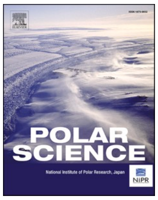
Polar Science 29 (2021) 100702

Contents lists available at ScienceDirect

Polar Science

journal homepage: www.elsevier.com/locate/polar



Gravity observations at Jang Bogo Station, Antarctica, and scale factor calibrations of different relative gravimeters

Yoichi Fukuda [a,*], Jun'ichi Okuno [a,b], Koichiro Doi [a,b], Choon-Ki Lee [c]

[a] National Institute of Polar Research, 10-3 Midoricho, Tachikawa, Tokyo, 190-8518, Japan
[b] The Graduate University for Advanced Studies, SOKENDAI, Tokyo, 190-8518, Japan
[c] Korea Polar Research Institute, 26 Songdomirae-ro, Yeonsu-gu, Incheon, 21990, Republic of Korea

ARTICLE INFO

Keywords:
Gravity monitoring
Absolute gravimeter measurement
Superconducting gravimeter
Scale factor calibration
LaCoste D gravimeter

ABSTRACT

We conducted gravity observations in Antarctica at Jang Bogo Station (JBS) during the 2019–2020 Austral summer season using an FG5-210 absolute gravimeter (AG) and a LaCoste & Romberg (LCR) Model D-58 relative gravimeter. Absolute gravity measurements were successfully made at reference gravity point JBSAG1 and newly established gravity point JBSAG2, yielding about 19,000 and 14,400 drops of data, respectively, with measurement precisions better than 0.4 μGal (1 μGal = 10^{-8} m s^{-2}). In addition, relative gravity measurements were conducted at 10 other newly established gravity points, with accuracies better than 10 μGal, to supplement the absolute gravity data. Superconducting gravimeter (SG) observation with an iGrav-021 instrument has been underway at JBS since 2016. Since an SG is a relative gravimeter, the calibration of the scale factor is essential for long-term gravity monitoring. In addition, the D-58 instrument was required for scale factor calibration. To calibrate the scale factors of these gravimeters, we first estimated a value for the iGrav-021 using parallel observations with the FG5-210 instrument. The D-58 scale factor was then estimated indirectly from parallel observations with the iGrav-021. These calibrations should ensure accurate gravity monitoring in future work.

1. Introduction

Gravity measurements in Antarctica have mainly been used to study subsurface density structures; examples of questions addressed include resolving basement topography beneath the ice sheet (*e.g.*, Yanai and Kakinuma, 1971; Abe et al.,1978); identifying crustal structures (*e.g.*, Kanao et al., 1994; Shibuya and Fukuda, 1999; Toda et al., 2013); and other geodetic–geophysical related studies such as establishing a gravity reference station (*e.g.*, Harada et al., 1963; Kaminuma et al.,1984). While early measurements used relative gravimeters, absolute gravity measurement in Antarctica began in the early 1990s, with the primary goal of providing accurate reference values for relative measurements. Today there is an increasing need to monitor gravity changes due to the Earth's dynamics, such as glacial isostatic adjustment (GIA) and elastic deformation associated with present day ice-mass changes. Since the launch of the Gravity Recovery and Climate Experiment (GRACE) in 2002, which greatly contributed to studies of mass changes in the Antarctic ice sheet (*e.g.*, Velicogna and Wahr, 2006; Yamamoto et al., 2008), ground-based precision gravimetry has been expected to contribute ground truth measurements to augment satellite observations and provides indispensable information for extraction of the GIA effect. High-precision gravity observations using absolute gravimeters (AGs) and superconducting gravimeters (SGs) (*e.g.*, Shibuya et al., 2003; Fukuda et al., 2005; Makinen et al., 2007; Aoyama et al., 2015) have strong potential for such studies.

JBS is the second Korean Antarctic research station in Terra Nova Bay, Victoria Land, and has been operated by the Korea Polar Research Institute (KOPRI) since 2014 (https://www.kopri.re.kr/eng/html/infra/02040101.html). KOPRI has made continuous SG observations with the GWR iGrav-021 instrument since 2016, and more recently introduced a Micro-g LaCoste (MGL) A10-036 absolute gravimeter (Lee et al., 2017). Since the SG is a relative gravimeter, the scale factor of the instrument must be determined before gravity variations can be discussed. For this purpose, parallel observation with an AG is strongly recommended (*e.g.*, Fukuda et al., 2005). At the Japanese-operated Syowa Station, the only other Antarctic observatory with SG measurements to date, SG instruments are occasionally calibrated using FG-5 absolute gravimeters (*e.g.*, Iwano et al., 2003; Fukuda et al., 2005; Aoyama et al., 2015); at JBS, however, SG instruments were previously calibrated only with the A10-036 instrument. Although an A10 is a useful instrument for

---

* Corresponding author.
E-mail address: fukuda.yoichi.48n@st.kyoto-u.ac.jp (Y. Fukuda).

https://doi.org/10.1016/j.polar.2021.100702
Received 18 February 2021; Received in revised form 24 May 2021; Accepted 25 May 2021

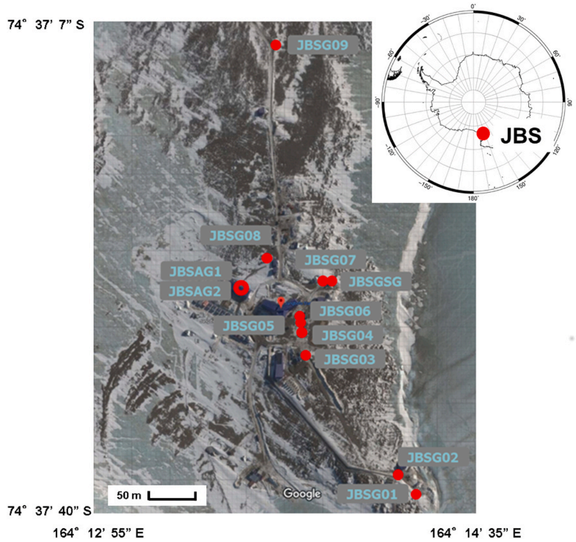


Fig. 1. Location of Jang Bogo Station (JBS) and gravity survey points at JBS research station, Antarctica.

field surveys (*e.g.*, Kazama et al., 2013), its accuracy is inferior to that of an FG-5. Therefore, to establish absolute gravity points at JBS and calibrate the scale factor of the iGrav-021 instrument, we conducted absolute gravity observations using FG5-210 at JBS during the 2019–2020 Austral summer season. In addition, to supplement AG measurements and to detect local gravity changes around JBS, we conducted gravity observations using a spring-type relative gravimeter, a LaCoste and Romberg (LCR) D-58 with feedback (L and R Meter Service, 2009).

