Gravity measurements with a portable absolute gravimeter A10 in Syowa Station and Langhovde, East Antarctica

Takahito Kazama a,*,1, Hideaki Hayakawa b,1, Toshihiro Higashi c,1, Shingo Ohsono d,1, Shunsuke Iwana e,2, Tomoko Hanyu b,1, Harumi Ohta f,1, Koichiro Doi b,1, Yuichi Aoyama b, Yoichi Fukuda a, Jun Nishijima g, Kazuo Shibuya b

a Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
b National Institute of Polar Research, Tokyo 190-8518, Japan
c TerraGrav LLC, Kyoto 612-8017, Japan
d GNSS Technologies Inc., Tokyo 160-0022, Japan
e Tomakomai National College of Technology, Hokkaido 059-1275, Japan
f Global Ocean Development Inc., Kanagawa 233-0002, Japan
g Graduate School of Engineering, Kyushu University, Fukuoka 819-0395, Japan

Received 26 March 2013; revised 13 June 2013; accepted 18 July 2013
Available online 31 July 2013

Abstract

Absolute gravity values were measured with a portable absolute gravimeter A10 in East Antarctica, for the first time by the Japanese Antarctic Research Expedition. This study aims to investigate regional spatiotemporal variations of ice mass distributions and associated crustal deformations around Syowa Station by means of repeated absolute gravity measurements, and we obtained the first absolute gravity value in Southern Langhovde on the Antarctic Continent. The average absolute gravity value at the newly installed benchmark AGS01 in Langhovde (obtained on 3 February 2012) was 982535584.2 ± 0.7 μgal (1 μgal = 1 × 10⁻⁸ [m/s²]), which was in agreement with the gravity values obtained by the past relative gravity measurements within 1 μgal. In addition, the average absolute gravity value obtained at AGSaux in Syowa Station was consistent with both previous absolute gravity values and those obtained by simultaneous measurements using an FG5 gravimeter, owing to adequate data corrections associated with tidal effects and time variations in atomic clock frequencies. In order to detect the gravity changes associated with the ice mass changes and other tectonic phenomena, we plan to conduct absolute gravity measurements at AGS01 again and at other campaign sites around Syowa Station as well in the near future, with careful attention paid to the impacts of severe environmental conditions in Antarctica on gravity data collection.

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Keywords: Absolute gravity; Antarctica; A10 gravimeter; Ice mass balance; Glacial isostatic adjustment

1. Introduction

Gravity measurements provide a powerful approach to the detection of time variations in mass distributions on Earth, such as those related to seismic crustal
deformations (e.g., Imanishi et al., 2004), volcanic eruptions (e.g., Furuya et al., 2003), and water transfer (e.g., Kazama et al., 2012). In Antarctica, gravity measurements have been conducted to monitor ice mass balance, the viscoelastic response of the Earth to past changes in ice mass loading (so-called postglacial rebound or glacial isostatic adjustment), and the elastic response of the Earth to present-day deglaciation (e.g., Mäkinen et al., 2007). In addition, crustal deformation data, such as those available from global positioning system (GPS) measurements (e.g., Ohzono et al., 2006) and InSAR (e.g., Rignot et al., 2011), are often used in conjunction with gravity data, because the gravity data alone cannot distinguish the sources of the gravity changes (e.g., Wahr et al., 1995).

In Syowa Station, a Japanese research station on East Ongul Island (white stars in Fig. 1a–b), several geodetic datasets have been obtained since the Japanese Antarctic Research Expedition (JARE) was launched in 1956. For example, FG5 absolute gravimeters (e.g., Niebauer et al., 1995) have been used to repeatedly measure absolute gravity values at International Absolute Gravity Basestation Network, category A site #0417 (IAGBN(A); Boedecker and Fritzer, 1986) in the Gravity Observation Hut (Gravity Hut; Fig. 2b) since 1995 (Sugawara, 2011). Also, superconducting gravimeters (SGs) in the Gravity Hut and GPS instruments located at SYOG (Fig. 2b) have continuously observed time variations in gravity and three-dimensional coordinates, respectively (Iwano et al., 2005; Ohzono et al., 2006). On the other hand, relative gravity and GPS measurements have been conducted only once a year at campaign sites on outcrops along Lützow-Holm Bay near Syowa Station (gray circles and triangle in Fig. 1b; Geospatial Information Authority of Japan (GSI), 2002), except for a continuous GPS site installed by GSI (GPScont; Fig. 2c). In addition, large systematic errors can be present in the relative gravity data on account of instrumental drift and gravity gaps, because transport of the gravimeters between Syowa Station and the campaign sites by snowmobile or helicopter subjects the gravimeters to vibrations. Therefore, to obtain precise gravity values at the campaign sites as well as at Syowa Station, absolute gravity measurements should be conducted with a portable absolute gravimeter.

Recently, satellite gravity data from GRACE (e.g., Tapley et al., 2004) and GOCE (e.g., Floberghagen et al., 2011) have been used to investigate
spatiotemporal gravity distributions in Antarctica. Fig. 1a–b shows gravity trends in Antarctica, estimated from release-5 GRACE data (provided by the Center for Space Research (CSR), University of Texas at Austin) for the period from January 2004 to September 2012, with the application of a 500-km Gaussian filter. Whereas glacier melting in West Antarctica has resulted in decreasing gravity values at a maximum rate of $-3.7 \mu mgal/year$ (Fig. 1d), gravity has increased at a rate of $+0.79 \mu mgal/year$ at Syowa.
Station (Fig. 1b and c) on account of an above-average snowfall (Yamamoto et al., 2008; Shepherd et al., 2012). However, small-scale (e.g., several tens of kilometers) gravity variations cannot be detected by GRACE due to its limited sensitivity. In order to inspect gravity changes related to snow accumulation, glacial isostatic adjustment, or other factors around Syowa Station at a higher resolution, in-situ gravity measurements using accurate gravimeters (such as absolute gravimeters) are required, not only at Syowa Station but also over widespread areas of East Antarctica.

