Construction of the Japan Gravity Standardization Net 2016

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Abstract

The Geospatial Information Authority of Japan (GSI) has carried out nationwide gravity surveys for about 60 years and provided a national gravity standard network, which has been widely used for various purposes such as calculation of orthometric heights, calibration of weighing instruments and exploration of underground structures. However, the gravity standard network needs to be revised since gravity changes have accumulated due to crustal deformation and it has become possible to measure gravity values more precisely thanks to recent improvements in gravimeters. Therefore, the GSI released an updated gravity network, named the Japan Gravity Standardization Net 2016 (JGSN2016), on 15 March 2017 for the first time in 40 years.

JGSN2016 consists of gravity values at 32 fundamental gravity points and 231 primary gravity points (as of Mar. 2017). Each gravity value was calculated as follows: 1) determining the absolute gravity value of each fundamental gravity point based on absolute gravity measurements, 2) measuring gravitational differences along each baseline by relative gravimeters and 3) calculating the most probable gravity value of each primary gravity point by carrying out the net adjustment calculation using the values determined in 1). In the course of the process, the influences of solid-earth tide, atmospheric pressure, polar motion and ocean tide were adopted after removing outliers by statistical screening. In addition, the most appropriate combination of parameters for the net adjustment was determined by the Bayesian Information Criterion (BIC). The absolute gravimeters were calibrated through the annual comparison campaign with other domestic organizations which have absolute gravimeters. Thanks to these various improvements, JGSN2016 achieved precision of 3 and 11 μGal for the fundamental and primary gravity points, respectively.

1. Introduction

The Geospatial Information Authority of Japan (GSI) has conducted gravity measurements all over Japan since the 1950s and maintained standard gravity values. The first gravity standardization net was the Japan Gravity Standardization Net 1975 (JGSN75) (GSI, 1976) and it has been widely used for various geodetic activities such as gravity correction for elevation and research on active faults. It has also played an important role in supporting daily life and social activities as an indispensable tool for calibrating measurement instruments that are affected by gravity. For instance, scales must be calibrated by reflecting the gravity value at the point of measurement in order to accurately measure the exact mass. Instruments such as barometers, pressure gauges, and torque meters also require accurate gravity calibration.

However, 40 years had passed since the publication of JGSN75 and discrepancies between its values and the actual ones had become large due to mainly crustal movements, and so there were growing calls for a new gravity standard (Yamamoto, 2005). In response, the GSI built a new gravity standardization net using the latest measurement results and released it as the Japan Gravity Standardization Net 2016 (JGSN2016) on 15 March 2017 (GSI, 2017a). It consists of 32 fundamental gravity points and 231 primary gravity points including benchmarks (as of March 2017), covering the whole land area of Japan at a spacing of about 70 km on average. The precision of JGSN2016 is estimated to be about 3 μGal at fundamental gravity points and 11 μGal at primary gravity points, which is approximately one order of magnitude better than that of JGSN75.

In this article, first we introduce a brief history and the purpose of the GSI's gravity surveys and then show the methodology used to construct JGSN2016, with an evaluation of its precision.

2. Overview of GSI's gravity survey

The GSI's gravimetric activity dates back to its predecessor organization. Its basis was the "Designation of international control points for gravity measurement (hereafter, 'proposal')" that the Geodesy Council of the then Ministry of Education, Science and Culture recommended to the then Minister of Construction in 1952 (Suzuki, 1976). The proposal recognized the importance of international cooperation in geodesy and required the collection of gravity data throughout Japan based on the internationally unified gravity standards in order to contribute to a better understanding of the shape of the Earth and make domestic gravity values consistent with the international standards.

Since then, the GSI has conducted gravity measurements all over Japan and installed gravity points, which provide standard gravity values. The first domestic gravity standardization net, JGSN75, was built in 1976 in conformance with the International Gravity Standardization Net 1971 (Morelli et al., 1974). This made it possible for users in Japan to carry out gravity measurements based on the unified standards (Suzuki, 1976).

In addition, thanks to the development of portable gravimeters, denser gravity measurements based on JGSN75 became possible and the GSI has determined nationwide orthometric heights by combining those gravity data with leveling results (Imakiire, 2004). Those gravity data have also been used for calculating gravimetric geoid models that are necessary for obtaining elevations from satellite positioning (e.g., Kuroishi, 2000).

Recently, we carry out two types of gravity measurement: absolute gravity measurement using a Micro-g LaCoste FG5 absolute gravimeter (hereafter, 'FG5 gravimeter') at fundamental gravity points, and relative gravity measurement using a spring-based LaCoste & Romberg gravimeter (hereafter 'LaCoste gravimeter') at primary gravity points. The gravity values of the primary gravity points are determined by referring to those of the fundamental gravity points. JGSN2016 is constructed based on the results of these measurements.