Since the D-58 is a relative gravimeter, calibration of its scale factor is also necessary. Usually, the scale factor of a spring-type gravimeter can be calibrated through net adjustment of measurements at points whose absolute gravity values are known and whose gravity differences are large (*e.g.*, Torge, 1989; Fukuda et al., 2017; Yahagi et al., 2019). However, such a method is almost impossible in this case, because JBS is a remote site in Antarctica and the measurement range of the D-58 is $<$ 200 mGal (1 mGal $= 10^{-5}$ m s^{-2}). Therefore, in this study we calibrate the instrument indirectly (*e.g.* Arnoso et al., 2014; Riccardi and Berrino, 2002, 2011, 2012; Meurers, 2012; Navarro et al., 2021). We first compared iGrav-021data with FG5-210 data and estimated the scale factor of the iGrav-021; we then compared parallel Earth tide observations for about 10 days using uncalibrated D-58 and calibrated iGrav-021 data. Although this method used only low-amplitude Earth tide signals, high-precision observations of the D-58 with feedback, which can continuously record tide signals with a precision ~0.1 μGal (1 μGal $= 10^{-8}$ m s^{-2}), allowed us to estimate the scale factor successfully.

We now describe the gravity measurements conducted at JBS, and then describe the scale factor calibration procedure and results.

Table 2
Summary of vertical gravity gradient measurements.

		Δh	ΔG	error	dg/dh	error
	(cm) (cm)	cm	μGal	μGal	μGal/cm	μGal/cm
JBSAG1	U (112.5) - D(0)	112.5	253.0	1.9	2.249	0.017
	U (112.5) - M (51.7)	60.8	149.0	2.1	2.451	0.035
	M (51.7) - D(0)	51.7	104.0	2.2	2.012	0.043
JBSAG2	U (82.2) - D(0)	82.2	246.4	2.9	2.997	0.035

*Heights were measured from the floor surface with the accuracy of better than 1 mm.

2. Gravity measurements at Jang Bogo station

2.1. *Absolute gravity measurements*

Fig. 1 shows the location map and gravity measurement points around JBS. The main part of JBS is constructed on the glacial sedimentary deposits covering early Paleozoic basement. There is an absolute gravity point inside the heavy gear maintenance building of JBS, labeled “JBSAG1” in the figure, which was occupied by the A10-036 gravimeter. Because JBSAG1 is at the bottom of the maintenance bay, the vertical gravity gradient is not expected to be linear, as discussed below. This may introduce additional uncertainty to comparisons of gravity data from different instrument types. Because we expect that at least one additional absolute gravity point will be necessary for long-term monitoring, we established a second measuring point on the flat floor of the same building (labeled “JBSAG2” in Fig. 1). Locations and complete descriptions of these points can be found in Appendix A.

We made measurements at JBSAG1 from 17 to November 25, 2019, comprising 100 drops/set at a 30-min set interval for 24 h on 18 and 19 November; 50 drops/set at a 60-min set interval for 24 h from 19 to 22 November; and 50 drops/set at a 30-min set interval for 24 h on 23 and 24 November. Measurement patterns were varied to ensure a longer measurement period without risking unnecessary exhaustion of the instrument; this is desirable for calibration of the iGrav-021 scale factor. Following these measurements, additional data were recorded at JBSAG2 from 25 to 28 November, with 100 drops/set at a 30-min set interval, for 24 h.

We used the “g9” software package (Micro-g LaCoste, 2012) for data processing. We calculated absolute gravity values at 130 cm and 0 cm relative to the floor above the gravity points, using gravity gradient values of −2.249 μGal/cm for JBSAG1 and −2.997 μGal/cm for JBSAG2 calculated according to the procedure described below. The absolute gravity values (weighted averages of projected values) at the 0 cm level are 982856218.0 ± 4.3 μGal for JBSAG1 and 982856039.8 ± 4.3 μGal for JBSAG2, a difference of 178.2 μGal. A gravity difference of 176 μGal was obtained from independent measurements with the D-58, showing good consistency between methods. These results are summarized in Table 1.

To calculate vertical gravity gradients, relative gravity differences at different heights above the gravity points were measured with the D-58 instrument. For site JBSAG2, we made measurements at two practical levels: 0 cm (*D*) and 82.2 cm (*U*), with a height difference $U - D = 82.2$ cm. Because JBSAG1 is located at the bottom of the maintenance bay, we

Table 1
Summary of absolute gravity measurements.

Station	Code	Lat (deg N)	Lon (deg E)	H (m)	Date (2019)	dg/dz (μGal/cm)	Number of accepted drops	Precision (μGal)	gravity at 130 cm (μGal)		gravity at 0 cm (μGal)	
Jang Bogo	JBSAG1	−74.62340	164.22547	18.3	Nov. 18-25	−2.249	19101	0.38	982855925.6	±1.9	982856218.0	±4.3
	JBSAG2	−74.62342	164.22553	19.4	Nov. 25-28	−2.997	14398	0.32	982855650.2	±1.9	982856039.8	±4.3

Table 3
Summary of relative gravity measurements.

