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ABSOLUTE GRAVITY MEASUREMENTS AT SYOWA STATION —RESULTS BY THE ABSOLUTE GRAVIMETER WITH A ROTATING VACUUM PIPE—

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Abstract: We measured absolute gravity values at Syowa Station, Antarctica, which is one of the subsets A of the International Absolute Gravity Basestation Network (IAGBN), from December 28, 1992 to February 5, 1993 by employing an absolute gravimeter with a rotating vacuum pipe (AGRVP) together with a transportable absolute gravimeter (No. 2) of the National Astronomical Observatory, Mizusawa (NAOM#2). The results of the AGRVP gave two solutions which differ by about 2.3×10^{-6} ms^{-2} (230 μGals). According to comparisons with results by other absolute gravimeters at Syowa Station, Esashi Gravity Station of National Astronomical Observatory and Gravity Station of Geographical Survey Institute, the solution with a lower value seems to be reasonable. An arithmetic mean of 43 gravity measurements was $9.82524113\pm0.6\times10^{-7}$ ms^{-2} with a standard deviation of 4.0×10^{-7} ms^{-2}. This value is about 4.0×10^{-7} ms^{-2} lower than that obtained by the absolute gravimeter NAOM#2, which was set on the same pier for almost the same period, and is about 1.4×10^{-6} ms^{-2} lower than that obtained by an absolute gravimeter of Sakuma-type, which was set on the same pier almost one year before. One possible cause for the difference between the two solutions is the misalignment of the falling object.

1. Introduction

One of the purposes of absolute gravity measurements at Syowa Station, Antarctica, is monitoring of the vertical crustal movements in Antarctica, which are related to the thickness of the ice sheet on the continent as well as sea-level changes. If climate becomes warmer, the amount of ice will decrease by melting and sea-level will rise. The reduced mass of the ice also brings about land uplifting of Antarctica in order to compensate for the deviation from isostatic balance. The velocity of land uplift (or subsidence) depends on the viscosity of the Earth's mantle and ice history. There is a more complicated relationship between gravity changes and the vertical crustal movements since gravity changes include not only height change which is equivalent to a change in distance from the Earth's center of mass, but also the attraction of sea-water distributed worldwide. Absolute gravimetry can detect a gravity change of larger than 1 μGal, which is equivalent to a vertical displacement of about 3 mm, without referring to gravity values measured at other stations. It is almost the only way to make absolute gravity measurements for monitoring of gravity changes at Syowa Station, since the gravity connection between Syowa Station and stations in the gravity network on other continents is difficult due to geographical distance and limited means of transportation.

Syowa Station, on the other hand, is selected as one of the subsets A of the International Absolute Gravity Basestation Network (IAGBN), which was established at the General Assembly of the International Association of Geodesy (IAG) held at Vancouver, Canada in 1987. The IAGBN consists of 36 stations which are located on geologically and seismologically stable continents and uniformly cover the Earth. The IAGBN has the purpose of monitoring global gravity changes related to the deformation of the Earth, changes in gravitational harmonics of lower degrees, changes in the Earth's orientation parameters and so on (BOEDECKER and FRITZER, 1986). Japan is responsible for maintaining Syowa Station.

We installed two absolute gravimeters; namely, a transportable absolute gravimeter (No. 2) of the National Astronomical Observatory, Mizusawa (NAOM#2) and an absolute gravimeter with a rotating vacuum pipe (AGRVP), both of which were developed at the NAOM, at Syowa Station as members of the 34th Japanese Antarctic Research Expedition, in order to increase the quantity of data and prevent instrument failure. This was the second series of absolute gravity measurements at Syowa Station, following the gravity measurements performed by the Geographical Survey Institute almost one year before. The second set of gravity measurements is as important as the first one in the sense that the gravity value at Syowa Station is more strongly fixed with another independent set of gravity measurements. In this paper, the progress of the experiments and results obtained by the AGRVP are described.

2. Absolute Gravity Measurements at Syowa Station

The AGRVP was transported from the icebreaker SHIRASE to Syowa Station on December 24, 1992 by two helicopters together with the NAOM#2. After truck transportation on East Ongul Island, where Syowa Station is located, the gravimeters were unpacked, and set on a pier in the Gravity Observation Hut (GOH) as shown in Fig. 1. There are two piers in the GOH ; the smaller pier is used for a superconducting gravimeter. Gravity measurements with the AGRVP were carried out almost every day from December 28, 1992 to February 5, 1993. Within this period, we calibrated the wavelength of the stabilized He-Ne laser (SP117, Spectra Physics Co.) employed in the AGRVP three times on December 29, 1992, January 21 and February 5, 1993. By employing two LaCoste & Romberg gravimeters, we also measured the vertical gradient of gravity at the points where the absolute gravimeters were set, as well as gravity differences among the points including the absolute gravity measurement points which constitute a gravity network on the island.

