Gravity survey at McMurdo Station, Scott Base, Cape Roberts and Mario Zucchelli Station, Antarctica, 4-30 November 2009

Technical Report by

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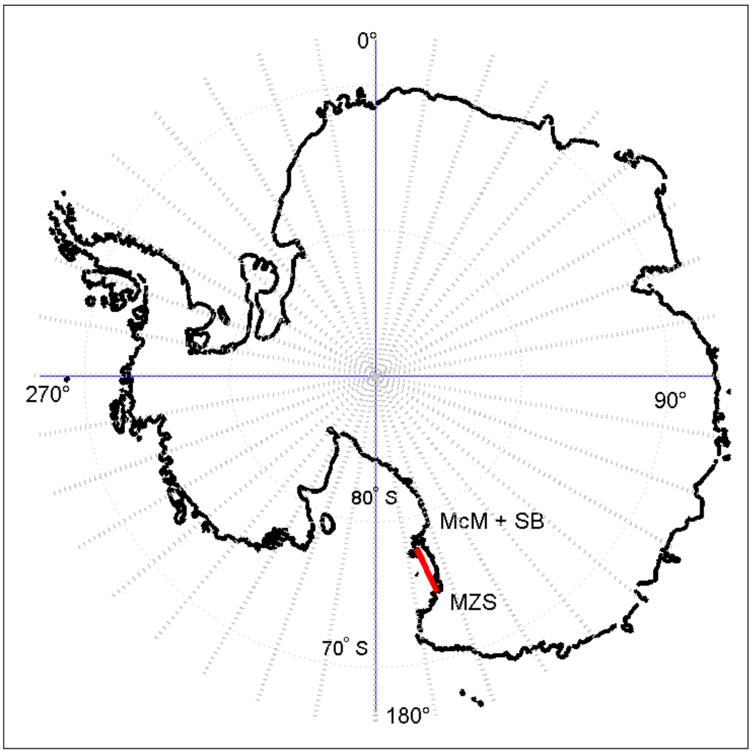
Abstract

From 10 until 23 November 2009, absolute gravity observations have been conducted at the USGS Thiel-1 gravity benchmark at McMurdo Station (US, 10-12 November), LINZ SBG-1 benchmark at Scott Base (NZ, 17-18 November) and Terra Nova Bay AB benchmark at Mario Zucchelli Station (I, 21-23 November) in Antarctica using the gravimeter FG5 #228. The three stations are located in remarkably quiet sites that are close to the sea ice, which is still formed at that time of the year. The absolute gravity measurements at Thiel-1 and SBG-1 stations are the first direct observations, whereas Terra Nova Bay AB Station had already been occupied in 1995 and 1997.

From 17 until 28 November 2009, Hut Point Station and Radarsat building at McMurdo Station and ROBE and CRN2 benchmarks at Cape Roberts have been tied to Thiel-1 Station, MMD-N benchmark at Scott Base has been tied to LINZ SBG-1 Station, and the absolute gravity reference station IAGS and relative gravity station IRGS at Mario Zucchelli Station have been tied to Terra Nova Bay AB Station with a Scintrex CG-5 gravimeter.



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FG5 #228 and Scintrex CG-5 at Terra Nova Bay AB Station.

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Chapter 1

Introduction

1.1 Gravity survey in Antarctica

Initially planned during the International Polar Year 2007-2008, the gravity survey described in this report was postponed twice until November 2009. It originally consisted in making Absolute Gravity (AG) and Relative Gravity (RG) measurements at McMurdo Station (McM), Scott Base (SB), Mario Zucchelli Station (MZS) and Dumont d'Urville (DdU), as well as RG measurements at Cape Roberts (CR). However, because of logistical incompatibilities, the observation at DdU was cancelled.

In the following chapters, we successively report on the observations made at McM, SB, CR and MZS. Where available, we compare the observations to measurements previously made at the same location.

1.2 Financial and logistical supports

Initiated as a part of project 337 *Variation de gravité et mouvement vertical dans les régions polaires - Apport aux problèmes du rebond post-glaciaire et de la déglaciation actuelle* funded by the French Institut Paul-Emile Victor (IPEV) and led by Jacques Hinderer (IPGS), the 2009 AG survey in Antarctica also benefited from the support of the Italian Programma Nazionale di Ricerche in Antartide (PNRA), Land Information New Zealand (LINZ), Antarctica New Zealand (ANZ), and US Antarctic Program (USAP) managed by the National Science Foundation (NSF). It is a part of the international Polar Earth Observing Network (POLENET) project.

1.3 Equipment

The AG observations were conducted with the free-fall FG5 #228 gravimeter designed by Micro-g Solutions Inc., owned by the French Institut National des Sciences de l'Univers (INSU), run by Géosciences Montpellier and operated by Nicolas Le Moigne who was assisted by Rachelle Winefield, Dave Collett, Larry Hothem and Yves Rogister. Observations consisted of sets of 100 drops, one drop every 10 seconds, which were hourly repeated. The AG raw data are corrected for Earth tide, ocean loading, polar motion and atmospheric pressure. The corrections and instrumental parameters are given, for each station, in Appendix E.

The RG observations were made with a Scintrex CG-5 gravimeter owned and run by Géosciences Montpellier. The operators were RW, NLM, LH, DC and YR.

Chapter 2

McMurdo Station (US)

2.1 AG at Thiel-1 Station

Brief history and description of McMurdo gravity stations can be found in the technical report by Diehl (2008). Thiel gravity station, whose geographical coordinates are given in Table 2.1, was established in Building 146 (Fig. 2.1) in 2000-2001 to replace the SATGRAV station. Thiel-1

Table 2.1: Geographical coordinates of and vertical gravity gradient at Thiel-1 Station.

Station	Latitude (°)	Longitude (°)	Elevation (m)	dg/dz (μGal/cm)
Thiel-1	77.8490 S	166.6794 E	46.21	-3.012 ± 0.030

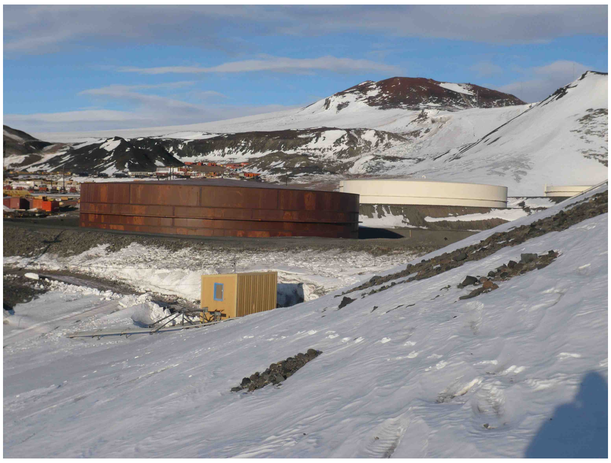

Figure 2.1: Yellow Thiel observatory (Building 146) at McMurdo Station. Fuel tank approximately 60 m behind.

benchmark is on a concrete pier inside the building (Fig. 2.2) and Thiel-2 benchmark is on a concrete pier outside the building. We only occupied Thiel-1 station. No direct AG measurements had been made at Thiel station before November 2009, but the AG had been determined by means of gravity ties (Table 2.2).

