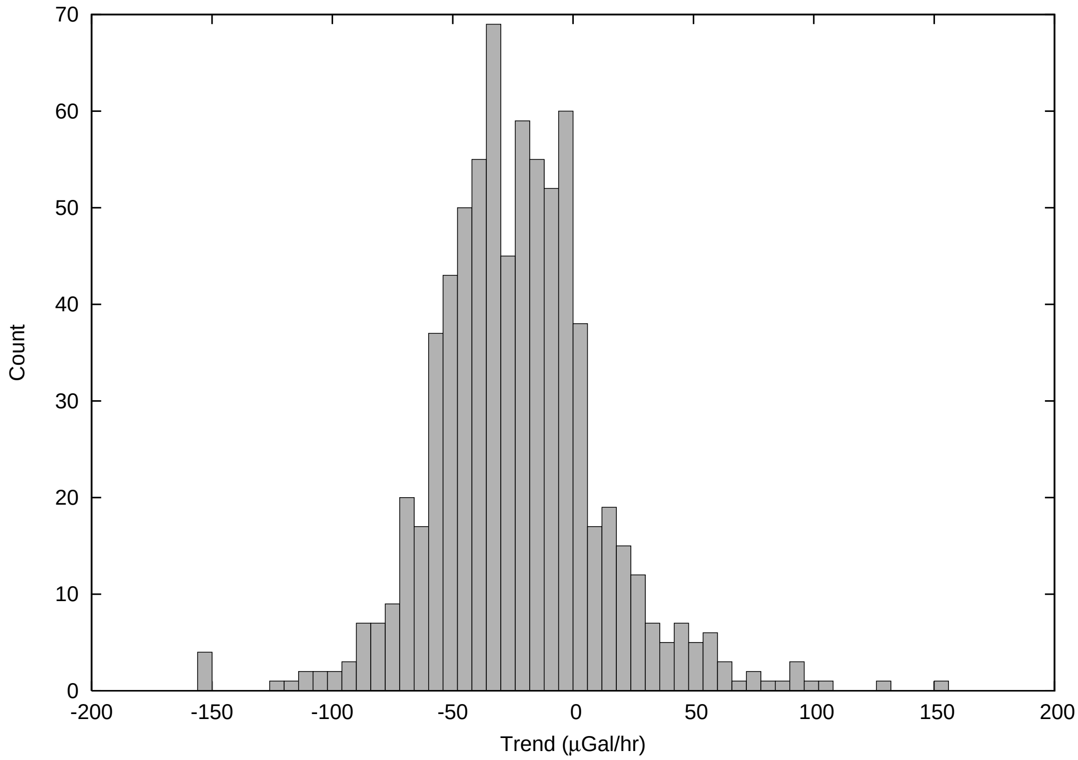

Figure 5.4: Histogram of trend values for all test series. Trends are reported in 6 μGal/hr intervals. Values above or below ± 150 μGal/hr are collected in the ± 150 μGal/hr bins. Note the peak, which is centered around -27 μGal/hr, not 0. This shift is the origin of the asymmetry in differences between extrapolation results and averages, shown in Figure 5.3.

5.4 shows a histogram of trend value, in μGal/hr, for all the test series. Note the symmetrical peak, which is centered around -27 μGal/hr. This shifted distribution influences the Thiele extrapolation results by causing the extrapolation to more often underestimate the weighted average result. These trends would not be removed by the analysis algorithm, as they are not above the 97 μGal/hr threshhold.

One reason for using the Thiele algorithm is to test if it is possible to extrapolate essentially the same value for a short time series as for a longer one. If possible, this would reduce the minimum time spent reading a station, and allow more stations to be occupied in a day, increasing the number of stations that can be used in a study. To test the difference between extrapolation with short and long time series, the full 15 min series were truncated after 16 records ($\sim$8 min) and input to the Thiele algorithm. Figure 5.5 shows the histogram of differences between the extrapolation results and averages. The general shape is the same as for full time-series results, but the peak has widened; more series are showing significant differences. Of the 746 series, 165 (22.1%) have differences >5 μGal in magnitude, and 46 (6.2%) are