Points	Lat (deg N)	Lon (deg E)	H (m)	G-diff[a] (mGal)	Error (mGal)	G-value[b] (mGal)	Error (mGal)	N of Obs.
JBSAG2	−74.62342	164.22553	19.4	0.000	0.005	982856.040	0.000	7
JBSG01	−74.62740	164.23935	0.7	5.395	0.006	982861.435	0.008	3
JBSG02	−74.62713	164.23754	9.2	4.265	0.005	982860.305	0.007	4
JBSG03	−74.62502	164.23080	21.7	0.641	0.006	982856.681	0.008	3
JBSG04	−74.62440	164.23004	21.0	0.312	0.005	982856.352	0.007	8
JBSG05	−74.62403	164.23087	22.5	0.304	0.006	982856.344	0.008	4
JBSG06	−74.62399	164.23094	20.7	0.334	0.006	982856.374	0.008	4
JBSG07	−74.62337	164.23188	21.5	0.115	0.006	982856.155	0.008	6
JBSG08	−74.62294	164.22777	26.1	−1.063	0.006	982854.977	0.008	4
JBSG09	−74.61877	164.22840	41.1	−5.255	0.007	982850.785	0.009	2
JBSGSG[c]	−74.62337	164.23208	18	0.841	0.008	982856.881	0.009	2

[a] Gravity difference relative to JBSAG2.

[b] Absolute gravity value at JBSAG2 (982856.040 mGal) was fixed.

[c] Position was indirectly estimated relative to JBSG07.

made measurements at three different levels: 0 cm (*D*), 51.7 cm (*M*), and 112.5 cm (*U*) above the reference point, and calculated gradient values for *U*−*D*, *U*–*M,* and *M*−*D*, respectively. Results are summarized in Table 2. Although the gradient values at JBSAG1 vary from 0.2 to 0.3 μGal/cm with respect to height, we used the *U*−*D* gradient value to calculate the gravity value on the floor because the actual measurement height of the FG-5 is about 128 cm, close to the height of *U* (112.5 cm).

More detailed descriptions, and the original datasets of the absolute gravity measurements, are found in Fukuda et al. (Polar Data Journal, *in prep.*).

2.2. Relative gravity measurements

We conducted relative gravity measurements at 10 newly established gravity points. Nine of these points, designated JBSG01–JBSG09, were located outside the buildings. Point JBSGSG was located next to the iGrav-021 in the iGrav observation hut. JBSG01–JBSG09 were located on flat concrete base of construction and/or monuments and marked with metal pins or paint to facilitate precise long-term measurements. The positions of these points were determined by GPS measurements with PPP (precise point positioning), and their heights were determined as the sum of the observed ellipsoidal heights and calculated geoid heights using the Earth Gravitational Model EGM2008 (Pavlis et al., 2012). The locations of these points are shown in Fig. 1 and detailed descriptions are found in Appendix A.

Relative gravity measurements used a mixture of the simple loop and profile methods (double occupation; Torge, 1989), starting from JBSAG2. Each loop was scheduled so that successive measurements could be completed within a few hours. Some control points were included in different loops to strengthen the net adjustments; consequently, each point was occupied 2–8 times, with an average of 4 occupations. Each measurement was conducted using the 2 Hz digital output of the D-58 feedback system. As a practical way to obtain an adopted value after unclamping the spring, we monitored the digital outputs for a few minutes, until the output fluctuations became less than a few μGals. Measured values were corrected for Earth tides, and instrumental drift was corrected for each loop using a least squares method (LSM) that assumes a linear trend in time and unknown gravity differences. Finally, gravity values at JBSAG02 were fixed and the gravity value at each point was calculated from the weighted averages of the loop measurements. Table 3 summarizes the results of the relative measurements; note that the scale factor for D-58 (0.99649), described

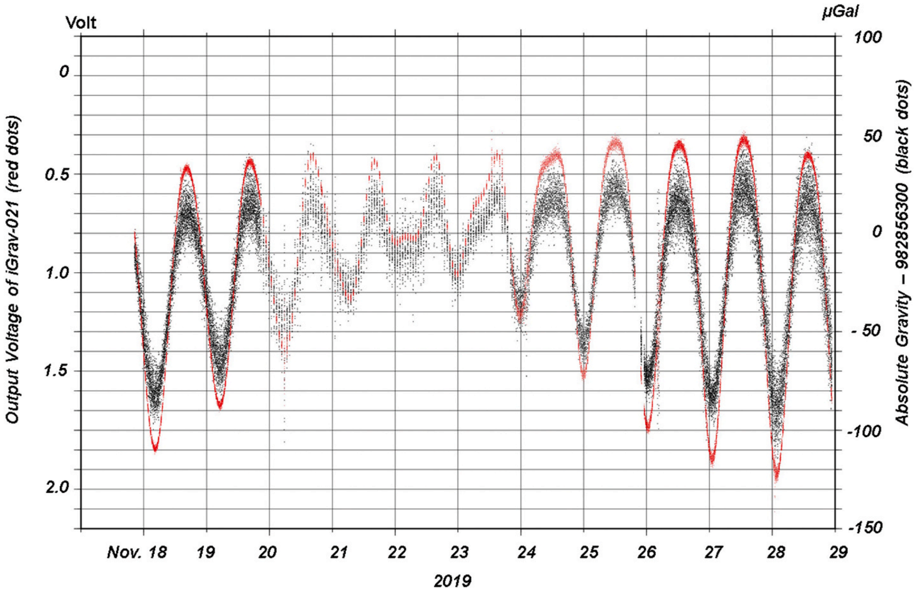


Fig. 2. Time variations in FG5-210 drop data (black dots) and corresponding iGrav-021 data (red dots). Note that iGrav data are plotted with inverted *y*-values for better visual comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