After the AG station was installed inside Thiel hut, a fuel tank was built some 60 m away from the gravity station (Fig. 2.1). The influence of the filling of the tank on the gravity measured at Thiel observatory is estimated in Appendix D. It is approximately 2 μGal, which is currently

Figure 2.2: Concrete pier and Thiel-1 benchmark inside Thiel observatory (building 146).

Table 2.2: AG at Thiel-1 Station measured by means of gravity ties.

Year	Reference	AG (mGal)
2003	Butcher 2003 (in Diehl 2008)	982 970.52
2004	Diehl 2008	982 969.7277
2008	Wilson and Tinto 2009	982 970.40 $\pm$ 0.06

at the level of detectability by an FG5 gravimeter. Assuming that the accuracy of the gravity measurements will increase in the future, the near presence of the fuel tank raises concerns about the long-term use of the Thiel hut as a reference gravity station. Therefore, the exploration for a new reference station, further away from the buildings of downtown McMurdo Station, has been initiated, but no firm decision has been taken yet.

AG observations (Fig. 2.3) ran from 11 November until 14 November 2009 (local time). Sea ice was still formed as far as approximately 50 km North of McMurdo Station. Although a snow storm blew for two days, on 13 and 14 November, the noise level in the data is very low because the site is remarkably quiet. The microseismic noise increased in the next few days after the storm. It was probably due to the swell that was generated by the storm and that loaded the Antarctic shorelines.

The vertical gravity gradient given in Table 2.1 was measured on 28 November with a relative gravimeter Scintrex CG-5 (Fig. 2.5).

Fig. 2.4 shows the 60 AG values at the ground level, with their error bars. The mean values at the ground level and 1 m above ground are given in Table 2.3.

Table 2.3: AG at Thiel-1 Station at ground level and 1 m above ground.

Altitude above ground (m)	AG (μGal)
0	982 970 532.28 $\pm$ 4.30
1	982 970 220.88 $\pm$ 2.07

Figure 2.3: FG5 #228 installed over Thiel-1 benchmark. Scintrex CG-5 on the left on the pillar.

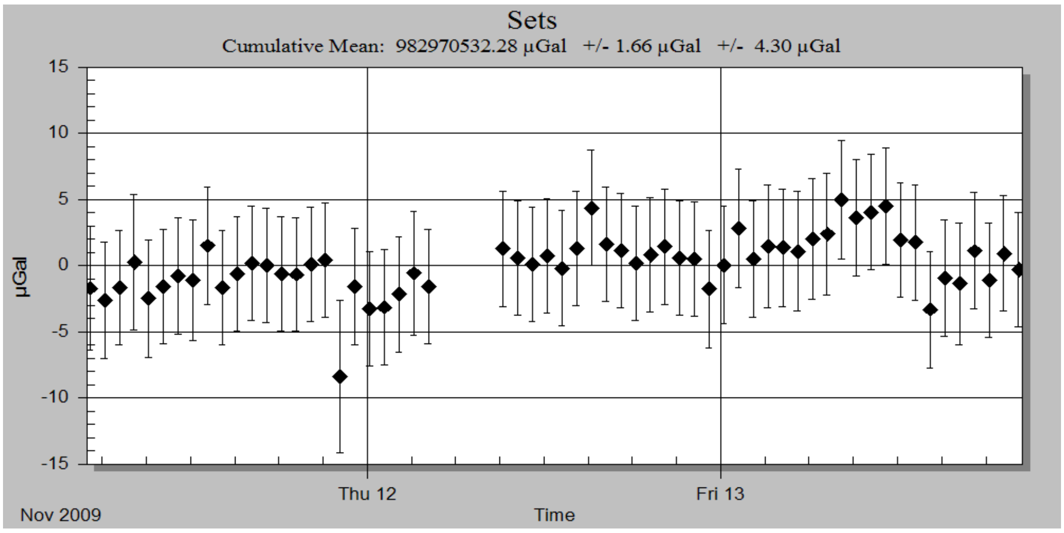

Figure 2.4: AG time series at ground level at Thiel-1 Station. Time is UT.

2.2 Gravity links to Hut Point Station and Radarsat building

On 27 November 2009, the Hut Point International Satellite Triangulation Station (Fig. 2.6 and Table 2.4), behind Scott's hut, was linked to Thiel-1 station (Fig. 2.5). As Table 2.5 shows, the present value of gravity is comprised between the 2003 (Butcher 2003, in Diehl 2008) and 2008 (Wilson and Tinto 2009) values, which differ by 1.03 mGal, but only differs by 0.1 mGal from Wilson and Tinto's value.

Table 2.4: Geographical coordinates of Hut Point Station.

Station	Latitude (°)	Longitude (°)	Elevation (m)
Hut Point	77.8448 S	166.6418 E	17.6

Figure 2.5: Tripod of Scintrex-CG5 over Thiel-1 benchmark.

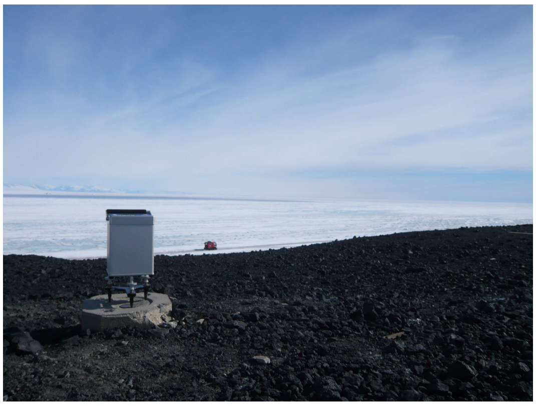

Figure 2.6: Scintrex-CG5 installed over Hut Point Station.

On the same day, a second link was established between Thiel-1 station and the Radarsat building (Fig. 2.2). In the future, the Radarsat building can possibly be used for hosting a new AG station. For the tie, a mark was drawn on a pillar of the building (Fig. 2.2). The AG at Radarsat station is also given in Table 2.5.

Figure 2.7: Radarsat building 71 and mark for gravity tie at Radarsat Station.

Table 2.5: AG at Hut Point and Radarsat stations measured by means of gravity ties.

Station	Year	Reference	AG (mGal)
Hut Point	2003	Butcher 2003 (in Diehl 2008)	982 976.62
	2008	Wilson & Tinto (2009)	982 975.65 ± 0.03
	2009	This report	982 975.754 ± 0.015
Radarsat	2009	This report	982 945.942 ± 0.015

Chapter 3

Scott Base (NZ)

3.1 AG at SBG-1 Station

In November 2008, at SB, Wilson and Tinto (2009) tied the newly established SBG-1 station (Figs 3.1 and 3.2, Table 3.1) to older stations where AG is known (Table 3.2). We tied SBG-1 station to Thiel-1 station and obtained a gravity value 1.64 μGal higher than the absolute value measured with the FG5 (Tables 3.2 and 3.3).

Table 3.1: Geographical coordinates of and vertical gravity gradient at SBG-1 Station

Station	Latitude (°)	Longitude (°)	Elevation (m)	dg/dz (μGal/cm)
SBG-1	77.8489 S	166.7691 E	9.1	-3.491 ± 0.030

Figure 3.1: *Left.* Behind the yellow panel, concrete pier holding gravity benchmarks SBG-1 and SBG-3. *Right.* Gravity benchmarks SBG-1 (centre) and SBG-3 (left).