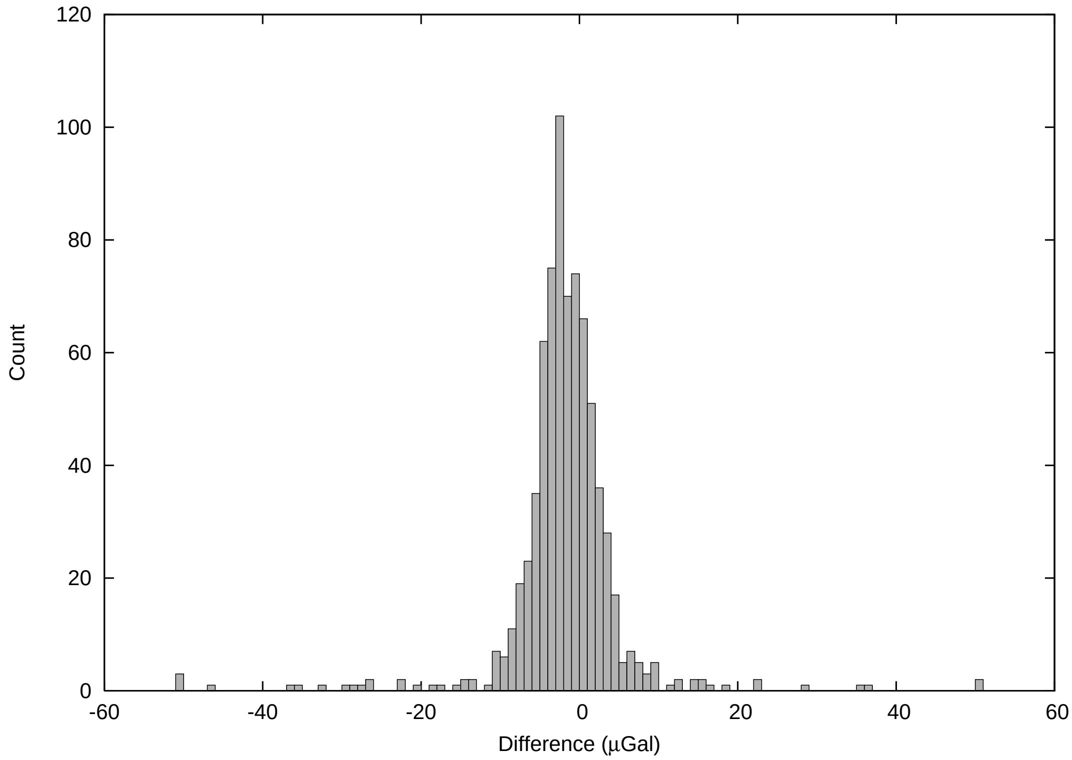

Figure 5.5: Histogram of differences between weighted average of full time series, and Thiele extrapolation on 16 record (<8 min) time series. Of the 746 time series, 165 have a difference >5 μGal.

different by more than 10 μGal. While larger than for full 15 min series, the number of stations significantly different from averages is still acceptable. A survey using shortened time series would have larger error bounds, as there is a reasonable chance that the extrapolation result is up to 5 μGal different from a 15 min average. If a survey can acccept accuracy at the 10 (or larger) μGal level, Thiele extrapolation with 8 min series will allow larger networks.

5.8 Thiele Extrapolation Error Analysis

Error analysis of the Thiele algorithm shows preservation of input error. That is, if the error of the input data is 3 μGal, the error in the Thiele algorithm result is 3 μGal. A Monte Carlo scheme was used for error analysis due to the complexity of an analytical treatment. One million realizations of a random time series of 18 points provided the test data for the Thiele algorithm. Comparison of the Thiele output to the a priori average yields the error data set. The standard deviation of this error data set is a measure of error in the Thiele algorithm. Comparison of the Thiele error s.d. to the s.d. of the input data indicates if the Thiele algorithm preserves, reduces, or increases input data error. For white noise error about a constant or sinusoidal mean, the Thiele algorithm preserves the error level in the input data.

Regardless of input error level, 6% of the generated time series converge to a point >3 s.d. from the a priori mean. Upon inspection, these series all show a distinct trend in the final four or more data points. This relatively large linear trend at the end of the time series causes the spurious result of the Thiele algorithm, and is one reason for the linear fitting quality check during CG-3M data processing, and the despiking/decimating filters in Aliod processing. In practice, none of the test data has a large trend in only the final points, and hence linear detrending prevents Thiele algorithm results from exhibiting this behavior.

Chapter 6

Additional Algorithms

Here are additional techniques that have been tried, and their results. For whatever reason, the techniques are not part of the standard processing flow, but are documented so future workers don't have to reinvent the wheel.