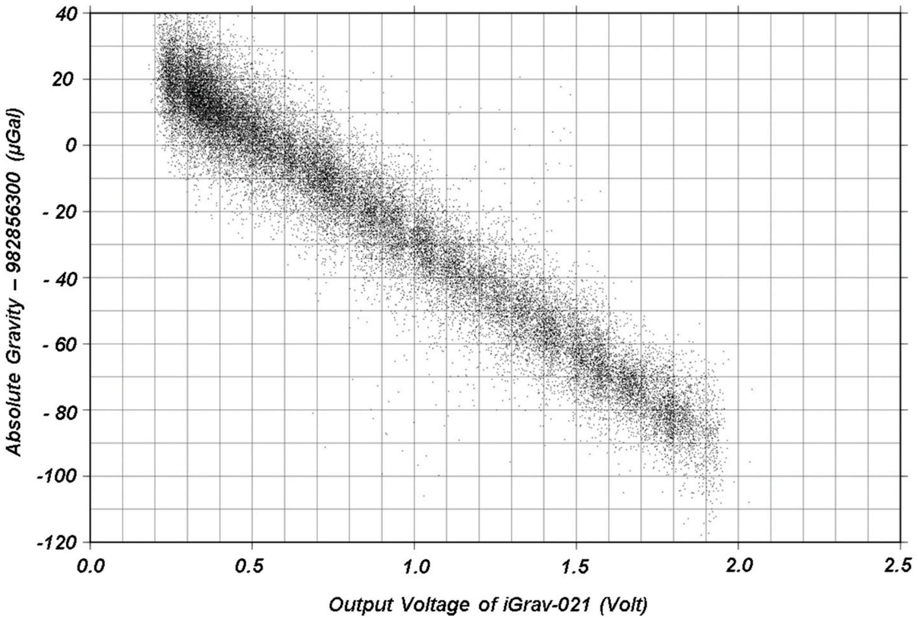


Fig. 3. Plots of all corresponding data points, iGrav-021 (abscissa) vs. FG5-210 (ordinate).

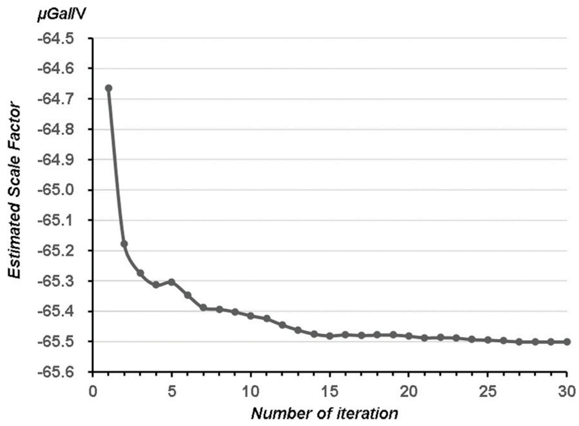


Fig. 4. Estimated scale factor of iGrav-021 (μGal/V) as a function of number of least squares iterations.

below, was applied to all relevant values before their inclusion in Table 3.

3. Scale factor calibration

3.1. Calibration of iGrav-021 with FG5-210

In spite of its high sensitivity and stability, an SG is a relative gravimeter, and therefore requires calibration of a scale factor that transforms an output signal in Volts to an acceleration in μGals. Parallel observations with an AG are often used for this purpose (*e.g.*, Iwano et al., 2003; Fukuda et al., 2005; Aoyama et al., 2015). We used FG5-210 drop values without geophysical corrections (*i.e.*, tide signals, atmospheric effects, and Earth rotation), collected as described above, to calibrate the iGrav-021 in this study. Then, using the time tags of the drop values, we determined output voltages at identical absolute sample times using 1 Hz data from the iGrav-021. Fig. 2 shows FG5 data as black dots and iGrav-021 data as red dots. Note that the gravity difference between JBSAG1 and JBSAG2 (178.2 μGal) was corrected in advance, and data at both points are plotted in Fig. 2. Therefore, we treated the FG5-210 drop data in Fig. 2 as if they were measured at the same point as JBSAG1.

To estimate the iGrav-021 scale factor, we assumed the observation equation.

$$ag\_v_i = A^*sg\_v_i + B^*t_i + C + \mathrm{res}_{\mathrm{i},}(i = 1, 2, \&, N) \quad (1)$$

and estimated the unknown parameters A (scale factor), B (drift rate), and C (constant bias) that minimized the sum of squares of the residuals res_i in a least-squares sense; here, ag_v_i are absolute values, sg_v_i are SG output voltages, t_i is an observation time in DOY (day of year), and N is the number of data points. Fig. 3 shows the plot of the raw sg_v_i vs. ag_v_i. At each step in the fitting, data for which the RMSE (root mean squares error) residuals exceed 2σ are excluded. Iterations continued until estimated parameters did not change. Fig. 4 plots the estimated scale factor A as a function of iteration number. Fig. 5 shows the final plot of the sg_v_i vs. ag_v_i output.

The final parameter values obtained were $A = -65.5006 \pm 0.0620$ μGal/V, $\mathrm{B} = 0.0324 \pm 0.0083$ μGal/day, and $\sigma = 4.94$ μGal. Note that the estimated drift rate (B) has a very small value, ~10 μGal/year. Also note that the 6 significant digits would be meaningless as the scale factor of iGrav-021. Considering its estimated error, $A = -65.50 \pm 0.062$ would be more appropriate. However, the value was also used for the calibration of D-58. Therefore, we kept more digits for the value. To fully utilize SG data in precise Earth tide and gravity monitoring studies, a calibration factor with an accuracy of 0.1% or better is desired (*e.g.*, Baker and Bos, 2001); the estimated factor suggests a relative accuracy of 0.095%, and thus fulfills this requirement.