The FG-5 #228 was setup over SBG-1 benchmark in a heated hut mounted on the concrete slab (Fig. 3.1) beneath the SB flagpole. AG observations ran on 17 and 18 November 2009 (local time). Because high winds were blowing snow inside the hut, the measurements had to be stopped after 24 hours of data acquisition. The measurement precision, 0.58 μGal, is higher than at McM (0.21μGal) but is still very good. The microseismic quietness of Ross Island had already been noticed by Sasagawa et al. (2004).

The vertical gravity gradient given in Table 3.1 was measured on 19 November with a relative gravimeter Scintrex CG-5.

Figure 3.2: Gravity benchmark SBG-1.

Table 3.2: AG at SBG-1 Station measured by means of gravity ties.

Year	Reference	AG (mGal)
2008	Wilson and Tinto 2009	982 977.83 ± 0.06
2009	This report	982 977.946 ± 0.015

Fig. 3.3 shows the 24 AG values at the ground level, with their error bars. A residual diurnal tidal signal is clearly visible. The set scatter, of order 2.9 μGal, is therefore higher than at McM where it was 1.7 μGal. However, thanks to the 24-hours duration of the observation, the tidal variation averages to zero. The mean values of gravity at the ground level and 1 m above ground are given in Table 3.3.

Table 3.3: AG at SBG-1 Station at ground level and 1 m above ground.

Altitude above ground (m)	AG (μGal)
0	982 977 945.91 ± 4.34
1	982 977 596.81 ± 2.15

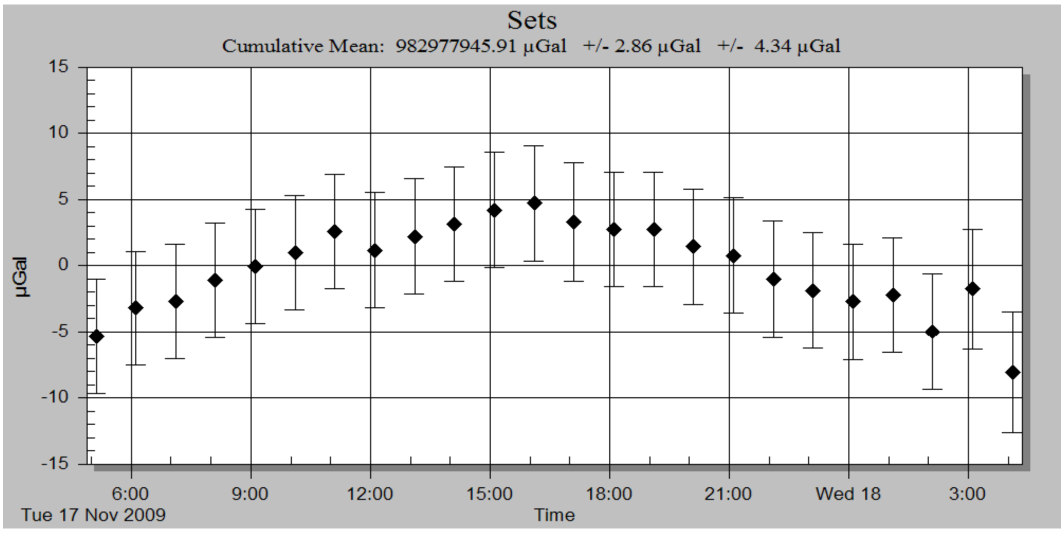

Figure 3.3: AG time series at ground level at SBG-1 Station. Time is UT.

3.2 Gravity link to Seismic Hut Station

Seismic Hut Station, labelled MMD-N (Table 3.4), was tied to absolute reference stations by Nakagawa (1983) and Wilson and Tinto (2009) (Table 3.5). On 27 November 2009, when linking SBG-1 station to Thiel-1 station, we also linked MMD-N to both Thiel-1 and SBG-1 stations. Our value for the gravity is approximately 130 μGal higher than Wilson and Tinto's value, as for Hut Point station (104 μGal) and SBG-1 station (116 μGal).

Table 3.4: Geographical coordinates of MMD-N Station

Station	Latitude (°)	Longitude (°)	Elevation (m)
MMD-N	77.8491 S	166.7567 E	33.2

Table 3.5: AG at MMD-N Station (Seismic Hut) measured by means of gravity ties.

Year	Reference	AG (mGal)
1983	Nakagawa (1983)	982 973.204
2008	Wilson & Tinto (2009)	982 973.40 ± 0.06
2009	This report	982 973.537 ± 0.015

Chapter 4

Cape Roberts

The LINZ ROBE benchmark (Table 4.1 and Fig. 4.1) is sealed in a rock approximately 100 meters away from the ANZ shelter. The LINZ CRN2 benchmark (Fig. 4.2), also known as ROB4 benchmark, is located a few hundred meters from the shelter, near the tide gauge and GPS station. A 45 minutes transportation by helicopter from either SB or McMurdo station is necessary to conduct gravity observations at CR. Sasagawa et al. (2004) conducted such a gravity tie in 1995 (Table 4.2). We conducted two RG observations on 18 and 20 November 2009. Each time, two hours were alloted on site. However, on the first observation sequence, we realized that two hours were not enough to complete accurate measurements at both ROBE and CRN2 stations. Therefore, on the second observation sequence, we did not repeat measurements at CRN2 station and focused on ROBE benchmark. The values given in Table 4.2 for the observations made on 18 November should be taken with caution.

Table 4.1: Geographical coordinates of ROBE and CRN2 stations

Station	Latitude (°)	Longitude (°)	Elevation (m)
ROBE	77.0035 S	163.1792 E	2.8
CRN2	77.0034 S	163.1902 E	14.6

Figure 4.1: Location of the LINZ ROBE benchmark (right) near the ANZ shelter (left).

Figure 4.2: Location of the LINZ CRN2 benchmark (bottom left-hand corner of the top image) near the tide gauge and GPS antenna (top).

Table 4.2: AG at ROBE and CRN2 stations measured by means of gravity ties.