We were thus motivated to measure absolute gravity values along the Soya Coast and Prince Olav Coast (Fig. 1b) as part of the 53rd Japanese Antarctic Research Expedition (JARE-53). We used a portable absolute gravimeter A10 (Liard and Gagnon, 2002; Micro-g LaCoste, 2008a) with serial number 017 (A10 #017); the A10 was chosen over the FG5 because of its lighter weight and smaller body dimensions (100 kg and 90 cm for the A10) and its capacity to run on 12-V DC electric power at cold temperatures (0–100°F). LaCoste & Romberg gravimeters and GPS receivers were also used to measure gravity values and three-dimensional coordinates at newly installed benchmarks. Although we first planned to measure absolute gravity values at several of the campaign sites shown by gray circles in Fig. 1b, operation schedules were substantially changed because of thick sea ice in Lützow-Holm Bay, which interrupted the approach of the icebreaker Shirase(5003) to Syowa Station. By the end of the expedition, we were only able to measure absolute gravity values at several of the campaign sites located approximately 27 km south of Syowa Station (triangle in Fig. 1b; Fig. 2c) on 3 February 2012. The location was chosen because we expected that the area around Langhovde Glacier (dashed ellipse in Fig. 2a) would be an appropriate site for monitoring gravity changes related to ice mass redistributions and consequent crustal deformations (Sawagaki et al., 2008; Sugiyama et al., 2012).

In this study, we will report on the results of the first absolute gravity measurements in Langhovde on the Antarctic Continent conducted by JARE-53; the results should be used as a reference of temporal gravity changes in future studies. Because the gravity values obtained previously by relative gravimeters were less accurate than the absolute gravity value, we were unable to determine with any degree of certainty the temporal variations in gravity values in the region. Instead, we will describe the technical details of absolute gravity measurements using the A10 gravimeter for future measurements.

2. Overview of the gravity and GPS measurements

2.1. Absolute gravity measurements using the A10 gravimeter

We employed a portable absolute gravimeter A10 for the absolute gravity measurements in Antarctica. The A10’s main body is composed of two pieces: a dropping chamber and an interferometer base (IB) unit (Micro-g LaCoste, 2008a). The IB unit (lower part of the A10 in Fig. 2d) contains a laser which can emit laser beams at two different wavelengths. Although the two wavelengths vary over time, the A10 estimates a true and stable absolute gravity value with a minimum accuracy of 10 μgal by averaging the gravity values obtained with the two laser beams (Niebauer et al., 1988). The main body is connected to the A10 controller and a laptop. The laptop uses ‘g’ Absolute Gravity Processing Software (g-soft, version 8.09.01.13; Micro-g LaCoste, 2008b) to estimate the gravity value for each drop of the corner-cube reflector, using both the falling distance measured by laser interferometry and the falling time measured by a 10-MHz rubidium clock in the A10 controller. During the gravity estimations, g-soft automatically corrects for gravity changes associated with air pressure changes, polar motions, solid-earth tides, and ocean tide loadings. The important setting parameters for g-soft are presented in Table 1, and other configurations are as follows: polar coordinates given by the International Earth Rotation and Reference Systems Service (IERS) Bulletin A and a delta factor of 1.164 for polar motion corrections; and a delta factor of 1.0 for permanent tide corrections.

We conducted absolute gravity measurements with the A10 #017 at three sites: [1] AGSaux, an auxiliary benchmark for gravity measurements in the Gravity Hut, Syowa Station (Fig. 2b); [2] BM2316, an outdoor benchmark in Syowa Station, located approximately 20 m southeast of AGSaux (Fig. 2b); and [3] AGS01, a newly installed benchmark on bedrock in Langhovde, located approximately 27 km south of Syowa Station (Fig. 2c and d). Gravity values at these sites were calculated according to the following procedure. First, a set gravity value was calculated as the average of 100-drop gravity values, which were automatically estimated by g-soft, according to the drops of the corner-cube reflector at 1 s intervals. Here, the gravity values just on the benchmark were estimated, using the vertical gravity gradient and the mechanical height at each site (Table 1). Second, at a typical interval of 3 min, two adjacent set gravities ($g_{pi}$ and $g_{mi}$) were...
Table 1
Parameters for the absolute gravity measurements. (a) Parameters for IAGBN(A), from Sugawara (2011). (b) See Table 2. (c) Prior to 10 January 2012, when an IB-unit tripod was not used. (d) On and after 10 January 2012, when an IB-unit tripod was used. (e) No data are available, because the pair gravity is not defined for FG5. Note that the mechanical height (“actual height” in g-soft) represents the sum of the reference height (or setup height) and the factory height.