3. Construction of JGSN2016

3.1 Installation of gravity points

JGSN2016 consists of 32 fundamental gravity points and 231 primary gravity points (as of March 2017) including both benchmarks and point markers attached to GNSS stations in Japan (Fig. 1). We used the gravity data obtained between fiscal 2002 and 2016 and calculated the most probable gravity values by the net adjustment calculation (see 3.2.3) in order to minimize the effect of time differences of the data. Regarding more than 14,000 second-order gravity points, we plan to convert their values based on JGSN2016 by the end of March 2019.

Accurate information on the location of the gravity measurement point is indispensable such as for tidal corrections, net adjustment calculation, and so on. In the course of constructing JGSN2016, we carefully inspected the position of each point and conducted additional surveys if needed. The horizontal locations of approximately one-half of the gravity points were determined within 0.01 second precision (approximately 0.3 m) by GNSS surveys. We used the GSI Maps (https://maps.gsi.go.jp/) to determine the positions of other gravity points for which it was impractical to carry out the GNSS survey due to the difficult environment. In these cases their precision was within 0.5 second. The elevations, which have a large influence on gravity values, were measured with better than 1 cm precision by leveling surveys for approximately 80% of the gravity points. The elevations of the remaining points were obtained by GNSS surveys or reading the GSI Maps.

3.2 Procedure of Construction

3.2.1 Absolute gravity measurement

1) Obtaining measurement data

We carried out absolute gravity measurements at fundamental gravity points using one of our three FG5 gravimeters (#104, #201, or #203). In order to calibrate them with other absolute gravimeters, the GSI has hosted the Domestic Comparison of Absolute Gravimeters

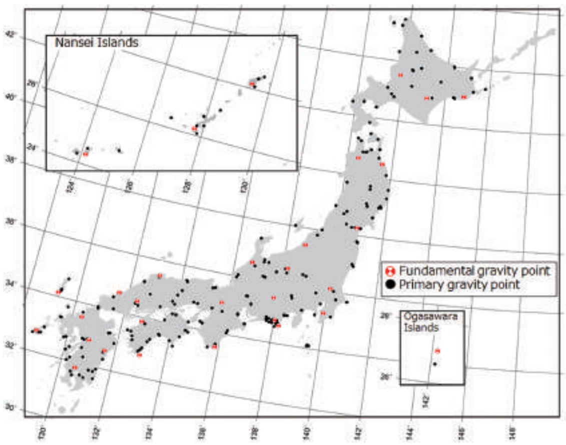

Fig. 1 Distribution map of JGSN2016 gravity points. JGSN2016 consists of 32 fundamental gravity points and 231 primary gravity points over Japan as of March 2017.

(DCAG) and invited other organizations since 2002 (Yamamoto et al., in press). Consistency between the gravimeters and international standards is evaluated by comparing them with FG5 (#213), which is owned by the National Institute of Advanced Industrial Science and Technology (AIST) and calibrated regularly through the Implementation of International Comparison of Absolute Gravimeters (ICAG) (Francis et al., 2014). This process guarantees consistency between JGSN2016 and the international standards.

When we carry out absolute gravity measurements using the FG5 gravimeter, we normally define one set as 160 drops and perform at least 125 sets (= 20,000 drops) for an observation period of approximately one week. This is enough to examine the data statistically and minimize various unexpected errors such as installation or adjustment errors of the instrument, noises caused by the surrounding environment, and tidal effects due to groundwater or inland water. In case we obtained different results at different times for the same fundamental gravity point, we basically used the latest one for JGSN2016 in order to minimize the effects of the time shift.

2) Correction of measured data

We used the g9.0 software package of Micro-g LaCoste (Micro-g LaCoste, Inc., 2012) for corrections of earth tide effects, polar motions, and standard atmosphere. We utilized the ETGTAB module of ETERNA 3.0 (Wanzel, 1996), which is integrated in g9.0, for the solid-earth tide correction. First, we estimated the effects of main tides of approximately 1,200 tide components by setting both the δ-factor and phase individually, and then calculated the total amount of correction by summing up all individual components. Here, the δ-factor is the response coefficient of the Earth's gravitational field to the tide-generating potential, which we set to 1.0 following Kuroishi (2000) in order to acquire the gravity values based on a zero-tide system, according to the resolution of the 18th General Assembly of IAG (IAG resolution, 1983).