Station	Date	Reference	AG (mGal)
ROBE	Nov. 1995	Sasagawa (2004)	982 905.904 ± 0.018
	18 Nov. 2009	This report	982 905.984 ± 0.020
	20 Nov. 2009	This report	982 905.914 ± 0.021
CRN2	18 Nov. 2009	This report	982 903.926 ± 0.020

Chapter 5

Mario Zucchelli Station (I)

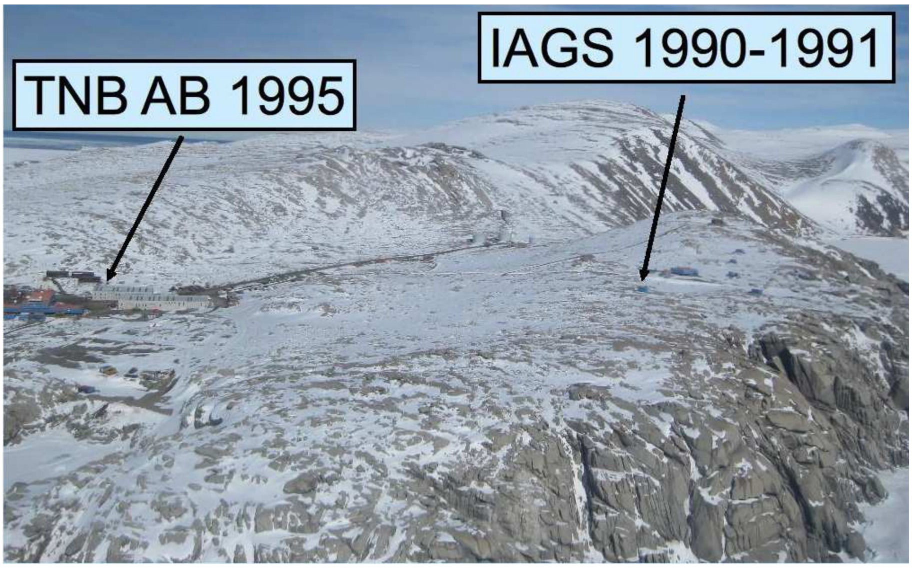

Figure 5.1: Aerial view of MZS. Indicated is the position of the TNB AB and IAGS stations, first measured in 1990-91 and 1995 respectively.

5.1 AG at Terra Nova Bay AB Station

AG observations at MZS in TNB were conducted in December 1990 (Cerutti et al. 1992), November 1995 (Sasagawa et al. 2004) and November-December 1997 (no direct reference but results published by Mäkinen et al. 2007). The first observation, in 1990, was performed by Cerutti et al. (1992) at the Italian AG Station (IAGS, Figs. 5.1, 5.4 and 5.5). Because the tripod of the FG5 #102 used by Sasagawa et al. (2004) was too large to fit the IAGS pillar, the experiments in 1995 and 1997 were moved to the vehicle hanger bay where a new AG station, named Terra Nova Bay AB, was established (Table 5.1 and Figs 5.1 and 5.2). The design of the tripod of the FG5 #228 would allow to occupy the IAGS pier. However, the time initially alloted on site was too short to occupy both the IAGS pier and TNB AB station. Therefore, for the sake of comparison to previous measurements, we decided to occupy TNB AB station to make the third AG observation at the same location in 14 years.

AG observations ran on 21 and 22 November 2009 (local time). Fig. 3.3 shows the 26 AG values at the ground level, with their error bars. Again, a residual diurnal tidal signal is clearly

Figure 5.2: TNB AB Station at MZS.

Table 5.1: Geographical coordinates of and vertical gravity gradient at TNB AB station. Elevation and gravity gradient given by Sasagawa et al. (2004).

Station	Latitude (°)	Longitude (°)	Elevation (m)	dg/dz (μGal/cm)
TNB AB	74.6933 S	164.0997 E	30	-3.120 ± 0.030

visible. The set scatter, however, is as low as 1.1 μGal. The measurement precision, 0.22 μGal, is almost the same as the one at McM.

The vertical gravity gradient was measured on 24 November with a relative gravimeter Scintrex CG-5. We obtained -3.047 ± 0.030 μGal/cm. However, to be consistent with the previous measurements, we use the value -3.120 μGal/cm measured by Sasagawa et al. (2004) and given in Table 5.1.

The mean values of gravity at the ground level and 1 m above ground are given in Table 5.2.

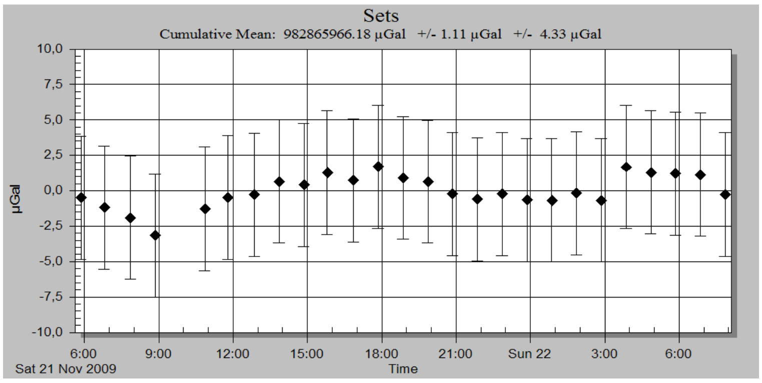

Figure 5.3: AG time series at ground level at TNB AB station. Time is UT.

Table 5.2: AG at TNB AB station at ground level and 1 m above ground. The 1995 value given by Sasagawa et al. (2004) has been corrected back by Mäkinen et al. (2007) for both Earth tides and instrumental factors. So, the same corrections have been applied to Sasagawa et al.'s data and our data, which allows for a comparison of the gravity values.

Year	Reference	Altitude above ground (m)	AG (μGal)
1995	Mäkinen et al. 2007	1	982 865 664.1 ± 2.1
1997	Mäkinen et al. 2007	1	982 865 663.4
2009	This report	0	982 865 966.18 ± 4.33
2009	This report	1	982 865 654.18 ± 2.09

Figure 5.4: Italian AG Station (IAGS) at MZS.

Figure 5.5: IAGS benchmark.

5.2 Gravity links to IAGS and IRGS Stations

Between 21 and 24 November, the IAGS (Figs 5.4 and 5.5) and IRGS (Fig. 5.6) stations have been tied to TNB AB station (Table 5.3). The IRGS benchmark is located near the helipad. It had been tied to the IAGS station by Cerutti et al. (1992) in 1990 and Sasagawa et al. (2004) in 1995. This is the first direct tie between the IAGS and TNB AB stations.

Figure 5.6: IRGS benchmark.

Table 5.3: AG at ground level at IAGS and IRGS stations

Station	Year	Reference	Type of measurement	AG (mGal)
IAGS	1990	Cerutti et al. (1992)	Direct	982 855.244 ± 0.007
	2009	This report	Tie to TNB AB	982 855.317 ± 0.012
IRGS	1990	Cerutti et al. (1992)	Tie to IAGS	982 863.890 ± 0.033
	1995	Sasagawa (2004)	Tie to TNB AB	982 863.935 ± 0.013
	2009	This report	Tie to TNB AB	982 863.951 ± 0.012

Chapter 6

Conclusions and recommendations for future observations

Despite the cancellation of the observation at DdU, the gravity survey has been very successful. AG has been measured with high accuracy at Thiel-1 station (McM), SBG-1 station (SB) and Terra Nova Bay AB station (MZS), which are extremely quiet sites. Various stations have been tied with a relative gravimeter to the AG reference stations: Hut Point station and Radarsat building (McM), Seismic Hut station (SB), ROBE and CRN2 stations (CR), and IAGS and IRGS stations (MZS).

The repetition of the AG measurements every few years, combined with measurements of the vertical displacement of the ground with GPS stations, is extremely useful to monitor the long-term deformation due, for instance, to the post-glacial rebound and present-day ice mass variation. Measurements of gravity variation and ground motion are also complementary to gravity satellite observations. Modelling of the glacial isostatic adjustment provides a gravity variation of a few μGal/yr, which can only be detected by using the most sensitive absolute gravimeters. However, the various models of glacial isostatic adjustment do not converge to a unique solution. Therefore, theoretical as well as observational efforts are still demanded to improve our knowledge and understanding of the evolution of the geodetic parameters in Antarctica.