The absolute gravimeter measures the acceleration of a falling object (a corner cube prism) by Michelson interferometer with a laser beam wavelength as a length standard and an atomic clock as a time standard. The AGRVP, which was developed at the National Astronomical Observatory, utilizes the centrifugal force in order to repeat measurements with a simple dropping device (HANADA *et al.*, 1987). We rotate a vacuum pipe 180 degrees by a motor with an angular velocity high enough to keep the falling object to one end of the pipe and stop its motion suddenly when it becomes vertical. Then the object drops facing the incident surface upwards and a chuck fixed to another end of the pipe catches it. The gravity acceleration g is not measured during this drop but is measured

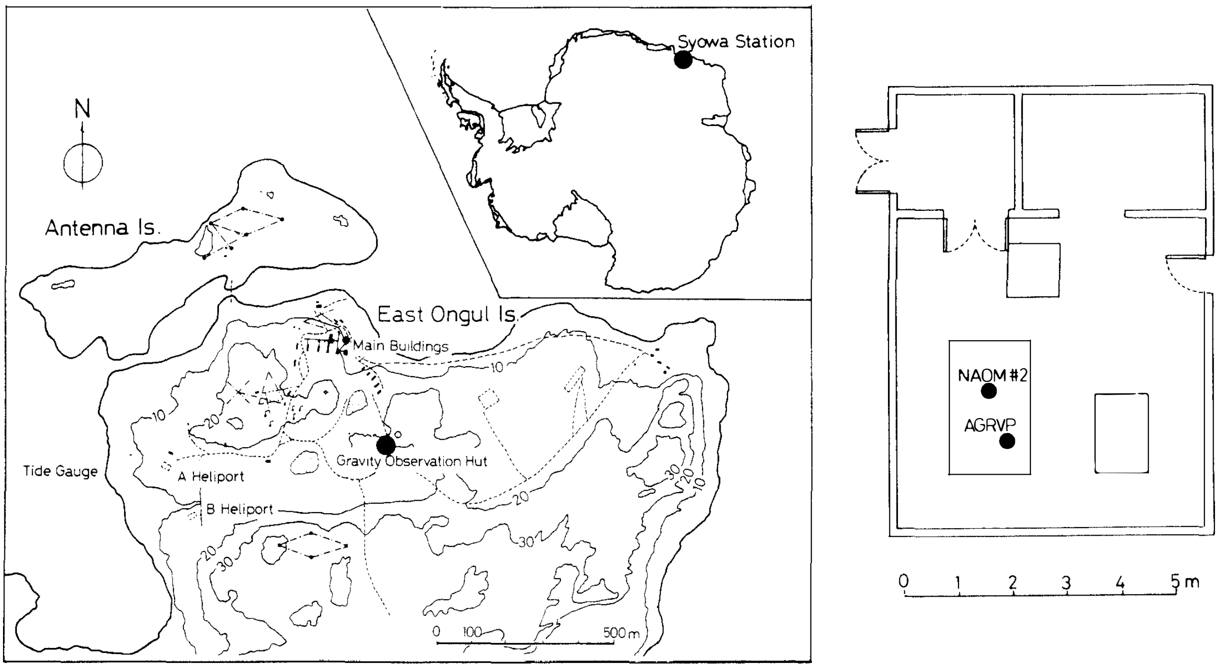

Fig. 1. Location of Gravity Observation Hut (left) and inside of the room (right). The points where the AGRVP and the NAOM#2 were set are shown by solid circles.

during the next drop when the incident surface faces the interferometer beneath the vacuum pipe (see Fig. 2). The next half revolution does not require quick motion since the falling object is held by the chuck. The falling object is at rest for a while after the vacuum pipe becomes vertical, and then begins to drop when the chuck opens triggered by a zero crossing of the seismic signal.

Fringe signals produced during the drop are sampled 250 times with spans of 5 μs at 1 ms intervals by a transient recorder (TR8828D, LeCroy). The burst sampling data at every 1 ms consist of 1024 digitized data of 2 ns time resolution. We determine the phase of the fringe signal at every 1 ms by applying the least squares method and obtain the relation between falling distance and time in order to determine g (MURATA, 1978; TSUBOKAWA, 1984). Figure 3 shows the experiments with the NAOM#2 and the AGRVP at GOH at Syowa Station.