3.2. Calibration of D-58 with iGrav-021

The D-58 with feedback has a function to output 2 Hz digital gravity values; using this, we recorded gravity signals from 27 November to December 6, 2019 at location JBSGSG, beside the iGrav-021 in the SG observation hut. For direct comparison with iGrav-021 data, D-58 gravity values were resampled to synchronize with the 1 Hz sampling interval of the iGrav-021; Fig. 6 plots the raw results, using red dots for 1 Hz iGrav-021 data and black dots for D-58 data. The D-58 instrument shows a large drift, ~100 μGal/day, while the drift of the iGrav-021 is negligible. On the other hand, the iGrav-021 data show noisy signals after 3 December, when wind speed was increasing and sea ice outflow intensified; the D-58 did not show such a significant noise effect here

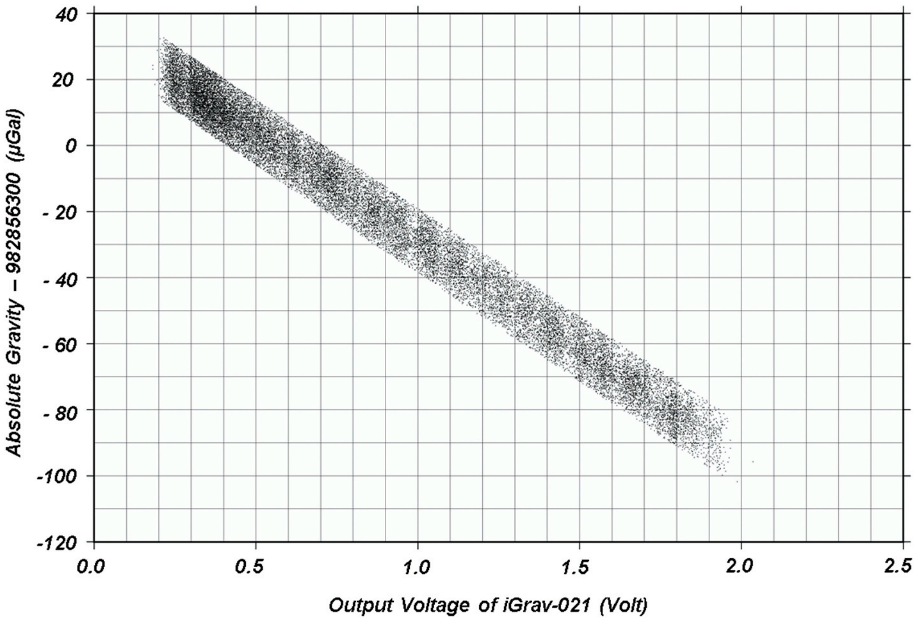


Fig. 5. Plots of all corresponding values, iGrav-021 data (abscissa) vs. FG5-210 drop data (ordinate), after discarding outliers through iterative least squares inversion.

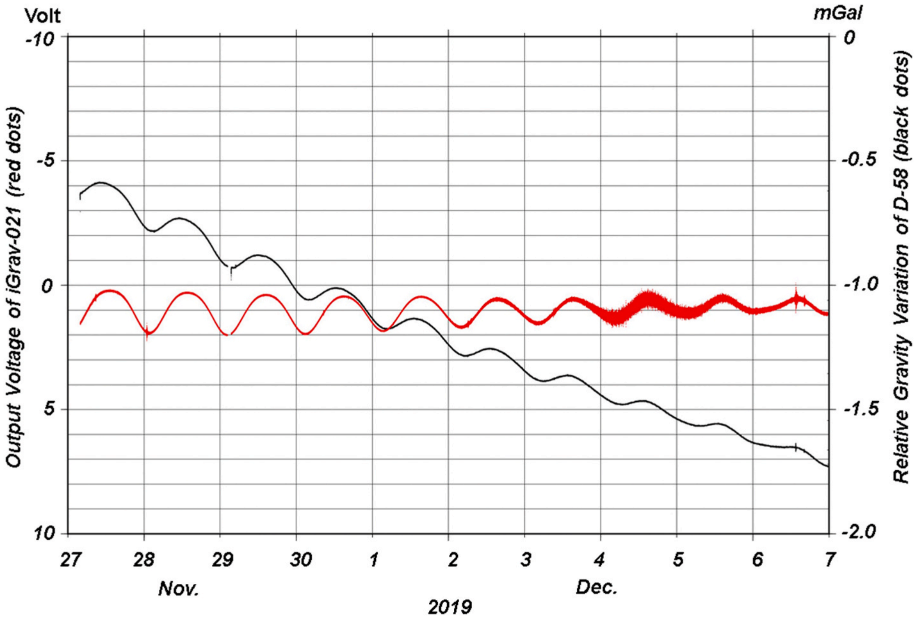


Fig. 6. Time variations in D-58 data (black dots) and corresponding iGrav-021 data (red dots). Note that iGrav data are plotted with their *y*-values inverted for better visual comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

because the characteristics of built-in lowpass filter are different from those of the iGrav-021; the latter is more sensitive to high-frequency signals.

The outline of the D-58 scale factor calibration procedure is as follows.

1) Assuming a D-58 scale factor of 1.0, estimate the iGrav-021 scale factor following the same calibration procedure as above, with FG5-210 data as reference values.
2) Compare the scale factor of the iGrav-021 estimated with the D-58 (*SF_D-58*) to the scale factor estimated for it with the FG5-210 (*SF_FG5*).
3) Indirectly estimate the adjustment factor for the scale factor of the D-58 as the ratio *SF_FG5/SF_D-58*.

The first step of this procedure has only one difference from the procedure using FG-5 data in §3.1: we assume a quadratic function for the drift model due to the large drift of D58 in Fig. 6. Thus, the modified form of the observation equation (1) is.

$$d58\_v_i = A * sg\_v_i + B * t_i^2 + C * t_i + D + res_i, (i = 1, 2, \&, N) \quad (2)$$

where $d58\_v_i$ are D58 gravity values with an assumed scale factor of 1.0, and the parameters A to D are iteratively estimated by least-squares inversion.