To achieve a reliable observation of the long-term variation of the gravity field in the Ross embayment, we list the following recommendations:

1. Long-term gravity observatories should be maintained at McM, SB, CR and MZS. The stations must be stable and perennial.

2. Repeat the gravity survey at the same time of the year, in November, when the sea ice is still formed. This reduces the micro-seismic noise generated by the sea movements.

3. At MZS, the two AG stations TNB AB and IAGS should be maintained.

4. At MZS, a FG5 with a vertical tripod is required at IAGS.

5. At CR, 5 to 6 hours on site are necessary for linking both the ROBE and CRN2 benchmarks.

6. At McM, the redundant fuel tank near Thiel hut is a possible source of disturbance for the future generation of gravimeters that will have a greater accuracy. As mentioned in Chapter 2, investigation has been initiated to establish a new gravity station further away from the centre of McM. However, Thiel observatory should be kept as a reference station at least until AG measurements have been made at the new station.

7. The size of a pier holding an AG mark should be at least 1.1×1.1 m^2.

8. The size of an AG hut should be at least 4×4 m^2

9. The working temperature in a hut is approximately 20 C.

10. *On the average*, 7 to 10 days on site are necessary for conducting a single AG observation (3 observations were conducted from 1st until 30 November). They include reasonable delays because of the difficult weather conditions encountered in Antarctica.

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Franco Ricci (MZS)

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Appendix A

List of Acronyms

AG	Absolute Gravity
ANZ	Antarctica New Zealand
CR	Cape Roberts
DC	Dave Collett
DdU	Dumont d'Urville
IAGS	Italian AG Station
INSU	Institut National des Sciences de l'Univers
IPEV	Institut Paul-Emile Victor
IPGS	Insitut de Physique du Globe de Strasbourg
IRGS	Italian RG Station
LH	Larry Hothem
LINZ	Land Information New Zealand
McM	McMurdo Station
MZS	Mario Zucchelli Station
NLM	Nicolas Le Moigne
NSF	National Science Foundation
PNRA	Programma Nazionale di Ricerche in Antartide
POLENET	Polar Earth Observing Network
RG	Relative Gravity
RW	Rachelle Winefield
SB	Scott Base
TNB	Terra Nova Bay
USAP	US Antarctic Program
USGS	US Geological Survey
YR	Yves Rogister

Appendix B

Web sites

ANZ	http://www.antarcticanz.govt.nz/
Géosciences Montpellier	http://www.gm.univ-montp2.fr/spip/index.php
INSU	http://www.insu.cnrs.fr/
IPEV	http://www.institut-polaire.fr/
IPGS	http://eost.u-strasbg.fr/IPGS/
LINZ	http://www.linz.govt.nz/
PNRA	http://www.pnra.it/
POLENET	http://www.polenet.org/
USAP	http://www.usap.gov/
USGS	http://www.usgs.gov/

Appendix C

Event Log

Local time is UT + 13.

31 Oct	LH arrives in ChC
01 Nov	NLM and YR arrive in ChC
04 Nov	C17 flight to McM. Arrive at 1500L. NLM gets a cold
06-07 Nov	NLM and YR attend mandatory survival school
08 Nov	Mount gravity hut to be installed at SB in the workshop of the Crary Lab
09 Nov	Dismount hut
10 Nov	Equipment arrives at McM. Equipment delivered at the Crary Lab. Meeting with DC and RW. Vacuum pump starts working at 8 pm
11 Nov	AM: Move equipment to Thiel hut. Request for complementary heating PM: Setup FG5. Misalignment of the laser output and optic fiber takes 90 minutes to be fixed. Observation begins at ∼1700L
12 Nov	AM Move hut to SB PM With Steven Kottmeier, look for a new location for AG station at McM
13 Nov	Snow storm
14 Nov	Snow storm. AG observation stops at ∼1200L
15 Nov	Snow storm
16 Nov	Setup the hut at SB. Dismount FG5 at McM
17 Nov	AM Move FG5 to SB PM Setup FG5. Misalignment of the laser output and optic fiber takes a few minutes to be fixed. Start observation at ∼1800L
18 Nov	AM Gravity link to CR with Scintrex CG5 by RW, DC, LH and YR via helicopter PM High wind starts blowing in early afternoon, gusts up to 70 km/h in the evening. Stop observation at SB at ∼1830L
19 Nov	Dismount FG5. Move FG5 to McM. Vertical gradient at SB

20 Nov	AM Pack FG5 for cargo for TNB. Gravity link to CR with Scintrex CG5 by RW, DC, and YR via helicopter (Departure 1000L return 1430L) PM Dismount hut at SB
21 Nov	900-1030L LH, NLM and YR fly with Twin Otter to TNB PM RG links to TNB IAGS and TNB IRGS with CG5. Setup FG5 at TNB AB. Observation starts at ∼1845L
22 Nov	900L Stop general heating in the AG hanger because it disturbs the FG5 when it turns on. RG links to TNB IAGS and TNB IRGS with CG5. AG observation stops at ∼2045L
23 Nov	RG links to TNB IAGS. Dismount FG5
24 Nov	Flight back to McM delayed. Vertical gradient at TNB AB
25 Nov	Flight back to McM delayed
26 Nov	Flight back to McM by Twin Otter
27 Nov	AM RG links to Hut Point and Radarsat Building 71 PM RG links at SB
28 Nov	Vertical gradient at Thiel station. Thanksgiving dinner
29 Nov	Dinner at SB with RW and DC
30 Nov	NLM and YR fly back to ChC. Arrive at 2000L
1 Dec	Pick up equipment at ChC airport for measurements at Godley Head. LH flies to South Pole

Appendix D

Gravitational attraction by the redundant fuel tank at the Thiel gravity observatory of McMurdo Station

Abstract

We derive an approximate formula for the gravitational field of a homogeneous cylinder, either filled or hollow, at a point located a few radius away from the axis of the cylinder. The accuracy of the result is better than 1 %. We estimate the influence of a 2 million gallons fuel container installed near the Thiel AG observatory at McMurdo station, Antarctica. We find that the difference between the gravitational attraction of a filled container and an empty container is approximately 2 μGal, which is also the accuracy of a FG5 absolute gravimeter. The influence of the 109 326 lbs container itself is approximately 0.008 μGal, which is clearly negligible.

D.1 Introduction

A tank meant to contain fuel has been installed approximately 200 ft away from the AG observatory at McMurdo station, Antarctica (rusty tank above Thiel hut in Fig. 2.1). The purpose of this note is to estimate the influence of both the container and fuel on the measured gravity at the Thiel gravity observatory.

Since no analytical expression can be obtained for the gravitational potential of a homogeneous cylinder, we derive an approximate formula by developing the inverse of the distance between two points in a Taylor series. We denote by y the distance from the axis of the cylinder and the observation point and b, the radius of the cylinder. In this case, $b/y \sim 1/3$. To achieve an accuracy better than 1 %, we extend the Taylor formula up to the fourth power of b/y.

D.2 Geometrical description

See Fig. D.1.