6.1 Exponential Function Inversion

A station occupation time-series is used as the data for a Marquadt-Levenburg non-linear inversion to the function

$$g(t) = A + B\exp(-Ct)$$

where $g(t)$ is the gravity reading as a function of time, t is time, and A, B, and C are the constants to be found. Constant A represents the infinite-time value of the function, and hence is the best measure of gravity at the station in this scheme.

The inversion scheme was tested with 746 station occupation time-series from the Salt Lake valley pilot and other studies. All occupations were with meter 711420, and used the same acquisition parameters (cycle time, read time, calibration count, etc.). Results of the inversions are compared to weighted averages, excluding the first 3 min, of the entire time-series.

For 83 series tested, the inversion process failed due to limits of machine precision. These stations are not used in the following discussion; in practice, these stations would have to analysed using weighted averages. Figure 6.1 shows a histogram of the difference between the infinite-time value of the exponential function (constant A) and the result of a weighted average for the same time-series. A difference of less than 5 μGal will typically be within the error bounds of stations, and hence is not considered significant. The lopsided nature of the plot indicates that the exponential function results more often underestimate the gravity value, compared to a weighted average. As the underestimation is not constant, it must be treated as error.

A significant difference is obtained in 158 of 661 series (23.8%). In every case, these differences are due to an attempt by the inversion to fit a systematic trend

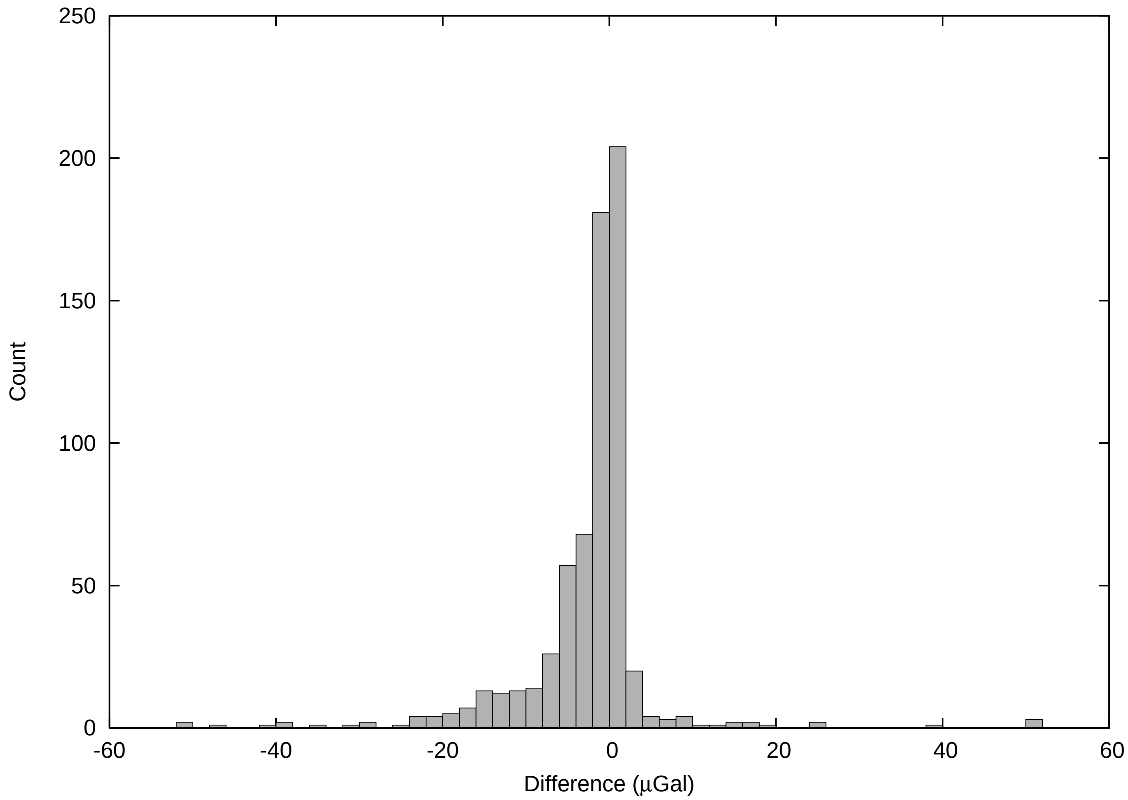

Figure 6.1: Histogram of differences between exponential function fitting results and weighted averages (disregarding the first 3 min of data). A total of 661 station time series are shown; 158 have a difference >5 μGal.

in the data. These trends do not generally exceed the 97.2 μGal/hr threshhold for detrending used in the pilot study's processing algorithm, and would not be removed from field data. For 12% of the series (85 of 746), no exponential function solution was obtained at all, due to lack of convergence of the algorithm. These series would have to be treated using another technique, and this would introduce further complication in the data processing interpretation.