Fig. 7 shows a plot of the raw sg_v_i vs. $d58\_v_i$. Fig. 8 shows the

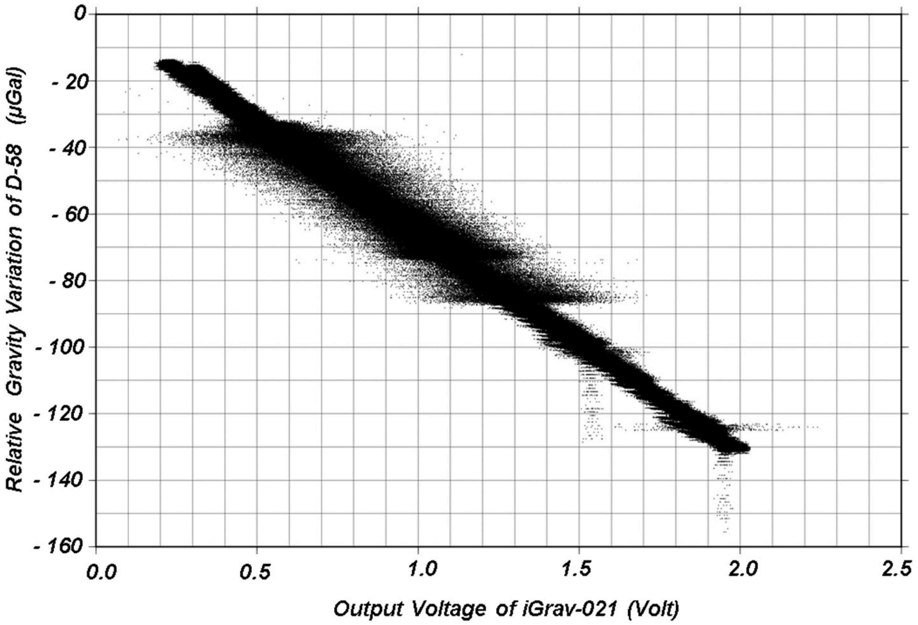


Fig. 7. Plots of all corresponding data points, iGrav-021 (abscissa) vs. D-58 (ordinate).

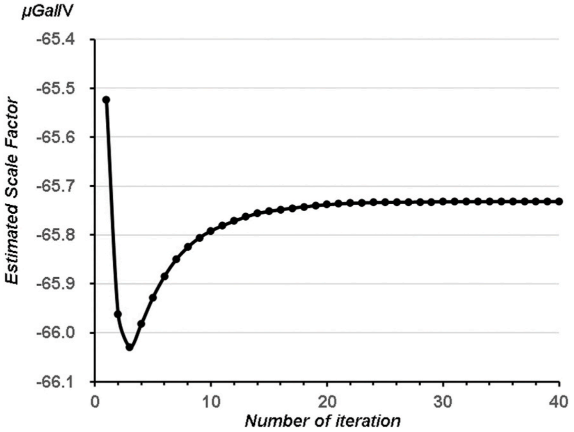


Fig. 8. Estimated scale factor of the iGrav-021 (in μGal/V) using D-58 reference data, as a function of number of least squares iterations. The scale factor of D-58 is assumed to be 1.0 here, as explained in §3.2.

estimated scale factor A as a function of iteration number, and Fig. 9 shows the final plot of sg_v_i vs. $d58\_v_i$ output. Note that Fig. 7 shows the large fluctuations in iGrav data described above, but some outliers are also present in the D58 data; these values were discarded during the iteration procedure. The final plot of Fig. 9 shows good correlation between datasets, which ensures more accurate estimation of the scale factor. We obtained parameter values for equation (2) of $A = SF\_D\text{-}58 = -65.7313 \pm 0.0042$ μGal/V, $B = 2.93641 \pm 0.00026$ μGal/day^2, $C = -302.846 \pm 0.0165$ μGal/day, and $\sigma = 1.51$ μGal. The adjustment factor for the scale factor of D58 can be calculated from $SF\_FG5/SF\_D\text{-}58 = (-65.5006 \pm 0.0620/-65.7313) = 0.99649 \pm 0.00096$, where we assumed that the original scale factor of D-58 was 1.0. We do not need to distinguish between the adjustment factor and the scale factor in this procedure, so this value can be used as a scale factor.

The scale factor of the D-58 was independently calibrated during gravity surveys in the northern part of Kumamoto Prefecture, Japan, in August 2018 (Kazama et al., 2019); the estimated value was 0.996992 ± 0.000085. This is coincident with the present value to within the estimated error, which supports the validity of the indirect calibration method in this study.

4. Conclusions

We successfully conducted absolute gravity measurements at two survey points in Jang Bogo Station (JBS), Antarctica, using an FG5-210 gravimeter, which is the *de facto* standard for precise absolute gravity measurements. These were made at one pre-established location and one new site, to facilitate reoccupation by future gravity surveys. The condition of the FG5-210 was checked by comparative measurements in Japan before and after the measurements at JBS, and no instrumental problems were encountered. We therefore conclude that the accuracy of our absolute gravity values is better than a few μGals, which should allow for future detection of small gravity trends due to glacial isostatic adjustment (GIA) and/or ice mass changes.

We also conducted relative gravity measurements using a D-58 instrument at 10 newly established points around JBS. A scale factor calibration for D-58 was determined via calibration of the iGrav-021 scale factor using FG-5 measurements. When the uncertainty in the scale factor is included, the accuracies of the obtained gravity values are estimated to be better than 10 μGals, and could contribute to detection of local effects on gravity changes at JBS in the future.

The number of absolute gravity points in Antarctica is still very small and the dataset of repeated measurements is even more limited (*e.g.*, Makinen et al., 2007). Establishing new absolute gravity monitoring sites, as well as taking regularly repeated measurements at existing sites, should feature prominently in future studies.