<table>
<thead>
<tr>
<th>Station</th>
<th>AGSaux</th>
<th>IAGBN(A)</th>
<th>BM2316</th>
<th>AGS01</th>
</tr>
</thead>
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<tr>
<td>Gravimeter</td>
<td>A10#017</td>
<td>FG5#210</td>
<td>A10#017</td>
<td>A10#017</td>
</tr>
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<td>-69.00673(a)</td>
<td>(b)</td>
<td>(b)</td>
</tr>
<tr>
<td>Longitude [deg]</td>
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<td>39.5869(a)</td>
<td>(b)</td>
<td>(b)</td>
</tr>
<tr>
<td>Altitude [m]</td>
<td>21.492(a)</td>
<td>21.492(a)</td>
<td>(b)</td>
<td>(b)</td>
</tr>
<tr>
<td>Mechanical height [cm]</td>
<td>70.50(c), 75.50(d)</td>
<td>128.42</td>
<td>75.50</td>
<td>75.65</td>
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<tr>
<td>Gravity gradient [µgal/cm]</td>
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<td>-3.339(a)</td>
<td>-3.339(a)</td>
<td>-3.429</td>
</tr>
<tr>
<td>Nominal pressure [hPa]</td>
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<td>984.08(a)</td>
<td>984.08(a)</td>
<td>1012.54</td>
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<tr>
<td>Barometric admittance [µgal/hPa]</td>
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<td>-0.32(a)</td>
<td>-0.32(a)</td>
<td>-0.30</td>
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<tr>
<td>Observed drops</td>
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<td>21920</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>Observed sets</td>
<td>562</td>
<td>179</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Observed pairs</td>
<td>275</td>
<td>n.d. (c)</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

measured with the two laser beams of different wavelengths:

\[ \lambda_p = 632.9918963 \text{ [nm]} \]  \hspace{1cm} (1)

\[ \lambda_m = 632.9909270 \text{ [nm]}, \]  \hspace{1cm} (2)

which were estimated during the A10 calibrations by the manufacturer (Micro-g Lacoste, February 2009). Third, a mean gravity value (\( g_{ai} \); hereafter called a pair gravity) and its error (\( \varepsilon_{ai} \)) were calculated by the following equations:

\[ g_{ai} = \frac{g_p + g_m}{2}, \]  \hspace{1cm} (3)

\[ \varepsilon_{ai} = \sqrt{\varepsilon_p^2 + \varepsilon_m^2} \]

\[ = \sqrt{\frac{\sigma_p^2}{100} + \frac{\sigma_m^2}{100}}. \]  \hspace{1cm} (4)

Here, the suffix \( i \) indicates the pair number, and \( \varepsilon_{ai} \) and \( \sigma_{ai} \) \((* = p, m)\) show the error value and the standard deviation of \( g_{ai} \), respectively. Finally, an average gravity value \( (g) \), its standard deviation \( (\sigma) \), and its standard error \( (\varepsilon) \) at each site were estimated from

\[ g = \frac{\sum g_{ai}/\varepsilon_{ai}^2}{\sum 1/\varepsilon_{ai}^2}, \]  \hspace{1cm} (5)

\[ \sigma = \sqrt{\frac{\sum (g - g_{ai})^2/\varepsilon_{ai}^2}{\sum 1/\varepsilon_{ai}^2}}, \]  \hspace{1cm} (6)

\[ \varepsilon = \frac{\sigma}{\sqrt{N}}, \]  \hspace{1cm} (7)

where \( N \) is the number of the pair gravity values. Note that in the processing by g-soft, the final gravity value \( (g) \) is originally calculated as the simple mean of the weighted averages of \( g_{pi} \) and \( g_{mi} \) (Micro-g LaCoste, 2008b). However, we first calculated the pair gravity \( (g_{ai}) \) from \( g_{pi} \) and \( g_{mi} \) (Eq. (3)), so as to verify the stability of the measured gravity values according to the deviation of \( g_{ai} \) from \( g \) (Eq. (5)).

2.2. Relative gravity measurements using LaCoste gravimeters

In order to check for local gravity changes due to crustal deformations, local mass movements, or other factors, we installed additional gravity benchmarks at AGS03 in Syowa Station (Fig. 2b), and at AGS01, GS005, GS006, GS007 and AGS02 along the Yatude Valley in Langhovde (Fig. 2c). In Syowa Station, we measured a gravity value at AGS03 relative to that at the gravity reference site IAGBN(A) in the Gravity Hut, using a LaCoste & Romberg gravimeter (serial number: G805). In Langhovde, we also measured gravity values at GS00i \((i = 5−7)\) and AGS02 relative to that at the absolute gravity site AGS01, using the other LaCoste gravimeter (serial number: G1110). In addition, the LaCoste G1110 was used to measure the vertical gravity gradient at AGS01. The gravity difference between each gravity site and the reference station was calculated, after correcting for the effects of tides, mechanical height variations, and instrumental drifts, assuming a linear instrumental drift.

2.3. GPS measurements

We determined precise three-dimensional coordinate positions of the gravity sites in Syowa and
Langhovde using a GPS receiver, to utilize the precise positions for gravity data processing, and to enable us to detect crustal deformations in East Antarctica in future studies. All GPS data was collected using a JAVAD GrAnt-G3T antenna and a GNSS GEM-1 receiver. At BM2316, AGS01 and AGS03 in Syowa Station (Fig. 2b and c), GPS signals were collected for about 1 day at a sampling rate of 1–30 s with the GPS antenna fixed. The GPS signals were also continuously collected during the relative gravity survey along the Yatude Valley in Langhovde at a sampling rate of 1 s; the GPS antenna was fixed for approximately 2 min immediately after the relative gravity measurements at GS00i (i = 5–7) and AGS02 (Fig. 2c).

The GPS data was analyzed with the precise point positioning algorithm included in the GIPSY/OASIS II software package (version 6.1.2). Here, static solutions were used to estimate the positions of BM2316, AGS01, and AGS03, and kinematic solutions were used to estimate the site positions along the Yatude Valley. The coordinates at GS00i (i = 5–7) and AGS02 were determined as the averages of the kinematic coordinate values during the periods when the GPS antenna was fixed. For both static and kinematic solutions, the cutoff angle for the minimum GPS elevation was set at 15.0°. The final coordinate values (latitude, longitude, and ellipsoidal height) of the antenna at each site were obtained in the WGS84 coordinate system, and the altitude of each benchmark was then calculated by subtracting the antenna height and the geoid height of EGM2008 (Pavlis et al., 2012) from the ellipsoidal height.