As for the correction of polar motion, we used the Earth Orientation Parameters (EOPs) provided by the International Earth Rotation and Reference Systems Service (IERS) as Bulletin B (Petit and Luzum, 2010). Since the EOPs vary within a day, we corrected the obtained data on an hourly basis by dividing them into 24 sessions (from UTC 0:00 to 24:00). The amount of polar motion correction, δg (μGal), is given by:

$$\delta_g = -1.164 \times 10^8 \omega^2 a \ \sin 2\varphi \,(x \cos\lambda - y \sin\lambda) \tag{1}$$

where ω is the Earth's rotation speed (rad/s), a is the radius of the Earth at the equator (m), φ and λ are the latitude and longitude of the measurement point (rad), and x and y are shifts of polar position in EOP (rad).

The correction of the standard atmospheric pressure is given by equation (2). Here, Cp (μGal) is the correction of the pressure change derived from measured pressure P (hPa). The standard atmospheric pressure at elevation H (m), P_n (hPa), is calculated from equation (3) following the recommendation of the International Gravimetric Bureau (BGI) (IGC-WG II, 1988).

$$C_p = 0.3(P - P_n) \tag{2}$$

$$P_n = 1.01325 \times 10^3 \left(1 - \frac{0.0065H}{288.15}\right)^{5.2559} \tag{3}$$

We calculated the ocean tide correction using GOTIC2 (Matsumoto et al., 2001) with the NAO99b and NAO99Jb models (Matsumoto et al., 2000). These models are provided by the National Astronomical Observatory of Japan and contain detailed tidal data around Japan. Since they are based on the previous Japanese geodetic coordinate system, we converted their coordinates into those based on the current coordinate system before processing.

3) Calculation of the most probable gravity value

The most probable gravity values were obtained as follows. First, we determined acceptable sets based on the dispersion of gravity values in each set. Then, we eliminated outliers by evaluating the significance of the dispersion among multiple sets using the analysis of variance. The most probable values were obtained by averaging gravity values of all accepted sets. The number of measurements of each set was utilized as weighting values throughout the process.

4) Gravity conversion to the ground

The final gravity values of JGSN2016 are defined as the values at the top surface of each gravity point. Therefore, we conducted vertical gravity conversion from the instrument height to the top of the gravity points for the results of 3). The instrument height of the FG5 gravimeter is approximately 1.30 m, which is defined as the position where the mirror is released inside its dropping chamber. We determined the vertical gravity gradient of each fundamental gravity point by measuring the gravity values at heights of 0.00 m and 1.20 m above the metal marker using our three LaCoste gravimeters. Since the average of errors of the vertical gradient at all 32 fundamental gravity points was 0.0068 μGal/cm and its standard deviation was 0.0035 μGal/cm, the precision of our vertical gravity conversion for 1.30 m was estimated to be about 1.0 μGal. The final gravity values at each fundamental gravity point were calculated as the most probable value by adopting this vertical gravity gradient.

3.2.2 Relative gravity measurement

1) Obtaining measurement data

In this article we define a ‘baseline’ as a combination of two measurement points in a relative gravity measurement and a ‘baseline value’ as the corresponding gravity difference of each baseline. The relative gravity measurements at primary gravity points were conducted with our three LaCoste gravimeters (G-83, G-118, and G-554) to maximize reliability and redundancy. They are calibrated annually using our calibration baseline installed in the Mt. Tsukuba (877 m) region, which is located close to the GSI (Yamamoto et al., in press). To minimize the time shift due to spring elongation, each measurement set basically consists of baselines for which it is possible to carry out round-trip observations within a single day. We also require at least a one-hour interval between the outward and homeward observations in order to maintain the independence of the data. In addition, the gravimeter was aligned along magnetic north during measurement to eliminate the effect of the geomagnetic field. According to these procedures, six baseline values were obtained for each baseline (double-run observations multiplied by three gravimeters).

2) Correction of reading values

To obtain a baseline value from a reading value of the LaCoste gravimeter, corrections based on the characteristics of each instrument and both their theoretical and empirical models are required. This process consists of five main steps: 1) conversion from the reading values to gravity differences using a conversion table; 2) solid-earth tide correction; 3) ocean tide correction; 4) atmospheric pressure correction; and 5) gravity reduction to the metal marker surface. These are described in detail below. First, we set the conversion factor to determine the gravity difference caused by the amount of spring elongation inside a LaCoste gravimeter. It consists of a linear response scaling factor and a conversion coefficient, which was provided by the manufacturer of the gravimeters in advance, and neither of them depends on the reading values. The most probable value of the scaling factor was estimated as one of the unknown parameters during the net adjustment calculations (see 3.2.3). Then we calculated both the solid-earth and ocean tide corrections using ETGTAB and GOTIC2, respectively, using the same process for the absolute gravity measurement data (see 3.2.1). The standard atmospheric pressure correction was also carried out for each baseline using a similar process for the absolute gravity data. Regarding the gravity reduction, in order to reduce the effect of the vertical gravity gradient, which is different at each measurement point, we assumed the height of the bottom surface of the LaCoste gravimeter, which is approximately 5 cm above the ground, as the reference height of the instrument.