Better results for the inversion should be possible using a fixed time constant for the exponential function, but the choice of the appropriate time constant is not clear. Results for the inversion of the test series have time constants varying over three orders of magnitude from 0.044 to 44 min^{-1}.

The convergence problems with 12% of test series, coupled with the significant different results for almost 25% of the test data (which would not be removed by detrending), makes the exponential function approach unappealing for field data. The inversion adds complexity, while still requiring the use of weighted averages where inversion fails.

6.2 Polynomial Drift Function

Previous high-precision gravity studies have used polynomial or adjusted polynomial drift functions [e.g. *Jachens et al.*, 1981], rather than the staircase scheme used in the reduction package. A formulation of an arbitrary degree polynomial drift function is presented here, following the same general inversion format as the staircase function.

Define the drift function as:

$$F(t) = \sum_{k=0}^{n} a_k t^k \tag{6.1}$$

where t is the time, n is the polynomial degree, and a_k are coefficients that are to be determined.

Available information is formed from repeated station occupation pairs; there are m such pairs in the data set. For each pair, there is a gravity difference, δg, and a difference in the drift function, δF:

$$\delta F_m = F(t_{2,m}) - F(t_{1,m}) = \sum_{k=0}^{n} a_k t_{2,m}^n - \sum_{k=0}^{n} a_k t_{1,m}^n = \sum_{k=1}^{n} a_k (t_{2,m}^n - t_{1,m}^n) \tag{6.2}$$

$$\delta g_m = g_{2,m} - g_{1,m} \tag{6.3}$$

Need to find a set of a_k such that:

$$[g_{2,m} - F(t_{2,m})] - [g_{1,m} - F(t_{1,m})] = 0 \forall m \tag{6.4}$$

This reduces to finding a set of a_k such that

$$\delta g_m = \delta F_m \forall m \tag{6.5}$$

which can be done with linear least squares; recast the problem into matrices of the form $Am = d$: Define data matrix, d, as

$$d = [\delta g_1, \ldots, \delta g_m]^T \tag{6.6}$$

and the operator matrix, A, as

$$A = \begin{bmatrix} (t_{2,1} - t_{1,1}) & \cdots & (t_{2,1}^n - t_{1,1}^n) \\ \vdots & \ddots & \vdots \\ (t_{2,m} - t_{1,m}) & \cdots & (t_{2,m}^n - t_{1,m}^n) \end{bmatrix} \tag{6.7}$$

The model matrix is $m = [a_1 \cdots a_n]^T$.

$\hat{W}$ is the weight matrix

$$\hat{W} = \mathrm{diag}(\frac{1}{\sigma_i^2}) \tag{6.8}$$

For large systems, computation of a best model is done using a matrix inversion of the matrix $A^T\hat{W}^2A$. The optimal solution is then computed from

$$m' = (A^T\hat{W}^2A)^{-1}\hat{W}^2d.$$

The resulting model, m', contains the optimal coefficients for the polynomial.

The degree of the polynomial is effectively arbitrary, although some statistical tests (such as the F-ratio test [*Stein and Gordon*, 1984]) can be applied to determine if increasing the degree significantly improves the fit. For single-day surveys a degree of 3 was found to be sufficient, according to the F-ratio test.

Chapter 7

Station Occupation Checklist

1. Remove the meter, in the transport case/bag, from the vehicle **without bumping it** and move to the station.

2. Setup tripod on station, centered on the station, with red-marked leg ("red leg") such that the meter will face the appropriate direction

   - Each station, when located for a project, must have a meter position and facing recorded so that every occupation will setup the meter in the same position and orientation.
   - To ease this, standard procedure is to orient the meter either with a cardinal direction (typically true north), or towards a nearby landmark (e.g. the fire hydrant next to a station, etc.)

3. Place the CG-5 on the tripod, with the upper left corner on the red leg.

4. Protect the meter from bad weather; the meter is "weather resistant", but some operators have had trouble with other meter types being damaged by weather.