Fig. 3a–c shows the deviations of the kinematic solution at the fixed GPS site, AGS01. Although the average values of the kinematic solution (dashed lines) are nearly equal to those of the static solution (solid lines), the kinematic solutions show unstable time variations, possibly due to the multipath effect and under/over-correction of the atmospheric delay. This fact suggests that systematic errors were present in the measurement of kinematic coordinates during the moving observations along the Yatude Valley in Langhovde. Here, we use the standard deviations of the kinematic solution at AGS01 (Fig. 3a–c):

![](image)

Fig. 3. Static and kinematic coordinates, estimated from GPS data collected at AGS01. In panels (a)–(c), the gray lines show the time variations in the kinematic solutions, from which each average coordinate value was subtracted. The solid and dashed lines show the coordinate values of the static solutions and the average values of the kinematic solutions (exactly equal to 0 in these panels). Differences between the static solutions and the averages of the kinematic solutions are displayed on the right sides of these figures. (a) Latitude. (b) Longitude. (c) Ellipsoidal height. (d) Elevation angle of GPS satellites seen from AGS01. GPS satellites with elevations less than 15° are shown by gray lines.
Latitude : $0.1256 \times 10^{-6}$ [deg] \hspace{1cm} (8)

Longitude : $0.2477 \times 10^{-6}$ [deg] \hspace{1cm} (9)

Height : $0.06080$ [m], \hspace{1cm} (10)

as substitutes for the systematic errors associated with the kinematic solutions at GS00i ($i = 5$–7) and AGS02.

3. Frequency calibration of the A10 rubidium clock

Nishijima et al. (2011) found that absolute gravity values observed at Kyushu University with the A10 #017 showed an artificial linear gravity decrease of approximately $-0.1$ $\mu$gal/day, possibly due to frequency changes of the rubidium clock, which measures the falling times of the corner-cube reflector. If the clock frequency changes from $F$ (=10 [MHz]) to $F + \dot{f}$ ($|\dot{f}| \ll |F|$), the artificial gravity change ($g_{\text{false}} - g_{\text{true}}$) can be expressed as

$$g_{\text{false}} - g_{\text{true}} = -2g_{\text{false}} \frac{\dot{f}}{F},$$

where $g_{\text{false}}$ and $g_{\text{true}}$ are the incorrect and true gravity values, respectively. Note that this equation neglects a term of the fourth power of the falling time associated with the vertical gravity gradient, although the term was taken into account in calculating the drop gravities in g-soft (Micro-g LaCoste, 2008b). According to this equation, the artificial gravity change is about 10 $\mu$gal (which is the accuracy of A10 gravimeters, as reported by Micro-g LaCoste, 2008a) if $|\dot{f}| = 0.05$ [Hz].

We thus calibrated the A10 clock frequency during the absolute gravity measurements in Antarctica, so as to obtain accurate absolute gravity values. Five available atomic clocks were available in Syowa Station: a hydrogen maser in the Seismographic Hut, a cesium clock, a spare portable rubidium clock for the FG5 and A10 gravimeters (denoted by S), the FG5’s rubidium clock (F), and the A10’s rubidium clock (A) in the Gravity Hut. During the gravity measurements in Antarctica, we regularly output two of the five clock signals on an oscilloscope in order to measure the frequency differences between the two clocks. We then assumed long-term frequency stability for the hydrogen maser and the cesium clock, and linear frequency variations of

$$f_i(t) = A_i + t \cdot B_i$$

for the other clocks ($i = S, F, A$), and determined the drift parameters ($A_i$ and $B_i$) using a least-squares method. The circles and solid lines in Fig. 4a–c show the measured and calculated frequency values, respectively. The calculated drift rates are

$$B_S = -0.000098 \ [\text{Hz/day}]$$
$$B_F = +0.000019 \ [\text{Hz/day}]$$
$$B_A = -0.001605 \ [\text{Hz/day}],$$

and the calculated frequency values on 1 January 2012 are

$$f_S(1 \text{ Jan. 2012}) = +0.001230 \ [\text{Hz}]$$
$$f_F(1 \text{ Jan. 2012}) = -0.000946 \ [\text{Hz}]$$
$$f_A(1 \text{ Jan. 2012}) = +0.172093 \ [\text{Hz}].$$

The right axes of Fig. 4a–c show the approximate correction values ($\Delta g$) for the conversion from incorrect gravity values ($g_{\text{false}}$) to true gravity values ($g_{\text{true}}$), given by

$$\Delta g = g_{\text{true}} - g_{\text{false}} = 2g_{\text{false}} \frac{\dot{f}}{F} \sim 200 \cdot f \ [\mu\text{gal}],$$

where $g_{\text{false}} \sim 1000$ [gal], $F = 10$ [MHz] and $\dot{f}$ is expressed in Hz. Whereas $\Delta g$ of the spare and FG5 clocks had a small amplitude (<1 $\mu$gal) and slow variation rate (<0.02 $\mu$gal/day), $\Delta g$ of the A10 clock was significantly greater than the A10 accuracy (10 $\mu$gal) and changed rapidly by about $-0.32$ $\mu$gal/day, whose order is consistent with that of Nishijima et al. (2011).

To obtain accurate absolute gravity values, the calculated frequency variations (solid lines in Fig. 4a–c) were put into g-soft when the collected gravity data was reprocessed, according to the clock used during each absolute gravity measurement. However, for the former 10 pair gravities obtained at AGS01 on 3 February 2012, we used the measured frequency value of the A10 clock (gray circle in Fig. 4c) of 0.122965 Hz, as Fig. 4c shows that the deviation between the measurements (circles) and the calculations (solid line) was large during February 2012 ($t \geq 30$ [day]).