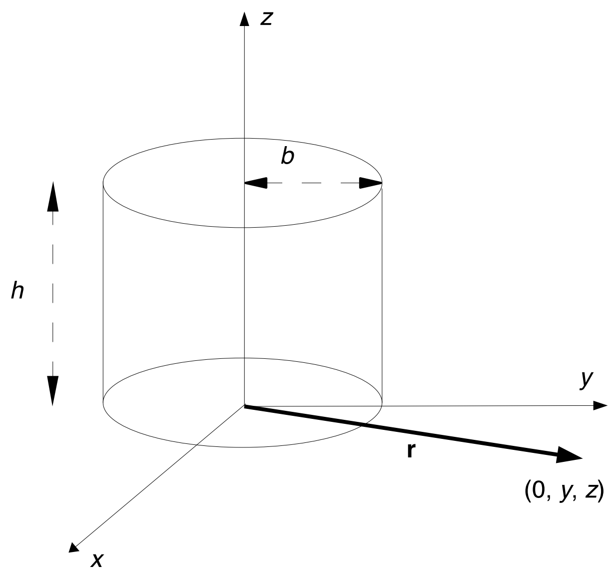

Figure D.1: Position of the gravity mark with respect to the tank.

D.3 Gravitational potential

The gravitational potential at point $\mathbf{r}$ due to a cylinder of density ρ is

$$V(\mathbf{r}) = -G \int\int\int_{\text{cylinder}} \frac{\rho}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}', \tag{D.1}$$

where

$$\mathbf{r}' = R'(\cos\varphi' \mathbf{e}_x + \sin\varphi' \mathbf{e}_y) + z' \mathbf{e}_z, \tag{D.2}$$

and $0 < R' \leq b$, $0 < z' \leq h$ and $0 < \varphi' \leq 2\pi$. Because of the rotational symmetry of the cylinder around the $z-$axis, we can assume that

$$\mathbf{r} = y\mathbf{e}_y + z\mathbf{e}_z. \tag{D.3}$$

Moreover, ρ is a constant. Therefore,

$$V(\mathbf{r}) = -G\rho \int_0^{2\pi}\int_0^h\int_0^b \frac{1}{\sqrt{y^2 + R'^2 - 2yR'\sin\varphi' + (z-z')^2}} R'\,dR'\,dz'\,d\varphi' \tag{D.4}$$

D.4 Orders of magnitude and approximations

D.4.1 Units conversion

1 ft = 0.3048 m
1 gallon = 0.003785412 m^3
1 lb = 0.45359237 kg

D.4.2 Distances

In the problem at hand, we have

b	h	y	z
61	34	~ 200	-10

All the distances are in ft. Thus,

$$R'/y \leq b/y \sim 1/3 \tag{D.5}$$

$$z'/|z| < h/|z| = 3.4 \tag{D.6}$$

$$|z|/y \sim 1/20 \tag{D.7}$$

$$z'/y \leq h/y \sim 1/6 \tag{D.8}$$

$$1 - z'/z \leq 4.4 \tag{D.9}$$

The inverse of the distance $|\mathbf{r} - \mathbf{r}'|$ is

$$[y^2 + R'^2 - 2yR'\sin\varphi' + (z - z')^2]^{-1/2} = y^{-1}\left[1 - 2\frac{R'}{y}\sin\varphi' + \frac{R'^2}{y^2} + \frac{z^2}{y^2}\left(1 - \frac{z'}{z}\right)^2\right]^{-1/2} \tag{D.10}$$

The second term is less than 2/3, the third term is less than 1/9 and the fourth term is less than approximately $20/400 = 1/20$. We will develop the expression in brackets up to the fourth power of R'/y and $(1 - z'/z)z/y$, which will provide a result accurate to better than 1 %. Since

$$(1 + x)^{-1/2} \simeq 1 - \frac{1}{2}x + \frac{3}{8}x^2 - \frac{5}{16}x^3 + \frac{7}{48}x^4, \tag{D.11}$$

we have

$$V \simeq -\pi G\rho\frac{b^2h}{y}\left[1 - \frac{b^2}{8y^2} + \frac{35b^4}{48y^4} - \frac{1}{2y^2}\left(z^2 - hz + \frac{h^2}{3}\right)\left(1 - \frac{27b^2}{16y^2}\right)\right.$$
$$\left. + \frac{3}{8y^4}\left(z^4 - 2hz^3 + 2h^2z^2 - h^3z + \frac{h^4}{5}\right)\right]. \tag{D.12}$$

D.5 Gravitational field

Given that

$$\mathbf{g} = -\nabla V, \tag{D.13}$$

the $y-$ and $z-$components of $\mathbf{g}$ are

$$g_y \simeq \pi G\rho\frac{b^2h}{y^2}\left[-1 + \frac{3b^2}{8y^2} - \frac{175b^4}{48y^4} + \frac{3}{2y^2}\left(z^2 - hz + \frac{h^2}{3}\right)\left(1 - \frac{45b^2}{16y^2}\right)\right.$$
$$\left. - \frac{15}{8y^4}\left(z^4 - 2hz^3 + 2h^2z^2 - h^3z + \frac{h^4}{5}\right)\right] \tag{D.14}$$

and

$$g_z \simeq \pi G\rho\frac{b^2h}{2y^3}\left[(2z - h)\left(-1 + \frac{27b^2}{16y^2}\right) + \frac{3}{4y^2}\left(4z^3 - 6hz^2 + 4h^2z - h^3\right)\right]. \tag{D.15}$$

We take $\rho = 900$ kg/m^3 as an upper limit for the density of the fluid and obtain

$$g_y = -17.8\,\mu\text{Gal} \tag{D.16}$$

$$g_z = 2.0\,\mu\text{Gal} \tag{D.17}$$

As could be intuitively expected from inspection of Fig. D.1, the y-component of the gravitational attraction is much bigger than the z-component.

D.6 Influence of the container

If σ denotes the surface mass density of the container, the gravitational potential is

$$V \simeq -\pi G\sigma\frac{bh}{y}\left[2-\frac{b^2}{2y^2}+\frac{35b^4}{s8y^4}+\frac{1}{y^2}\left(z^2-hz+\frac{h^2}{3}\right)\left(-1+\frac{27b^2}{8y^2}\right)\right.$$
$$\left.+\frac{3}{4y^4}\left(z^4-2hz^3+2h^2z^2-h^3z+\frac{h^4}{5}\right)\right]. \tag{D.18}$$

The $y-$ and $z-$components of the gravitational field are

$$g_y \simeq \pi G\sigma\frac{bh}{y^2}\left[-2+\frac{3b^2}{y^2}-\frac{175b^4}{8y^4}+\frac{3}{y^2}\left(z^2-hz+\frac{h^2}{3}\right)\left(1-\frac{45b^2}{8y^2}\right)\right.$$
$$\left.-\frac{15}{4y^4}\left(z^4-2hz^3+2h^2z^2-h^3z+\frac{h^4}{5}\right)\right] \tag{D.19}$$

and

$$g_z \simeq \pi G\sigma\frac{bh}{y^3}\left[(2z-h)\left(-1+\frac{27b^2}{8y^2}\right)+\frac{3}{4y^2}\left(4z^3-6hz^2+4h^2z-h^3\right)\right]. \tag{D.20}$$

The mass of the container being $2\pi\sigma bh = 109\ 326$ lbs, we find

$$g_y = -0.08\,\mu\text{Gal} \tag{D.21}$$
$$g_z = 0.008\,\mu\text{Gal} \tag{D.22}$$

D.7 Conclusion

The estimated gravity variation due to the installation of a tank of 109 326 lbs and 61 ft radius at approximately 200 ft from the Thiel AG station at McMurdo is 0.008 μGal, which is presently undetectable. The filling of the tank with fuel will decrease the measured gravity by approximately 2 μGal, which is at the level of detectability by a FG5 absolute gravimeter. However, improvement in the accuracy of the instrument will make the influence of the tank significant.