SG observations in Antarctica have been conducted at only two research stations to date: Japan's Syowa Station and South Korea's Jang Bogo Station (JBS). In particular, iGrav-021 observations at JBS are expected to facilitate future SG observations in Antarctica, because operation of the iGrav is much less complicated than that of older SG instruments. In this study, AG data were used to calibrate the scale factor of the SG with a relative accuracy better than 0.1%. We therefore expect that the calibrated iGrav-021 data will be used for additional geodynamic studies in the future, not only GIA and ice mass changes in Antarctica, but global phenomena like Earth tides and/or Earth rotations.

Combining AG and SG observations is widely recommended (*e.g.*, Crossley and Hinderer, 2009; Wilmes et al., 2009) and its effectiveness

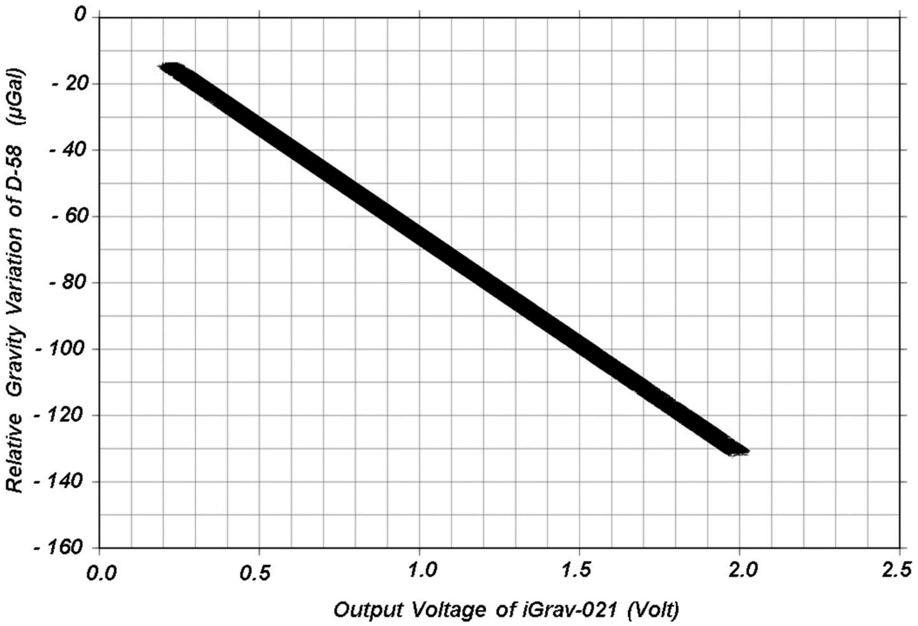


Fig. 9. Plots of corresponding data points, iGrav-021 (abscissa) vs. D-58 (ordinate), after discarding outliers through iterative least squares inversion.

for long-term gravity monitoring in Antarctica has already been demonstrated (*e.g.*, Aoyama et al., 2016). Therefore, SG observations with AG measurements in Antarctica should be expanded in coming years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Field observations at JBS were supported by Dr. Taejin Choi, the station leader, and all the other members of the summer party and wintering party. Without their support, this study would not have been completed. We thank all those who supported this study.

This study was partially supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant No. 17H06321 and a Korea Institute of Marine Science and Technology Promotion (KIMST) research grant (KIMST20190361; PM20020).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.polar.2021.100702.

References

Abe, Y., Yoshimura, A., Naruse, R., 1978. Gravity anomalies and bedrock relief in Mizuho Plateau. Mem. Natl. Inst. Polar Res. - Special Issue 7, 37–43.

Aoyama, Y., Ikeda, H., Hayakawa, H., Doi, K., Fukuda, Y., Shibuya, K., 2015. Observation and data archiving system of a superconducting gravimeter at Syowa Station, Antarctica. Int. J. Geosci. 6, 1116–1126.

Aoyama, Y., Doi, K., Ikeda, H., Hayakawa, H., Shibuya, K., 2016. Five years' gravity observation with the superconducting gravimeter OSG#058 at Syowa Station, East Antarctica: gravitational effects of accumulated snow mass. Geophys. J. Int. 205, 1290–1304. https://doi.org/10.1093/gji/ggw078.

Arnoso, J., Riccardi, U., Hinderer, J., Cordoba, B., Montesinos, F.G., 2014. Analysis of co-located measurements made with a LaCoste&Romberg Graviton-EG gravimeter and two superconducting gravimeters at Strasbourg (France) and Yebes (Spain). Acta Geod Geophys 49, 147–160. https://doi.org/10.1007/s40328-014-0043-y.

Baker, T.F., Bos, M.S., 2001. Tidal gravity observations and ocean tide models. J. Geodetic Soc. Jpn. 47, 76–81.

Crossley, D., Hinderer, J., 2009. The contribution of GGP superconducting gravimeters to GGOS. In: Sideris, M.G. (Ed.), Observing Our Changing Earth. International Association of Geodesy Symposia, vol. 133. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-85426-5_97.

Fukuda, Y., Iwano, S., Ikeda, H., Hiraoka, Y., Doi, K., 2005. Calibration of the superconducting gravimeter CT#043 with an absolute gravimeter FG5#210 at Syowa Station, Antarctica. Polar Geosci. 18, 41–48.

Fukuda, Y., Takiguchi, H., Kazama, T., Nishijima, J., Gulyaev, S., Natusch, T., Amos, M., Stagpoole, V., Pearson, C., 2017. New absolute gravity measurements in New Zealand. In: International Association of Geodesy Symposia, vol. 148. Springer, Berlin, Heidelberg, pp. 95–101. https://doi.org/10.1007/1345_2017_18.

Harada, Y., Kakinuma, S., Murata, I., 1963. Pendulum determination of the gravity difference between Tokyo, Mowbray and Syowa base. Antarct. Rec. 17, 35–50.