Strictly speaking, the reference height should be the center of mass of the gravimeter, but in practice it is impossible to measure it directly. Since it is evident that the mass is located near the bottom of the gravimeter according to its manual, we assumed that the error caused by choosing the bottom surface as the reference plane is negligible. We utilized the free-air gradient (3.086 μGal/cm) as the vertical gravity gradient for the gravity reduction of the primary gravity points to simplify the procedure and shorten the observation time at each point so that we could increase the number of observed gravity points.

The drift caused by temporal change of the spring during the measurement was not corrected at this stage to prevent overlooking outliers in the measurements, but was estimated as one of the unknown parameters by the least-squares method during the net adjustment calculations (see 3.2.3). The periodic errors of each LaCoste gravimeter were also estimated through the process. On the other hand, we did not take into account the polar motion correction because our relative gravity measurements were completed within half a day, which is short enough to neglect the effects of the polar motion, and which are mostly cancelled out in the course of calculating the baseline values.

3) Outlier detection and provisional baseline values determination

To confirm whether obtained data contain mis-readings or tears, which are abrupt elongations of the spring due to strong shocks, we calculated the differences between outward and homeward observations for each instrument and compared them against a threshold value determined from our past observations. The unbiased standard deviation of reading values obtained between 2007 and 2013 was 26 μGal, which was estimated by the least-squares method after correcting the drift coefficient. Therefore, we assumed that these data followed a normal distribution of N (0, 26) (μGal) and measured results should be included in 2σ (52 μGal) with 95% confidence. To verify measured data quickly on site, we simplified the threshold as follows:

$$-50 < g_2 - g_1 - t < 50 \tag{4}$$

where g_1 and g_2 are gravity values of the outward and homeward observations (μGal) after applying various corrections to reading values, and t is the time difference between the outward and homeward observations (hour). These values are rounded down to the nearest integer.

Even if the results of the round-trip measurements are consistent for each instrument, there may be a discrepancy between them. Therefore, we assumed a standard dispersion for the gravimeters and evaluated whether the deviation was statistically significant or not by the χ^2 test. We empirically estimated the population variance of accurate measurements, σ^2, and compared it to the unbiased variance of measured values, s^2, to detect outliers. The population variance, σ^2, is described by equation (5) and each term of the right-hand side of (5) is equal to 10 μGal as the uncertainty of reading values (tolerance limit of observation), $15/\sqrt{2}$ μGal as the uncertainty of the periodic error (Völgyesi et al., 2007), and 0.0002 as the uncertainty of the scale factor which was empirically determined from past estimation data. Δg (μGal) is the baseline value from a double-run observation. According to the above conditions, the χ^2 distribution becomes χ^2 (5, 0.05) = 11.07, therefore the rejection condition of s^2 is given by:

$$\sigma^2 = 10^2 \times 2 + \left(15/\sqrt{2}\right)^2 \times 2 + (0.0002 \times \Delta g)^2 \tag{5}$$

$$s^2 > 11.07 \times \sigma^2/5 \tag{6}$$

3.2.3 Net adjustment calculation

The final gravity values of the primary gravity points were determined by conducting least-squares fitting for the baseline values obtained in 3.2.2 with the gravity values of fundamental gravity points obtained in 3.2.1. The baseline map is shown in Fig. 2. We selected the optimum combination of unknown parameters in the model using the Bayesian Information Criterion (BIC) (Schwarz, 1978). Consequently, the gravity values at the primary gravity points, the drift coefficients of each instrument, the periodic errors up to the fifth period, and the scale factors at higher and lower latitude regions were chosen as the estimated parameters to express the model.

The observation equation of the net adjustment calculation is described by equation (7) and we considered it for each baseline of the relative gravity measurements:

$$v_{ij} = \delta g_j - \delta g_i + \delta d_k t_{ij} - (g'_j - g'_i)\delta sf + (\delta O_j - \delta O_i) - \{(O_j - O_i) - (g'_j - g'_i)\} \quad (7)$$

where g' is the first approximate gravity value calculated by adding the baseline value (Δg) in 3.2.2 and the absolute gravity value of its starting point, δg is the difference between g' *and* the most probable gravity value, d_k is the drift coefficient of each instrument k, t (hour) is the time difference between the outward and homeward observations, sf is the scale factor, O is the reading value, δO is the periodic error for the reading value, and v is the residual. Indices i and j denote the start and end points of a baseline, respectively, and variables prefixed with "δ" are to be estimated.