Although we do not know the reason(s) for the large frequency drift in the A10 clock, Imanishi et al. (2002) also speculated that an unstable rubidium clock was responsible for the large drift in absolute gravity values observed using an FG5 gravimeter at Matsushiro, one of the SG stations in Japan. One possible cause of the rubidium clock instability may be related to the permeation of helium gas into the cell of rubidium gas in the A10 unit (Herbulock et al., 2004),
as the A10 #017 was installed adjacent to an SG at Cibinong, Indonesia once a year during the period 2009–2011 (e.g., Fukuda et al., 2010; Itakura et al., 2013); the helium gas emitted when filling the SG with liquid helium may have caused the A10 clock instability. Note that the A10’s rubidium clock was replaced after the gravity measurements in Antarctica, because the $D_g$ values significantly exceeded the typical gravity uncertainty associated with clock frequency inaccuracy, which are about 0.5 μgal (Micro-g LaCoste, 2008b). For the new A10 clock, the frequency deviation from 10 MHz and its variation rate (i.e., $|f_A|$ and $|B_A|$) in November 2012 were less than $10^{-3}$ Hz and $10^{-2}$ μgal/day, respectively; these values were consistent with those of the spare and FG5 clocks (Fig. 4a–b).

4. Results of absolute gravity measurements

4.1. AGSaux, Syowa Station

We obtained over 50,000 drops of absolute gravity values at AGSaux in the Gravity Hut during the period from 30 December 2011 to 28 January 2012 (second column in Table 1). Fig. 5a shows the gravity values of the effective 275 pair gravities at AGSaux. Although the gravity difference ($\Delta g_i = g_{pi} - g_{mi}$) varied from approximately 80–250 μgal (Fig. 5c), the values of $g_{ai}$ were nearly constant and much less dispersed than those of $g_{pi}$ or $g_{mi}$ (Fig. 5a); in addition, the $g_{ai}$ values were normally distributed, as shown in Fig. 5d. We determined the absolute gravity value at AGSaux as

$$g_{AGSaux} = 982524324.6 \pm 0.4 \, \text{μgal}. \quad (20)$$

Using the gravity difference at IAGBN(A) relative to AGSaux (−1.3 μgal; Sugawara, 2011), the gravity value at IAGBN(A) can be calculated as

$$g_{IAGBN(A10)} = 982524323.3 \pm 0.4 \, \text{μgal}. \quad (21)$$

Fig. 5e shows the absolute gravity values measured at IAGBN(A) with the FG5 #210 from 2 January to 8 January 2012 (Higashi et al., 2013). The FG5 data was processed along with the A10 data, except that the mechanical height of the FG5 was used for the height correction (see the third column in Table 1), and the pair gravity was not defined for the FG5 data because the FG5 gravity was measured using a single laser with
a stabilized wavelength (Niebauer et al., 1995; Micro-g LaCoste, 2006). The average gravity value obtained by the FG5 was

$$g_{\text{IAGBNA}}(\text{FG5}) = 982524321.5 \pm 0.1 \text{ [\mu gal]}.$$

The gravity value obtained by the FG5 #210 was consistent with that obtained by A10 #017 (Eq. (21)) within 2 \(\mu\)gal, which confirms the reliability of the absolute gravity values obtained by the A10. This result also suggests that the accuracy of the A10 would be better than the official accuracy (10 \(\mu\)gal; Micro-g LaCoste, 2008a), as long as the gravity is measured at a stable site and gravity disturbances such as tides and clock effects are adequately corrected (Schmerge and Francis, 2006; E et al., 2011).

### 4.2. BM2316, Syowa Station

We conducted static GPS and absolute gravity measurements at BM2316 near the Gravity Hut (Fig. 2b) on 12–13 January 2012, in order to check the measurement procedures in the field. The coordinates determined from the GPS data are shown in Table 2. The estimated altitude at BM2316 (19.985 m above sea
level) differs from that of the past result (21.15 m; GSI, 2002) by about 1.2 m, because the latter altitude referred to the local mean sea level at Nishinoura in Syowa Station (Fig. 2b; Shibuya et al., 1999).

Fig. 6 shows the gravity values obtained at BM2316. Here, three parameters (the gravity gradient, nominal pressure, and barometric admittance) at IAGBN(A) and AGSaux were used as substitutes for those at BM2316 to correct for gravity changes associated with changes in air pressure and instrumental height (Table 1). However, the prolonged duration of transportation (about 20 min) between the Gravity Hut and BM2316 in the absence of an electric power supply resulted in a cooling and instability of the A10 laser in the IB unit, and the resulting absolute gravity measurements at BM2316 were therefore less reliable than those obtained at AGSaux. For example, deviations of the pair gravity \( g_{ai} \) at BM2316 were

<table>
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<th>Station</th>
<th>BM2316</th>
<th>AGS01</th>
<th>AGS03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate values obtained by GPS</td>
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<td>Sampling interval [s]</td>
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<td>Gravity differences relative to IAGBN(A), measured using the LaCoste G805</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative gravity [μgal]</td>
<td>+178</td>
<td>n.d.</td>
<td>+1647</td>
</tr>
</tbody>
</table>

Fig. 6. Absolute gravity values obtained with the A10 #017 at BM2316 in Syowa Station on 12 January 2012. (a) The triangles and inverted triangles show the set gravities \( g_{pi} \) and \( g_{mi} \), respectively. The circles show the pair gravity, \( g_{ai} \). Each error bar shows the standard error value \( \varepsilon_{pi} \), \( \varepsilon_{mi} \), and \( \varepsilon_{ai} \). (b) Difference between the set gravities, \( \Delta g_i = g_{pi} - g_{mi} \). (c) Histogram of the pair gravity. \( N \), \( g \), \( \sigma \), and \( \varepsilon \) are the number, average, standard deviation, and standard error of the pair gravity values, respectively. Note that the excluded pair gravity value, shown as white symbols in panels (a) and (b), was not counted in this histogram.
greater than those at AGSaux (Fig. 5(b)). If the first pair gravity is omitted from the dataset (since the original data of the first pair gravity was poorly correlated with parabolic lines on account of laser instability), the average gravity value is calculated as

\[ g_{BM2316(A10)} = 982524599.5 \pm 13.0 \text{ [μgal]} \quad (23) \]