Iwano, S., Kimura, I., Fukuda, I., 2003. Calibration of the superconducting gravimeter TT70 #016 at Syowa Station by parallel observation with the absolute gravimeter FG5 #203. Polar Geosci. 16, 22–28.

Kaminuma, K., Abe, K., Tanaka, H., 1984. Leveling and gravity surveys at Syowa station, Antarctica. Antarct. Rec. 83, 62–74 (in Japanese with English abstract).

Kanao, M., Kamiyama, K., Ito, K., 1994. Crustal density structure of the Mizuho plateau, East Antarctica from gravity survey in 1992. Polar Geosci. 7, 23–36.

Kazama, T., Hayakawa, H., Higashi, T., Ohsono, S., Iwanami, S., Hanyu, T., Ohta, H., Doi, K., Aoyama, Y., Fukuda, Y., Nishijima, J., Shibuya, K., 2013. Gravity measurements with a portable absolute gravimeter A10 in Syowa station and Langhovde, East Antarctica. Polar Science 7, 260–277. https://doi.org/10.1016/j.polar.2013.07.001.

Kazama, T., Yoshikawa, S., Naganawa, K., Miyauchi, Y., Ohkura, T., Fukuda, Y., 2019. Absolute gravity measurements and scale factor calibration of relative gravimeters in the northern part of Kumamoto Prefecture in August 2018. Bull. Earthq. Res. Inst. Univ. Tokyo 94, 13–28 (in Japanese with English abstract).

L and R Meter Service, LLC, 2009. LRFG-300 Feedback Upgrade User's Manual, p. 37. www.gravitymeter-repair.com.

LaCoste, Micro-g, 2012. g9 User's Manual. www.microglacoste.com.

Lee, C.-K., Lee, W.S., Eom, J., Seo, K.-W., Kim, S.-H., 2017. Absolute and relative gravity monitoring in the Jangbogo Station, Antarctica. In: Presented at (Korea Geophysical Physics Exploration Society) Korean Society of Earth and Exploration Geophysicists, 2017. Spring Meeting, 2017.05.11~2017.05.12.

Makinen, J., Amalvict, M., Shibuya, K., Fukuda, Y., 2007. Absolute gravimetry in Antarctica: status and prospects. J. Geodyn. 43, 339–357.

Meurers, B., 2012. Superconducting gravimeter calibration by colocated gravity observations: results fromGWRC025. International Journal of Geophysics 12. https://doi.org/10.1155/2012/954271, 2012, Article ID 954271.

Navarro, J.C., Miranda, S.A., Herrada, A.H., Pacino, M.C., 2021. Rigorous calibration of a spring gravimeter for accurate Earth tide parameters at san juan (Argentina). Pure Appl. Geophys. 178, 517–528. https://doi.org/10.1007/s00024-021-02668-4.

Pavlis, N.K., Holmes, S.A., Kenyon, S.C., Factor, J.K., 2012. The development and evaluation of the Earth gravitational model 2008 (EGM2008). J. Geophys. Res. 117, 4406. https://doi.org/10.1029/2011JB008916.

Riccardi, U., Berrino, G., 2002. Changes in the instrumental sensitivity for some feedback equipping LaCoste & Romberg gravity meters. Metrologia 39, 509. https://doi.org/10.1088/0026-1394/39/5/13, 15.

Riccardi, U., Rosat, S., Hinderer, J., 2011. Comparison of the Micro-g LaCoste gPhone-054 spring gravimeter and the GWR-C026 superconducting gravimeter in Strasbourg

(France) using a 300-day time series. Metrologia 48, 28–39. https://doi.org/10.1088/0026-1394/48/1/003.

Riccardi, U., Rosat, S., Hinderer, J., 2012. On the accuracy of the calibration of superconducting gravimeters using absolute and spring sensors: a critical comparison. Pure Appl. Geophys. 169, 1343–1356. https://doi.org/10.1007/s00024-011-0398-8.

Shibuya, K., Fukuda, Y., 1999. Gravity survey along the L-and AB-routes, East dronningmaud Land, Antarctica. JARE data report. Earth Sci. 5, 16–30.

Shibuya, K., Doi, K., Aoki, S., 2003. Ten years' progress of Syowa Station, Antarctica, as a global geodesy network site. Polar Geosci. 16, 29–52.

Toda, S., Miyamachi, H., Murakami, H., Tsutsui, T., Kanao, M., 2013. Gravity survey along the Mizuho Traverse routes, East Antarctica: SEAL seismic Exploration in 1999-2000. Int. J. Geosci. 4, 1392–1400. https://doi.org/10.4236/ijg.2013.410136.

Torge, W., 1989. Gravimetry. Walter De Gruyter, Berlin New York, p. 465p.

Velicogna, I., Wahr, J., 2006. Measurements of time-variable gravity show mass loss in Antarctica. Science 311, 1754–1756. https://doi.org/10.1126/science.11237785.

Wilmes, H., Wziontek, H., Falk, R., Bonvalot, S., 2009. AGrav- the new international absolute gravity database of BGI and BKG and its benefit for the global geodynamics project (GGP). J. Geodyn. 48, 305–309.

Yahagi, T., Yoshida, K., Miyazaki, T., Hiraoka, Y., Miyahara, B., 2019. Construction of the Japan gravity standardization net 2016. Bulletin of the Geospatial Information Authority of Japan 66, 49–58.

Yamamoto, K., Fukuda, Y., Doi, K., Motoyama, H., 2008. Interpretatioin of the GRACE-derived mass trend in Enderby Land, Antarctica. Polar Science 2, 267–276. https://doi.org/10.1016/j.polar.2008.10.001.

Yanai, K., Kakinuma, S., 1971. Measurement of gravity along the Traverse routes syowa-south Pole. JARE Special Scientific Report 2, 131–150.