Equation (7) can be expressed as equation (8) by defining a design matrix $\boldsymbol{A}$, comprising coefficients of variables for estimated values, and an observation vector $\boldsymbol{L}$ comprising observed values:

$$\boldsymbol{V} = \boldsymbol{AX} - \mathbf{L} \quad (8)$$

where $\boldsymbol{X}$ is an unknown vector of estimated parameters and $\boldsymbol{V}$ is the residual vector.

The normal equation (9) is derived from equation (8), and the most probable values can be obtained from equation (10) by solving (9) for the unknown vector $\boldsymbol{X}$ and considering the weight matrix $\boldsymbol{P}$ from measured values. The standard deviation of this process is given by:

$$\boldsymbol{A}^t\boldsymbol{PAX} = \boldsymbol{A}^t\boldsymbol{PL} \quad (9)$$

$$\boldsymbol{X} = (\boldsymbol{A}^t\boldsymbol{PA})^{-1}\boldsymbol{A}^t\boldsymbol{PL} \quad (10)$$

$$M = \boldsymbol{V}^t\boldsymbol{PV}/q - r \quad (11)$$

$$m_0 = \sqrt{M}$$

$$m_{x_i} = m_0\sqrt{Q_{ii}}$$

where M is the variance of the most probable value, q is the number of observation equations, r is the number of estimated parameters (baseline values, drift coefficients, scale factors, and periodic errors), m_0 is the standard deviation per unit weight, m_{Xi} is the estimated standard deviation at each point, and Q_{ii} is the i-th diagonal component of the matrix $(\boldsymbol{A}^t\boldsymbol{PA})^{-1}$.

The weights of the measured values were set for each instrument assuming that observed values are influenced by dispersion characteristics unique to each LaCoste gravimeter. Specifically, we used the results of annual calibration for relative gravimeters conducted at the Mt. Tsukuba calibration baseline between 2007 and 2013. Outlier values were removed using the same procedure described in 3.2.2 and the unbiased standard deviation of the accepted baseline values was adopted. Since some approximations were used for minor terms in the observation equation (7), we performed iterative calculations by updating input values successively. The final values of the estimated standard deviation (m_{Xi}) at each measurement point showed a distribution close to the normal distribution of N (5.9, 1.7 μGal).

Diurnal round-trip observations were possible for most gravity stations on remote islands, such as Okinawa and Ishigaki in the Nansei Islands, by commercial flights from the main island. These data were integrated into the net adjustment calculations for JGSN2016. However, this is impossible for the gravity stations in Chichijima and Hahajima in the Ogasawara Islands because they are only accessible by ship and it takes 25 hours one way. Therefore, we installed a fundamental gravity point on Chichijima and determined its gravity value by absolute gravity measurement. A gravity net in the Ogasawara Islands was defined separately from the main island and gravity values at the primary gravity points inside it were obtained by independent calculations. We used the same measurement method and estimated parameters of Chichijima for the net adjustment calculations as those for the calculation of the mainland.

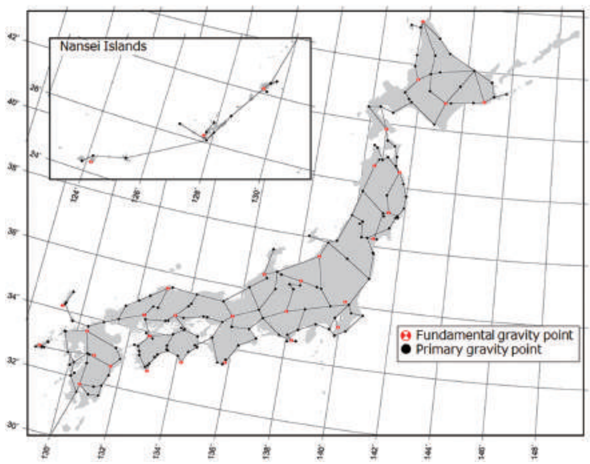

Fig. 2 Baseline map for the gravity net adjustment.

4. Evaluation of precision

4.1 Precision of gravity values

The error of gravity values at the fundamental gravity points was estimated as the sum of measurement errors of the FG5 gravimeter and the error of the gravity reduction process. These errors were assessed to be 2 μGal for the nominal accuracy of the FG5 gravimeter results, 1.9 μGal for the standard deviation of the difference among FG5s reported from the ICAG, and 1.0 μGal for the gravity reduction discussed in 3.2.1. By considering the error propagation, the precision of the gravity value at the fundamental gravity points is estimated to be 3.0 μGal.