However, this gravity value differs from that obtained with the LaCoste G805 on 15 February 2012 of

\[ g_{BM2316(LC)} = 982524501 \text{ [μgal]} \quad (24) \]

by approximately 100 μgal. Note that this gravity value was obtained using the gravity difference between BM2316 and IAGBN(A) (Table 2) and the reference gravity value at IAGBN(A) (Eq. (21)). The cause for this inconsistency in the obtained gravity values might also be the laser failures in the A10, rather than instrumental errors of the LaCoste gravimeter. These results emphasize the importance of warming gravimeter instruments, even when not making measurements, to obtain precise absolute gravity values under ambient environmental conditions in Antarctica.

### 4.3. AGS03, Syowa Station

We installed the benchmark AGS03 near the Earth Science Laboratory in Syowa Station (Fig. 2b) as the new reference site for future absolute gravity measurements; static GPS and relative gravity measurements were conducted at AGS03 on 17 and 18 February 2012. The fourth column of Table 2 shows the three-dimensional coordinates and the gravity difference at AGS03 relative to IAGBN(A). The absolute gravity value at AGS03 was calculated as

\[ g_{AGS03} = 982525970 \text{ [μgal]} \quad (25) \]

using the reference gravity value determined at IAGBN(A) by the A10 #017 (Eq. (21)).

### 4.4. Langhovde

We conducted gravity and GPS measurements in Langhovde from 2 to 4 February 2012. Fig. 2d shows the measurement setting of the A10 gravimeter on 3 February 2012. The dropper and the IB unit were installed in a bottomless tent on a new benchmark AGS01, and the A10 controller was set up in an adjacent tent. Electric power was supplied by a generator in Yukidorizawa Cottage, via a battery charger and four batteries in case of power failure. To prevent artificial gravity changes caused by laser cooling (as described above in relation to the measurements at BM2316), we warmed up the instruments for about 4 h before starting the measurements. In addition, the vertical gravity gradient at AGS01 was measured by the LaCoste G1110 and determined to be \(-3.429 \pm 0.024 \text{ [μgal/cm]}\).

Fig. 7a–c shows the absolute gravity values obtained at AGS01, using the parameters in Tables 1 and 2 for the gravity calculations in g-soft. Most of the two set gravities (\(g_{pi}\) and \(g_{mi}\)) are symmetric about the dashed line, but five pair gravities, shown as white symbols in Fig. 7a, deviate from the dashed line by about 20 μgal. The deviations are related to a decrease in the \(g_{pi}\) value of the five set gravities by about 40 μgal, although we do not fully understand why only the value of \(g_{pi}\) decreased in this interval. If we average all of the pair gravity values, the averaged gravity can be calculated as

\[ g_{AGS01(20pairs)} = 982535580.4 \pm 1.8 \text{ [μgal]} \quad (26) \]

On the other hand, if we exclude the five deviant gravity values from the average estimation, the averaged gravity becomes

\[ g_{AGS01(15pairs)} = 982535584.2 \pm 0.7 \text{ [μgal]} \quad (27) \]

We adopted the latter gravity value as the final one, since the error value in Equation (27) is smaller than that in Equation (26). Note that Fig. 7c shows a histogram of the pair gravity values, excluding the five deviant gravity values.

Table 3 shows the measured relative gravity values and kinematic GPS coordinates at GS00i (\(i = 5–7\)) and AGS02 in the Yatude Valley. The free-air gravity anomaly (\(\Delta g_F\)) can be estimated from the absolute gravity value (\(g\)), altitude (\(h\)), and latitude (\(\phi\)), according to

\[ \Delta g_F(x,y) = g(x,y) + \frac{dy}{dh}h(x,y) - \gamma(\phi(x,y)), \quad (28) \]

where \((x,y)\), \(\gamma\), and \(dy/dh\) are the horizontal coordinates, and the normal gravity and its vertical gradient (=3.086 [μgal/cm]), respectively. Here, Equation (27) was used to calculate the absolute gravity values at the gravity sites along the Yatude Valley. The estimated free-air gravity values (solid circles in Fig. 7d) are consistent with the cross-section values of the local free-air anomaly model (Fig. 7e; Fukuda et al., 2012) between AGS01 and AGS02 (along E29°S) within the
modeled error range (gray area in Fig. 7d). The deviation of the free-air gravity at GS007 is larger than those at the other sites, possibly because of a small-scale free-air anomaly around GS007. Additional gravity measurements will be required in the future to verify the existence of the small-scale gravity anomaly in this area. In addition, repeated gravity measurements will be necessary in future studies, in order to monitor temporal changes in gravity values.

5. Discussion

5.1. Comparison with past gravity values

Absolute gravity values have been measured in the Gravity Hut at Syowa Station since the 1990s, mainly for the purpose of detecting gravity changes related to postglacial rebound (e.g., Hiraoka et al., 2005; Sugawara, 2011). In addition, campaign
Gravity measurements have been conducted on bedrock areas around Syowa Station, including in Langhovde, since the 1950s, using IAGBN(A) as the reference gravity station (e.g., GSI, 2002). Here, our absolute gravity values obtained during JARE-53 are compared with those of past gravity measurements.