Although it usually took only a few days until we obtained the first measured value, the condition of the AGRVP was not good at Syowa Station. There was something wrong with the ion pump attached to the vacuum pipe of the AGRVP and also with the computer program which calculated g from the digitized fringe signals. The supply current for the ion pump was not stable, and the pump often originated electrical noises, which induced uncontrollable motion of the motor and mistriggering of the transient recorder. One reason why the ion pump did not work well seems to be that we exposed the inside of the vacuum chamber to dusty air containing fine mica flakes several times for repair or adjustment of the dropping device and the falling object. The computer program including a bug, on the other hand, brought about a normal solution only once in about ten drops. An abnormal solution was easily recognizable since the curve which represents the relation between falling time and distance artificially deviated from a

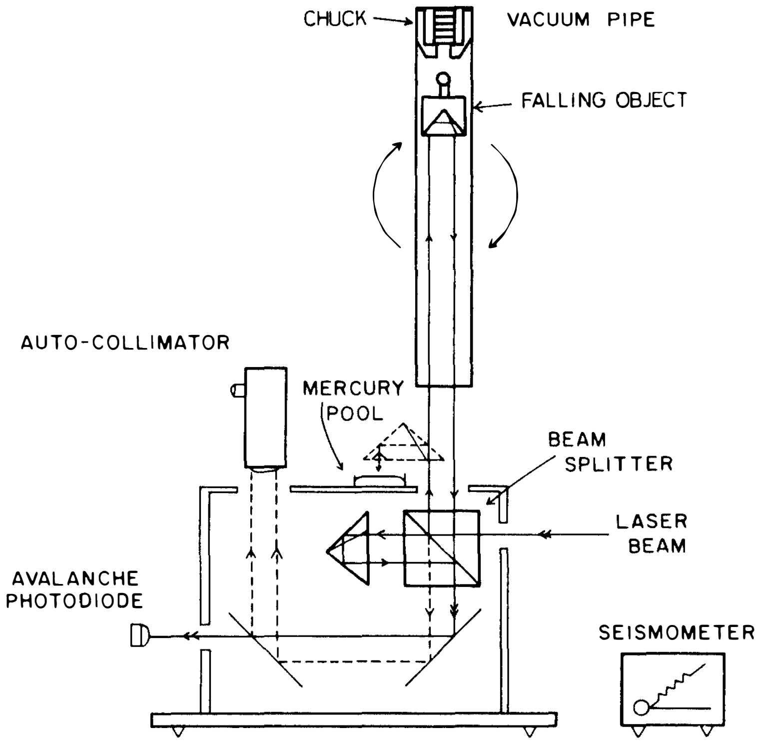

Fig. 2. A schematic drawing of the absolute gravimeter with a rotating vacuum pipe.