Appendix E

Set processing log for AG measurements

Ground values are in red, 1-meter above ground values are in blue.

E.1 McMurdo Station

```
Micro-g Solutions g Processing Report

g Acquisition Version:  4.040500
g Processing Version:  7.070307

Station Data
Name:  Mac Murdo
Site Code:  Thiel-1
Lat:  -77.84890 Long:  166.67910 Elev:  46.21 m
Setup Height:  12.50 cm
Transfer Height:  0.00 cm
Transfer Height:  100.00 cm
Actual Height:  129.10 cm
Gradient:  -3.114 µGal/cm
Nominal Air Pressure:  1007.71 mBar
Barometric Admittance Factor:  0.30
Polar Motion Coord:  0.2205 " 0.2365 "
Earth Tide (ETGTAB) Selected Potential Filename:  ETCPOT.dat
Delta Factor Filename:  Mac Murdo.dff
Delta Factors
Start Stop Amplitude Phase Term
0.000000 0.002427 1.000000 0.0000 DC
0.002428 0.249951 1.160000 0.0000 Long
0.721500 0.906315 1.154250 0.0000 Q1
0.921941 0.974188 1.154240 0.0000 O1
0.989049 0.998028 1.149150 0.0000 P1
0.999853 1.216397 1.134890 0.0000 K1
1.719381 1.906462 1.161720 0.0000 N2
1.923766 1.976926 1.161720 0.0000 M2
1.991787 2.002885 1.161720 0.0000 S2
```

2.003032 2.182843 1.161720 0.0000 K2
2.753244 3.081254 1.07338 0.0000 M3
3.791964 3.937897 1.03900 0.0000 M4
Ocean Load ON, Filename: OceanLoad-Mac Murdo.olf
Waves: M2 S2 K1 O1 N2 P1 K2 Q1 Mf Mm Ssa
Amplitude (μGal): 0.673 0.258 1.845 1.488 0.094 0.621 0.069 0.347 0.278 0.219 0.203
Phase (deg): -329.0 -119.3 -157.0 -145.7 -11.6 -158.9 -149.3 -141.9 -20.6 -11.2 -16.5

Instrument Data
Meter Type: FG5
Meter S/N: 228
Factory Height: 116.60 cm
Rubidium Frequency: 10000000.00000 Hz
Laser: WEO100 (192)
ID: 632.99117754 nm (0.54 V)
IE: 632.99119473 nm (0.06 V)
IF: 632.99121259 nm (-0.33 V)
IG: 632.99123023 nm (-0.53 V)
IH: 632.99136890 nm (-1.50 V)
II: 632.99139822 nm (-1.46 V)
IJ: 632.99142704 nm (-1.45 V)
Modulation Frequency: 8333.395 Hz

Processing Results
Date: 11/12/09
Time: 13:06:16
DOY: 316
Year: 2009
Time Offset (D h:m:s): 0 0:0:0
Gravity: 982970532.28 μGal
Gravity: 982970220.88 μGal
Set Scatter: 1.66 μGal
Measurement Precision: 0.21 μGal
Total Uncertainty: 4.30 μGal
Total Uncertainty: 2.07 μGal
Number of Sets Collected: 60
Number of Sets Processed: 60
Set #s Processed:
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60
Number of Sets NOT Processed: 0
Set #s NOT Processed:
Number of Drops/Set: 100
Total Drops Accepted: 5913
Total Drops Rejected: 87
Total Fringes Acquired: 700
Fringe Start: 12
Processed Fringes: 610
GuideCard Multiplex: 4
GuideCard Scale Factor: 250

Acquisition Settings
Set Interval: 60 min
Drop Interval: 10 sec
Number of Sets: 60
Number of Drops: 100

Gravity Corrections
Earth Tide (ETGTAB): -74.17 μGal
Ocean Load: 0.33 μGal
Polar Motion: -2.12 μGal
Barometric Pressure: -5.14 μGal
Transfer Height: 402.02 μGal
Reference Xo: -0.00 μGal

Uncertainties
Sigma Reject: 3.00
Earth Tide Factor: 0.001
Average Earth Tide Uncertainty: 0.07 μGal
Ocean Load Factor: 0.10
Average Ocean Load Uncertainty: 0.03 μGal
Barometric: 1.00 μGal
Polar Motion: 0.05 μGal
Laser: 0.05 μGal
Clock: 0.50 μGal
System Type: 1.10 μGal
Tidal Swell: 0.00 μGal
Water Table: 0.00 μGal
Unmodeled: 0.00 μGal
System Setup: 1.00 μGal
Gradient: 3.87 μGal (0.03 μGal/cm)
Gradient: 0.89 μGal (0.03 μGal/cm)

E.2 Scott Base

```
Micro-g Solutions g Processing Report

g Acquisition Version:  4.040500
g Processing Version:  7.070307

Station Data
Name:  Scott
Site Code:  SBG 1
Lat:  -77.85000 Long:  166.76700 Elev:  9.10 m
Setup Height:  12.15 cm
Transfer Height:  0.00 cm
Transfer Height:  100.00 cm
Actual Height:  128.75 cm
Gradient:  -3.491 μGal/cm
Nominal Air Pressure:  1012.29 mBar
Barometric Admittance Factor:  0.30
Polar Motion Coord:  0.2254 " 0.2384 "
Earth Tide (ETGTAB) Selected Potential Filename:  ETCPOT.dat
Delta Factor Filename:  Scott.dff
Delta Factors
Start Stop Amplitude Phase Term
0.000000 0.002427 1.000000 0.0000 DC
0.002428 0.249951 1.160000 0.0000 Long
0.721500 0.906315 1.154250 0.0000 Q1
0.921941 0.974188 1.154240 0.0000 O1
0.989049 0.998028 1.149150 0.0000 P1
0.999853 1.216397 1.134890 0.0000 K1
1.719381 1.906462 1.161720 0.0000 N2
1.923766 1.976926 1.161720 0.0000 M2
1.991787 2.002885 1.161720 0.0000 S2
2.003032 2.182843 1.161720 0.0000 K2
2.753244 3.081254 1.07338 0.0000 M3
3.791964 3.937897 1.03900 0.0000 M4
Ocean Load ON, Filename:  OceanLoad-Scott.olf
Waves:  M2 S2 K1 O1 N2 P1 K2 Q1 Mf Mm Ssa
Amplitude (μGal):  0.485 0.159 2.745 2.246 0.122 0.912 0.063 0.475 0.000 0.000 0.000
Phase (deg):  -227.4 -200.2 -167.8 -157.2 -193.9 -167.9 -198.6 -152.3 0.0 0.0 0.0

Instrument Data
Meter Type:  FG5
Meter S/N: 228
Factory Height:  116.60 cm
Rubidium Frequency:  10000000.00000 Hz
Laser:  WEO100 (192)
ID: 632.99117754 nm ( 0.54 V)
IE: 632.99119473 nm ( 0.06 V)
IF: 632.99121259 nm ( -0.33 V)
IG: 632.99123023 nm ( -0.53 V)
```