Regarding the primary gravity points, the maximum standard deviation from the net adjustment calculations performed in 3.2.3 was estimated to be 11 μGal. This is approximately one order of magnitude better than that of JGSN75 (0.1 mGal) estimated by Kuroishi and Murakami (1991). This refinement would be a consequence of various improvements such as the increased number of fundamental gravity points from one point at Tokyo in JGSN75 to 32 nationwide points in JGSN2016, the introduction of the FG5 gravimeters for determining highly precise absolute gravity values at each fundamental gravity point, and the revision of both observation and correction processing procedures for the relative gravity measurements by the LaCoste gravimeters.

4.2 Evaluation of consistency by loop closures

The consistency of each closed loop was evaluated using gravity differences between both the fundamental and primary gravity points based on the baseline map of the net adjustment (Fig. 3). In total, 35 loops were checked using average values of the relative gravity measurements for each baseline that passed the outlier detection described in 3.2.2. The tolerance limit of a closed loop was set to $22\sqrt{N}$ μGal considering that the value should be within twice the standard deviation at the measurement points through the net adjustment calculation (2σ, σ=11.2 μGal). N is the number of baselines in a loop.

Ideally, the closed-loop evaluations should be conducted prior to the net adjustment calculations in order to detect baselines where observation errors might be problematic and redo those measurements. However, it is not easy in practice to conduct measurements for the same baseline several times due to the cost. Hence, we performed the closed-loop evaluations based on the results of the net adjustment calculations, assuming that significantly abnormal measurement results had been removed in advance by the outlier detection process in 3.2.2.

As a result, four loops exceeded the tolerance limit (a1, a2, b1, and b2 in Fig. 3). Since loops a1 and a2, as well as b1 and b2, are adjacent, it is considered that common baselines of each pair would be the cause of the

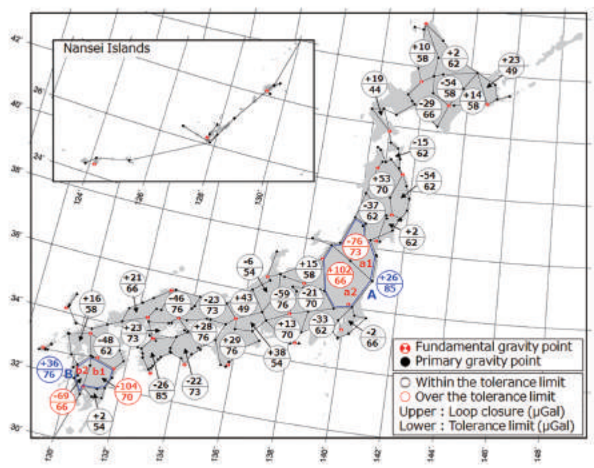

Fig. 3 Errors of loop closure for JGSN2016. Each blue circle corresponds to the result of each blue loop (A and B) which consists of two loops (a1/a2 or b1/b2) that exceed the tolerance limit.

increased error. In fact, the values of the loop closure that combined two adjacent loops A (a1 and a2) and B (b1 and b2) were +26 μGal (tolerance limit ± 82 μGal) and +36 μGal (tolerance limit ± 73 μGal), respectively (Fig. 3). Considering this result, we removed the intermediate gravity points that were located in each shared baseline of a1/a2 and b1/b2 from the released version because their gravity values might contain large errors.

4.3 Comparison with JGSN75

Figure 4 shows a comparison of gravity values between JGSN75 and JGSN2016 for 72 gravity points: 26 that had not been relocated or reinstalled during this period and 46 that had experienced relocation but had records of connection measurements. The largest increase was +0.07 mGal at the primary gravity point "Miyako" in Miyako City, Iwate Prefecture, while the largest decrease was −0.11 mGal at the primary gravity point "Aikawa" in Sado City, Niigata Prefecture. Gravity values decreased as an overall trend, and the average of the gravity change was −0.04 mGal. If the measurement and analysis procedures were not changed between JGSN75 and JGSN2016, we can consider that this gravity change was purely caused by a time variation between the two periods. However, in fact it contains the uncertainty of each standardized net. Especially, JGSN75 might have a large systematic error due to its limits of measurement accuracy because we did not have reliable absolute gravimeters at that time. For instance, the reason for the smaller gravity changes in the Kyushu region compared to other regions would be caused by the difference of the correction values, which were used to remove the systematic error when shifting to JGSN75 from the former gravity standardization net, Potsdam gravity system (Borrass, 1911; Suzuki, 1974). The correction values were −14.0 mGal in the Kyushu region and −13.8 mGal in the rest of Japan (GSI, 1976). This difference did not have a significant impact at that time due to lower measurement precision, but has now become clear thanks to the improvement in measurement accuracy in recent years. On the other hand, we can also recognize some gravity changes that would be caused by crustal activity in Fig. 4. For instance, the gravity increase near the Pacific coast of the Tohoku region is mainly the result of the tectonic subsidence over a wide area during the 2011 Great East Japan Earthquake off the Pacific coast of Tohoku. In addition, the smaller decreases in gravity along the Pacific coast close to the Nankai Trough might be the effect of long-term subsidence accompanying plate tectonic motion.