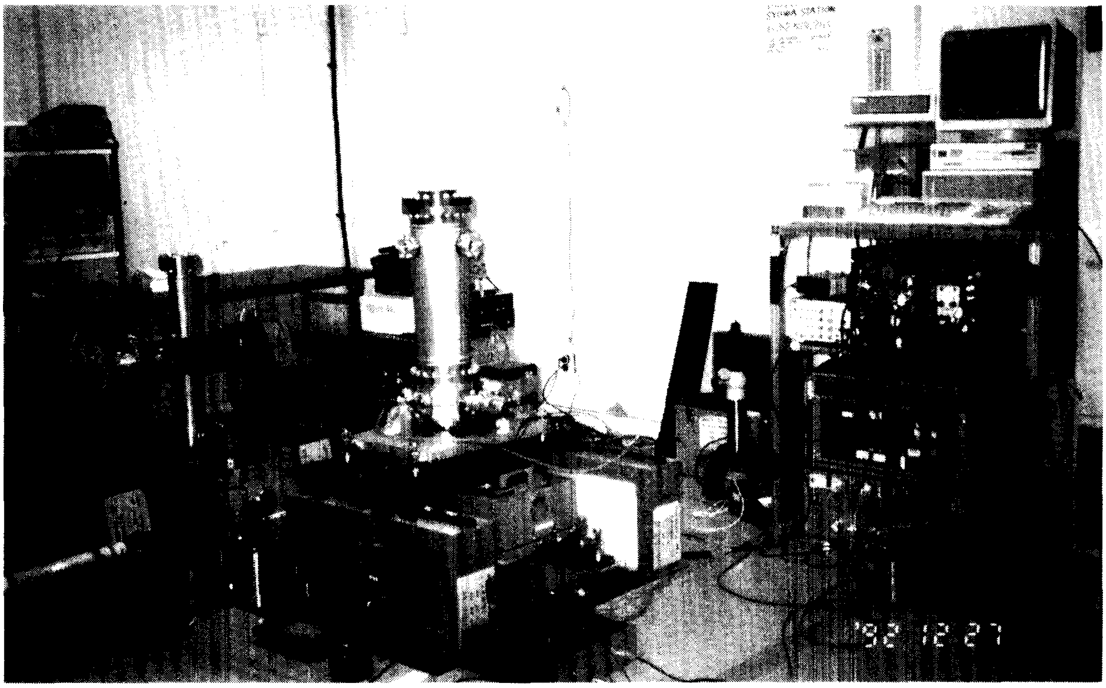

Fig. 3. The experiments with two absolute gravimeters at the GOH at Syowa Station.

parabola. It took about one year until we found that an integral variable which controlled the transient recorder and a real variable which represented the phase of the fringe were given by the same name and then were confused.

We did not obtain very much data by the AGRVP due to the troubles described above in spite of numerous days spent on the experiments. The number of data obtained was 374 for about 30 days. Figure 4 shows the measured gravity values taken by the AGRVP from December 28, 1992 to February 5, 1993. As an unusual case, measured gravity values can be divided into two groups according to their values. There is a group of data distributed around the value of about $982524.1\times10^{-5}\,\mathrm{ms}^{-2}$ (group A) and those distributed around the value of about $982524.3\times10^{-5}\,\mathrm{ms}^{-2}$ (group B). Forty three data included in group A often appeared during the periods from January 3 to 10 and from February 4 to 5, and 304 data in group B appeared from December 29 to February 4. Although there were in addition 27 data which largely deviated from both groups A and B and therefore do not appear in Fig. 4, we omitted them as abnormal data. We have not bound the cause which altered the measured gravity values by about $2\times10^{-6}\,\mathrm{ms}^{-2}$ yet. The arithmetic mean of the measured values in group A corrected for Earth tides, ground vibration, air pressure, laser wavelength and polar motion is $9.82524113\pm0.6\times10^{-7}\,\mathrm{ms}^{-2}$ with a standard deviation of $4.0\times10^{-7}\,\mathrm{ms}^{-2}$ (40 μGals), and that in group B is $9.82524345\pm0.4\times10^{-7}\,\mathrm{ms}^{-2}$ with $6.5\times10^{-7}\,\mathrm{ms}^{-2}$ (65 μGals), respectively. These are converted from the measured gravity values at the so-called effective height to those at the height of the surface of the pier, by applying the vertical gradient of gravity of $3.34\times10^{-6}\,\mathrm{ms}^{-2}/\mathrm{m}$ (0.334 mGals/m) measured by four LaCoste & Romberg gravimeters in January 1992 (FUJIWARA *et al.*, 1993). These values do not include the Honkasalo correction which corresponds to the effect of permanent tidal deformation. The Honkasalo correction for Syowa Station amounts to $4.90\times10^{-7}\,\mathrm{ms}^{-2}$ (49.0 μGals) if we assume that the tidal factor of gravity is 1.0. The arithmetic means for groups A and B including the Honkasalo correction then become $9.82524162\,\mathrm{ms}^{-2}$ and $9.82524394\,\mathrm{ms}^{-2}$, respectively.