The circles in Fig. 8a show absolute gravity values at IAGBN(A) in Syowa Station during 1995–2012. In this figure, the gravity values during 1995–2010 and their decreasing trend in Sugawara (2011) were utilized, and the lengths of error bars indicate five times standard error values, according to Fig. 5 in Sugawara (2011). The gravity value measured by the A10 is consistent with the past gravity values within ±5 μgal, as well as with the gravity value simultaneously measured by the FG5 (Eq. (22)). In addition, the gravity value of the A10 overlaps with the decreasing trend of the gravity values during 1995–2010 (dashed line; Sugawara, 2011). In these respects, the A10 #017 provided reasonable absolute gravity measurements during JARE-53.

Table 4 shows the gravity differences relative to the IAGBN(A) reference, measured in Langhovde with the Scintrex, LaCoste, and A10 gravimeters over the past 20 years (1990s–2010s). The subscripts i and j represent site and survey numbers, respectively; thus, the absolute gravity value at the i-th site on the j-th survey can be written as $g_{i,j}$. Using the gravity values measured at BM3702 (i = 2; a benchmark next to the continuous GPS site, GPScont), BM3903 (i = 3; a benchmark approximately 100 m away from AGS01), and GPScamp (i = 4; a campaign GPS site next to BM3903) (Fig. 2c), the relative gravity value at AGS01 (i = 1) to IAGBN(A) (defined as i = 0) on the j-th survey was calculated as

$$g_{1,j} - g_{0,j} = \left( g_{i,j} - g_{0,j} \right) - \left( g_{i,0} - g_{1,0} \right)$$

$\equiv \left( g_{i,j} - g_{0,j} \right) - \left( g_{i,0} - g_{1,0} \right)$ \hspace{1cm} (29)

$$g_{2,0} - g_{1,0} = -4742 \text{ [μgal]}$$ \hspace{1cm} (30)

$$g_{3,0} - g_{1,0} = -13 \text{ [μgal]}$$ \hspace{1cm} (31)

$$g_{4,0} - g_{1,0} = -182 \text{ [μgal]}.$$ \hspace{1cm} (32)

Here, the gravity differences at BM3702, BM3903, and GPScamp relative to AGS01 were assumed to be constant and equal to those measured in November 2012 with the LaCoste G805 (defined as $j = 0$). Moreover, the absolute gravity value at AGS01 ($g_{1,i}$) was calculated from Equation (29), using the measured gravity difference ($g_{ij} - g_{0,j}$; Table 4) and the estimated absolute gravity change at IAGBN(A) ($g_{0,j}$; dashed line in Fig. 8a).

The circles in Fig. 8b show the calculated absolute gravity values at AGS01 (i.e., $g_{1,i}$), except for the rightmost circle, which shows the gravity value measured during JARE-53 with the A10 #017.
The previous gravity values deviate from the A10’s value by approximately 50 mgal to 1 mgal at most, suggesting that the previous relative gravity values contained significant systematic errors, possibly due to instrumental drifts and/or gravity tares during transportation between Syowa Station and Langhovde. We would like to emphasize here that in-situ absolute gravity measurements should be conducted repeatedly, so as to accurately monitor gravity changes at the bedrock areas on the Antarctic Continent. In the near future, we will use the A10 #017 again to measure absolute gravity values not only at AGS01 but also at other bedrock stations, to detect the spatiotemporal variations in absolute gravity in East Antarctica.

5.2. Some notes on absolute gravity measurements in Antarctica

The 53rd Japanese Antarctic Research Expedition (JARE-53) made its first measurement of the absolute gravity values at AGS01, calculated from the relative gravity data (Table 4) and the estimated absolute gravity change at IAGBN(A) (dashed line in the panel (a)), except that the rightmost circle shows the absolute gravity measured with the A10 #017 during JARE-53 (Eq. (27)). The right axis shows the difference value between the previous gravity data and the absolute gravity value obtained during JARE-53.

The previous gravity values deviate from the A10’s value by approximately 50 μgal to 1 mgal at most, suggesting that the previous relative gravity values contained significant systematic errors, possibly due to instrumental drifts and/or gravity tares during transportation between Syowa Station and Langhovde. We would like to emphasize here that in-situ absolute gravity measurements should be conducted repeatedly, so as to accurately monitor gravity changes at the bedrock areas on the Antarctic Continent. In the near future, we will use the A10 #017 again to measure absolute gravity values not only at AGS01 but also at other bedrock stations, to detect the spatiotemporal variations in absolute gravity in East Antarctica.

Table 4

<table>
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<tr>
<th>j</th>
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<th>Equipment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Reference</th>
</tr>
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<tr>
<td>1</td>
<td>37th Jan. 1996</td>
<td>Scintrex-CG3M</td>
<td>(12225)</td>
<td>7553</td>
<td>n.d.</td>
<td>11973</td>
<td>(a)</td>
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<tr>
<td>2</td>
<td>40th Jan. 1999</td>
<td>Scintrex-CG3M</td>
<td>(11321)</td>
<td>6573</td>
<td>11313</td>
<td>n.d.</td>
<td>(a)</td>
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<tr>
<td>3</td>
<td>45th Oct. 2004</td>
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<td>n.d.</td>
<td>n.d.</td>
<td>11538</td>
<td>(b)</td>
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<tr>
<td>4</td>
<td>45th Jan. 2005</td>
<td>LaCoste-G1110</td>
<td>(11476)</td>
<td>n.d.</td>
<td>11393</td>
<td>11363</td>
<td>(b)</td>
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<tr>
<td>5</td>
<td>48th Dec. 2006</td>
<td>LaCoste-G583</td>
<td>(11404)</td>
<td>6645</td>
<td>11407</td>
<td>n.d.</td>
<td>(c)</td>
</tr>
</tbody>
</table>
gravity at AGS01 on the Antarctic Continent. We would like to make some remarks on absolute gravity measurements in Antarctica.