IH: 632.99136890 nm (-1.50 V)
II: 632.99139822 nm (-1.46 V)
IJ: 632.99142704 nm (-1.45 V)
Modulation Frequency: 8333.395 Hz
Processing Results
Date: 11/17/09
Time: 16:36:50
DOY: 321
Year: 2009
Time Offset (D h:m:s): 0 0:0:0
Gravity: 982977945.91 μGal
Gravity: 982977596.81 μGal
Set Scatter: 2.86 μGal
Measurement Precision: 0.58 μGal
Total Uncertainty: 4.34 μGal
Total Uncertainty: 2.15 μGal
Number of Sets Collected: 24
Number of Sets Processed: 24
Set #s Processed:
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24
Number of Sets NOT Processed: 0
Set #s NOT Processed:
Number of Drops/Set: 100
Total Drops Accepted: 2371
Total Drops Rejected: 29
Total Fringes Acquired: 700
Fringe Start: 12
Processed Fringes: 610
GuideCard Multiplex: 4
GuideCard Scale Factor: 250

Acquisition Settings
Set Interval: 60 min
Drop Interval: 10 sec
Number of Sets: 36
Number of Drops: 100

Gravity Corrections
Earth Tide (ETGTAB): -38.19 μGal
Ocean Load: 0.04 μGal
Polar Motion: -2.16 μGal
Barometric Pressure: -5.47 μGal
Transfer Height: 449.47 μGal
Reference Xo: -0.00 μGal

Uncertainties
Sigma Reject: 3.00
Earth Tide Factor: 0.001
Average Earth Tide Uncertainty: 0.04 μGal
Ocean Load Factor: 0.10

Average Ocean Load Uncertainty: 0.00 μGal
Barometric: 1.00 μGal
Polar Motion: 0.05 μGal
Laser: 0.05 μGal
Clock: 0.50 μGal
System Type: 1.10 μGal
Tidal Swell: 0.00 μGal
Water Table: 0.00 μGal
Unmodeled: 0.00 μGal
System Setup: 1.00 μGal
Gradient: 3.86 μGal (0.03 μGal/cm)
Gradient: 0.86 μGal (0.03 μGal/cm)

E.3 Mario Zucchelli Station

Micro-g Solutions g Processing Report

g Acquisition Version: 4.040500
g Processing Version: 7.070307

Station Data
Name: Mario Zucchelli Station
Site Code: Terra Nova Bay AB
Lat: -74.69477 Long: 164.11478 Elev: 30.00 m
Setup Height: 13.35 cm
Transfer Height: 0.00 cm
Transfer Height: 100.00 cm
Actual Height: 129.95 cm
Gradient: -3.120 μGal/cm
Nominal Air Pressure: 1009.65 mBar
Barometric Admittance Factor: 0.30
Polar Motion Coord: 0.1915 " 0.2168 "
Earth Tide (ETGTAB) Selected Potential Filename: ETCPOT.dat
Delta Factor Filename: Terra Nova Bay.dff
Delta Factors
Start Stop Amplitude Phase Term
0.000000 0.002427 1.000000 0.0000 DC
0.002428 0.249951 1.160000 0.0000 Long
0.721500 0.906315 1.154250 0.0000 Q1
0.921941 0.974188 1.154240 0.0000 O1
0.989049 0.998028 1.149150 0.0000 P1
0.999853 1.216397 1.134890 0.0000 K1
1.719381 1.906462 1.161720 0.0000 N2
1.923766 1.976926 1.161720 0.0000 M2
1.991787 2.002885 1.161720 0.0000 S2
2.003032 2.182843 1.161720 0.0000 K2
2.753244 3.081254 1.07338 0.0000 M3
3.791964 3.937897 1.03900 0.0000 M4
cean Load ON, Filename: Terra Nova Bay.olf
Waves: M2 S2 K1 O1 N2 P1 K2 Q1 Mf Mm Ssa
Amplitude (μGal): 0.672 0.304 2.109 1.760 0.057 0.709 0.092 0.423 0.301 0.246 0.224
Phase (deg): -304.9 -139.0 -161.5 -150.8 -44.0 -162.9 -165.5 -145.5 -20.1 -11.4 -14.8

Instrument Data
Meter Type: FG5
Meter S/N: 228
Factory Height: 116.60 cm
Rubidium Frequency: 10000000.00000 Hz
Laser: WEO100 (192)
ID: 632.99117754 nm (0.54 V)
IE: 632.99119473 nm (0.06 V)
IF: 632.99121259 nm (-0.33 V)
IG: 632.99123023 nm (-0.53 V)

IH: 632.99136890 nm (-1.50 V)
II: 632.99139822 nm (-1.46 V)
IJ: 632.99142704 nm (-1.45 V)
Modulation Frequency: 8333.395 Hz
Processing Results
Date: 21/17/09
Time: 19:12:18
DOY: 325
Year: 2009
Time Offset (D h:m:s): 0 0:0:0
Gravity: 982865966.18 μGal
Gravity: 982865654.18 μGal
Set Scatter: 1.11 μGal
Measurement Precision: 0.22 μGal
Total Uncertainty: 4.33 μGal
Total Uncertainty: 2.09 μGal
Number of Sets Collected: 27
Number of Sets Processed: 26
Set #s Processed:
1,2,3,4,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24, 25, 26, 27
Number of Sets NOT Processed: 1
Set #s NOT Processed: 5
Number of Drops/Set: 100
Total Drops Accepted: 2451
Total Drops Rejected: 15
Total Fringes Acquired: 700
Fringe Start: 12
Processed Fringes: 610
GuideCard Multiplex: 4
GuideCard Scale Factor: 250

Acquisition Settings
Set Interval: 60 min
Drop Interval: 10 sec
Number of Sets: 36
Number of Drops: 100

Gravity Corrections
Earth Tide (ETGTAB): -38.86 μGal
Ocean Load: -0.31 μGal
Polar Motion: -2.37 μGal
Barometric Pressure: -10.00 μGal
Transfer Height: 405.44 μGal
Reference Xo: -0.00 μGal

Uncertainties
Sigma Reject: 3.00
Earth Tide Factor: 0.001
Average Earth Tide Uncertainty: 0.04 μGal
Ocean Load Factor: 0.10

Average Ocean Load Uncertainty: 0.00 μGal
Barometric: 1.00 μGal
Polar Motion: 0.05 μGal
Laser: 0.05 μGal
Clock: 0.50 μGal
System Type: 1.10 μGal
Tidal Swell: 0.00 μGal
Water Table: 0.00 μGal
Unmodeled: 0.00 μGal
System Setup: 1.00 μGal
Gradient: 3.90 μGal (0.03 μGal/cm)
Gradient: 0.90 μGal (0.03 μGal/cm)