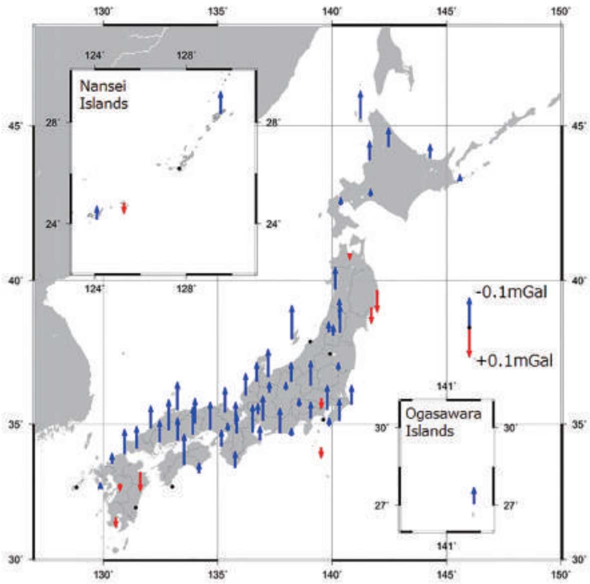

Fig. 4 Gravity difference between JGSN75 and JGSN2016 at 72 gravity points where both values are available. Blue arrows indicate decreases of the gravity value, while red arrows indicate increases.

5. Summary and future outlook

The GSI has conducted ground-based gravity surveys since the 1950s and has established gravity standards throughout Japan. They have supported various activities such as the determination of land elevation, the calibration of weighing equipment, and the investigation of concealed active faults. The updated Japanese gravity standardization net, called JGSN2016, was released on 15 March 2017 for the first time in 40 years based on the latest gravity measurement data using FG5s and LaCoste gravimeters. These gravity values are confirmed to be consistent with international standards through the calibration campaign of the absolute gravimeters. They are available with a resolution of 0.01 mGal for public use. Users can access those values via the GSI's web service (GSI, 2017b). We also plan to convert the gravity values of the remaining 14,000 legacy second-order gravity points over Japan based on JGSN2016 by the end of March 2019.

The absolute gravity values at the fundamental gravity points are also registered in the Absolute Gravity Database (AGrav) (Federal Agency for Cartography and Geodesy, 2017), which supports the activities of the Global Geodetic Observation System (GGOS) operated by the International Association of Geodesy (IAG).

The GSI has also measured gravity values continuously at point markers attached to the Continuously Operating Reference System (CORS) stations in Japan. By combining those gravity values with the continuous three-dimensional positions derived from CORS data, we anticipate being able to evaluate whether gravity changes would be caused by elevation changes or subsurface structural changes. In addition, these open-air gravity points enable users to access JGSN2016 easily.

The demand for a high-precision geoid model, which is indispensable to obtain elevation from satellite positioning, has been increasing with the rapid development of GNSS in recent years. The establishment of high quality and spatially uniform nationwide gravity data is crucial to construct a precise gravimetric geoid model. For this purpose, the GSI launched a new project of airborne gravity measurements over Japan in 2018 (Yahagi, 2018). The gravity values of JGSN2016 will be used as the reference for the airborne gravity data and will provide uniform and high-quality gravity standards, which are necessary for the construction of a higher-precision gravimetric geoid model.

Both techniques and technologies related to gravity measurement have been advancing steadily and their significance not only for various social activities but also constructing a precise geoid model for obtaining elevations from satellite positioning has been increasing. The GSI will continue to maintain precise gravity standards to meet the expectations of society.

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References

Borrass, E. (1911): Bericht uber die relativen Messungen der Schwerkraft mit Pendelapparaten in der Zeit von 1808-1909, uber ihre Darstellung im Potsdamer Schweresystem, Verh. 16 allg. Konf. internat. Erdmess. London and Cambridge, 1909, Teil 3, Berlin, 280.