5.2.1. Power supply

Electrical power should be continuously supplied to the A10 during both transportation and gravity measurements. For example, DC 12 V power was supplied to the A10 dropper via a battery, both onboard the ship and during helicopter transport, so as to maintain the vacuum in the dropper and minimize the necessity of vacuuming operations at Syowa Station. High-capacity batteries and a charger were also connected to the A10 controller in Syowa Station and Langhovde (see Section 4.4 and Fig. 2d), in anticipation of temporary blackouts of AC 100 V power during gravity measurements. Note that sufficient batteries must be available for outside gravity measurements, because low temperatures in Antarctica substantially reduce battery power and lifetime.

5.2.2. Mica

Small particles of weathered black mica in gneissic bedrock outcropping around Syowa Station are suspended in the air during takeoff and landing of helicopters; these particles can cause failures of electronic instruments. During transportation by helicopter between Syowa Station and Langhovde, we covered the main body of the A10 gravimeter with static-free plastic bags to prevent mica from entering the A10 body. The measurement tents also protected the A10 from mica particle contamination during outside gravity measurements.

5.2.3. Tidal effects

In principle, adequate tidal models are required to accurately correct for tidal gravity changes, although few sophisticated tidal models are available for Antarctica (e.g., Kim et al., 2011). We applied Iwano et al. (2005) and the CSR3.0 model (one of the tidal model options in gsoft) to correct for the tidal gravity changes in Syowa Station and Langhovde, respectively, because our computational tests showed that these models minimized the standard deviations of the measured gravity values at AGSaux and AGS01. The tidal gravity values calculated with the Iwano and CSR3.0 models are in good agreement with those of the Schwiderski model (the default tidal model in gsoft) within about 3 μgal (Fig. 9b, d). These results suggest that systematic errors associated with tidal models are negligible with respect to typical gravity measurements with A10 gravimeters, whose official

Fig. 9. Tidal gravity changes, including the effects of solid-earth tide and ocean tide loading. (a) The solid and gray lines show the tidal gravity changes at the Gravity Hut in Syowa Station, derived using the models of Iwano et al. (2005) and Schwiderski. (b) The solid curve shows the difference between the tidal gravity changes derived using the Iwano and Schwiderski models (panel (a)). (c) The solid and gray lines show the tidal gravity changes at AGS01 in Langhovde, derived using the CSR3.0 and Schwiderski models. (d) The solid curve shows the difference between the tidal gravity changes derived using the CSR3.0 and Schwiderski models (panel (c)). Note that in panels (a) and (c), an arbitrary value is added to each tidal gravity, and each permanent tide is shown as a dashed line.
accuracy is 10 μgal (Micro-g LaCoste, 2008a). However, corrections based on adequate tidal models should be applied, when precise gravity trends are determined from absolute gravity values obtained with FG5 gravimeters in Syowa Station (e.g., Sugawara, 2011).

6. Conclusions

During JARE-53 (2011–2012), we conducted absolute gravity measurements at AGSaux, BM2316, and AGS01 in East Antarctica, using the portable absolute gravimeter A10 #017, with the goal of investigating the spatiotemporal gravity distributions in the vicinity of Syowa Station. The average value of the measured gravity at AGSaux in the Gravity Hut of Syowa Station was 982524824.6 ± 0.4 μgal, which was in agreement with both past absolute gravity values and those simultaneously obtained using the FG5 #210. Our results suggested that the accuracy of A10 gravimeters can be better than that of the officially stated systematic error of 10 μgal, as long as gravity measurements are conducted at a stable site and precise corrections are made for time-dependent gravity disturbances due to tides and frequency changes of atomic clocks. At the new benchmark AGS01 in Southern Langhovde, the A10 was warmed up prior to gravity measurements, because we found that temperature effects caused absolute gravity values to deviate from the relative value obtained at BM2316. The measured gravity value at AGS01 was 982535584.2 ± 0.7 μgal, which was the first absolute gravity data obtained on the Antarctic Continent by JARE. This gravity value was consistent with previous relative gravity values within 1 mgal, although the previous data may contain significant systematic errors associated mainly with instrumental drifts and gravity steps during transportation.

During JARE-53, absolute gravity values on the Antarctic Continent were obtained only at AGS01, on account of navigation delays of the icebreaker Shirase(5003) due to thick sea ice, which forced us to alter our operation schedule. However, the results of our investigations will be useful in future absolute gravity measurements at AGS01 and other campaign sites around Syowa Station (gray circles in Fig. 1b).

Acknowledgments

This study was conducted as a project of the 53rd Japanese Antarctic Research Expedition (JARE-53; project number: AP18-53). The icebreaker Shirase(5003) (Japan Maritime Self-Defense Force), Helicopter Resources Pty. Ltd., and construction members of JARE-52/53 supported us in the transportation of the A10 #017 and the FG5 #210 to Antarctica. The Geospatial Information Authority of Japan (GSI) provided us with the cesium clock in the Gravity Hut at Syowa Station, the relative gravity data obtained by JARE-48, and the previous absolute gravity data at IAGBN(A). We thank S. Miyazaki, T. Ohkura (Kyoto University), Y. Ohta (Tohoku University), T. Kim (National Institute of Polar Research), N. Izumi (Japan Coast Guard), and Y. Tamura (National Astronomical Observatory of Japan) for their helpful advice regarding the processing of GPS and tide data. We also thank J. Deal, O. Francis, and one anonymous reviewer for their help in improving the manuscript. GMT (version 4.5.7; Wessel and Smith, 1998) and Google Earth (Version 5.1.2600.3; http://earth.google.com/) were used to create some of the figures in this report.

References