   - Use an umbrella to protect the keypad and screen from rain and snow. Plastic bags can also be used, but are often hard to see through for meter setup and operation.
   - Wind is generally not a problem for a CG-5 on concrete or other stable ground; on dirt or other soft ground, wind will likely increase the standard deviations of readings by a factor of 3-50. Nearby trees will increase the standard deviation of stations, but within acceptable limits.
   - The meter may be shielded from wind by the vehicle. Vehicles can be parked next to a station without affecting the readings, so long as the vehicle doesn't touch the gravimeter! Pick up and stow the meter before moving the vehicle.

- Other types of portable wind breaks or weather-proofing can be used, so long as they don't touch the gravimeter, and **cannot knock the meter off the tripod due to a wind gust!**

5. Level the instrument using a **bubble level** on the faceplate. This will get the instrument nearly level, which will speed the fine level adjustment, later.
6. Turn on the instrument using the `ON/OFF` button.
7. Increment the station ID (offset) by using the `NEXT STAT.` key (F4).
8. If the `NEXT STAT.` option is not available on the screen, return to the main screen (pressing `CANCEL` or `SETUP`), and then press the `MEASURE CLR` key. Then increment the station ID as above.
9. Press `MEASURE CLR` key to get to the level screen; `F5 (LEVEL)` will also work.
10. Level the meter to within ± 5 arcsec in X and Y. This will cause a happy face icon to appear on the levelling screen.
11. Let the meter settle for a few seconds, to be sure the levels are stable and within 5 arcsec in both X and Y.
12. Press F5 to start the measurements; the screen will change to the numeric or graphic measuring screen, depending on which option the operator chose.
13. Watch for the first measurements; these should be reasonable numbers.
    - If the readings are near 0 or 7000 mGal, the meter may be broken. Watch the **standard deviation** (not standard error) of the readings for the first cycle; if less than 0.020 mGal, the meter is likely malfunctioning.
    - Generally projects will not cover regions with gravity changes of more than 100 mGal; changes larger than 100 mGal between stations may indicate a malfunctioning meter.
    - If all station readings consistently have measurements with standard deviations of less than 0.020 mGal, be wary of the meter. Most real field stations have standard deviations (for 30 s averages) of 0.030 mGal or larger. Exceptionally quiet stations will be 0.020 and less, but they are uncommon.
    - If previous surveys are available, compare the current readings and standard deviations with previous values; large differences (> 1 mGal in reading, >50% in s.d.) may indicate problems.
14. After checking the first measurements, back away from the meter and start a 12-minute timer.

15. Record the station ID (offset), station name, and start time in the field book. If you forget this step, the data may not be usable in the office!
    - Compare the expected station ID from the field book with the instrument. If there is a question as to whether the station ID (offset) is correct in the instrument, skip station IDs. That is, if the field book indicates this station ID should be 10, but you can't remember if the instrument showed 9 or 10, skip to 11 or 12 at the next station.
    - The list of station IDs can have holes; there is no penalty to skip more than 1 between station IDs. It is better to have station IDs skipped (no station ID 10) than out of order (e.g. station ID 36 is between 9 and 10).
16. Stay **at least** 3 m away from the instrument while reading, and off the concrete pad or station monument with the instrument.
17. Watch for noise and safety concerns:
    - Anything that can cause vibrations should be watched: people near the meter, dogs sniffing the meter, trucks driving nearby, etc.
    - Protect the meter from impact, and tipping, but do **not** worry about people or cars travelling beside (and not touching!) the meter.
    - Pay particular attention near schools when children are present.
    - If necessary, stop the meter and pick it up to prevent impact or tipping of the meter. In extreme cases (e.g. charging bison), just grab the meter and run.
18. After at least 12 minutes, approach the meter and press the `STOP` button (`F5`). If possible, press the button while not standing on the concrete pad or monument.
19. Check the final reading to be sure it is still on-range (as when you started the instrument).
20. Note if the X or Y tilts are different by more than 10 arcsec from the start.
21. Turn off the display using the `ON/OFF` button.
22. Put the meter back into the bag, and clip the cover closed.
23. Replace the meter back into the transport location, and **DON'T FORGET THE TRIPOD**.
24. Record all notes regarding the station, including adverse weather, noise sources (pedestrians, trucks, etc.) in the field book.
25. Move to the next station and repeat.

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