Federal Agency for Cartography and Geodesy (2017): AGrav (Absolute Gravity Database – Meta-Data), http://agrav.bkg.bund.de/agrav-meta/ (accessed 7 Jul. 2018).

Francis, O., H. Bauimann and Participants (2014): International Comparison of Absolute Gravimeters, final report, 1-31.

Geospatial Information Authority of Japan (1976): Establishment of the Japan Gravity Standardization Net 1975, Journal of the Geodetic Society of Japan 22, 2, 65-76. (in Japanese)

Geospatial Information Authority of Japan (2017a): Release of new gravity value standards of Japan updated for the first time in 40 years, http://www.gsi.go.jp/buturisokuchi/gravity_JGSN2016.html (accessed 7 Jul. 2018). (in Japanese)

Geospatial Information Authority of Japan (2017b): GSI's browsing service for Japanese CORS data, https://sokuseikagis1.gsi.go.jp/top.html (accessed 7 Jul. 2018). (in Japanese)

Imakiire, T. and E. Hakoiwa (2004): JGD2000 (vertical) – The New Height System of Japan –, Bulletin of the Geographical Survey Institute, 51, 31-51.

International Association for Geodesy (1983): Standard Gravity Corrections System, Bull. B. G. I. 53, 214.

International Gravity Commission-Working Group II (1988): IAGBN Absolute Gravity Observation Data Processing Standards and Station Documentation, Bull. d'Inform. BGI, 63, 51-57.

Kuroishi, Y. and M. Murakami (1991): Results of Absolute Gravity Measurements by Geographical Survey Institute (III), Bulletin of the Geographical Survey

Institute, 36, 21-31.

Kuroishi, Y. (2000): Precise Gravimetric Determination of Geoid for Japan, Journal of the Geodetic Society of Japan, 46, 1, 1-20. (in Japanese)

Matsumoto, K., T. Takanezawa, and M. Ooe (2000): Ocean Tide Models Developed by Assimilating TOPEX/POSEIDON Altimeter Data into Hydrodynamical Model: A Global Model and a Regional Model Around Japan, Journal of Oceanography, 56, 567-581.

Matsumoto, K., T. Sato, T. Takanezawa, and M. Ooe (2001): GOTIC2: A Program for Computation of Oceanic Tidal Loading Effect, J. Geod. Soc. Japan, 47, 243-248.

Micro-g LaCoste, Inc. (2012): g9 User's manual, http://www.microglacoste.com/pdf/g9Help.pdf (accessed 7 Jul. 2018).

Morelli, C., C. Gantar, T. Honkasalo, R. K. McConnell, J. G. Tanner, B. Szabo, U. Uotila, and C. T. Whalen (1974): The International Gravity Standardization Net 1971 (I.G.S.N. 71), Publ. Spec., 4, Bull. Geod., 1-194.

Petit, G. and B. J. Luzum (eds.) (2010), IERS Conventions (2010), IERS Technical Note 36, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 179.

Schwarz, G. E. (1978): Estimating the dimension of a model, Annals of Statistics, 6 (2): 461-464, MR 468014, doi:10.1214/aos/1176344136.

Suzuki, H. (1974): Establishment of the Gravimetric Network in Japan, Bulletin of the Geographical Survey Institute, 20, 1-150.

Suzuki, H. (1976): The International Gravity Standardization Net 1971 and the Japan Gravity Standardization Net 1975, Journal of the Geodetic Society of Japan, 22, 2, 112-129. (in Japanese)

Völgyesi, L., L. Földváry, and G. Csapö (2007): Improved processing method of UEGN-2002 gravity network measurements in Hungary, Dynamic Planet - Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools, Edited by Paul Tregoning and Chris Rizos. ISBN 978-3-540-49349-5. Berlin: Springer, p.202.

Wenzel, H.-G. (1996): The nanogal software: Earth tide data processing package ETERNA 3.30. Bulletin d'Informations Mareés Terrestres, vol. 124, 9425-9439, Bruxelles 1996.

Yahagi, T. (2018): Future plan of the Japanese vertical datum, 2018 Report Meeting of GSI, http://www.gsi.go.jp/common/000201352.pdf, (accessed 7 Jul. 2018). (in Japanese) Yamamoto, A. (2005): The Absolute Gravity Reference System: Current Status, Problems and Perspective, Journal of the Geodetic Society of Japan, 51, 2, 107-112. (in Japanese)

Yamamoto, H., B. Miyahara, K. Yoshida, Y. Sugawara, and T. Miyazaki (in press): Gravity Survey by the Geospatial Information Authority of Japan, Journal of the Geospatial Information Authority of Japan. (in Japanese)