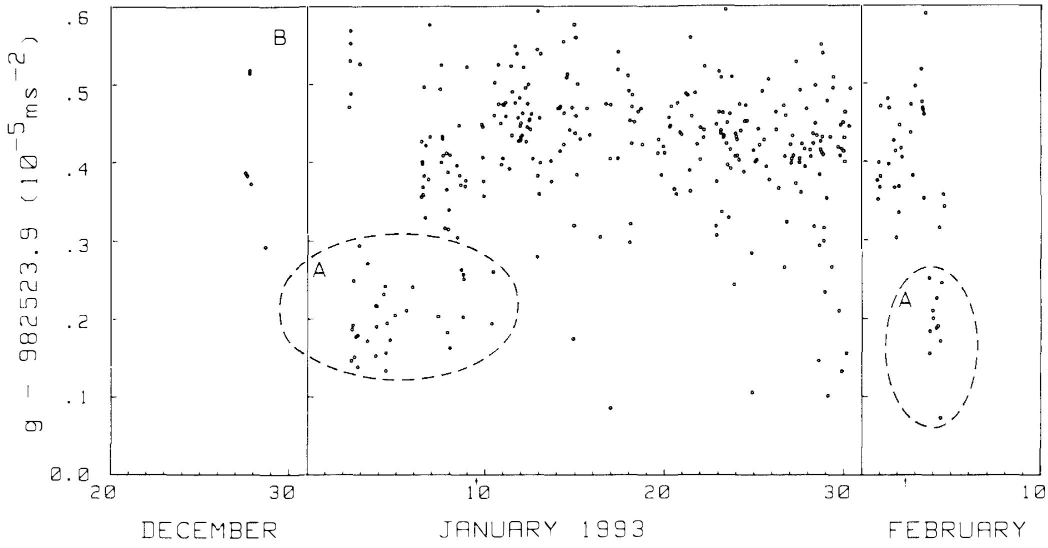

Fig. 4. The absolute gravity values obtained by the AGRVP at the GOH at Syowa Station. Two arrows under the horizontal axis indicate the replacement of the falling object. The data included in group A are surrounded by broken lines.

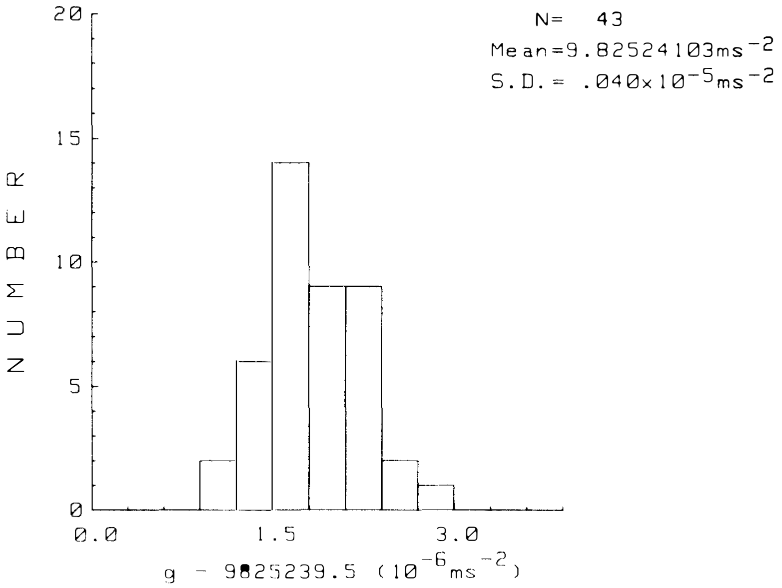

Fig. 5. A histogram of the measured gravity values in group A.

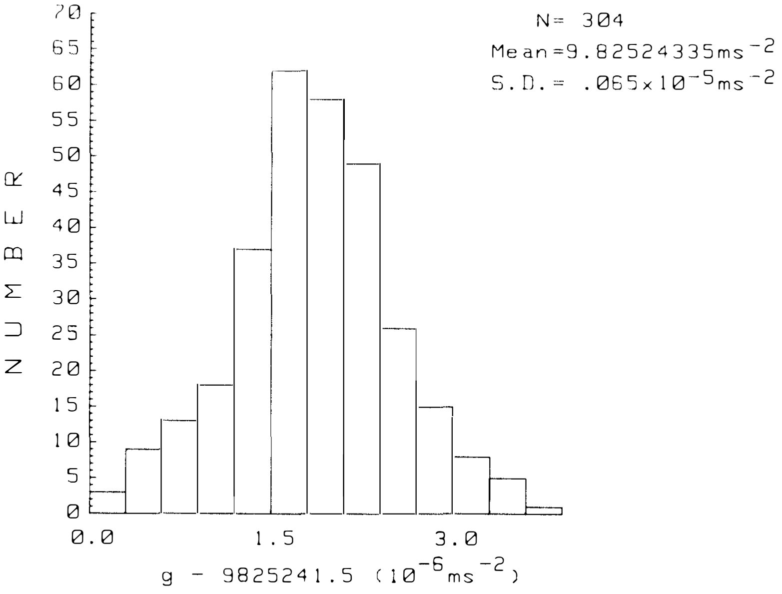

Fig. 6. A histogram of the measured gravity values in group B.

Histograms of groups A and B are respectively shown in Figs. 5 and 6.

3. Discussion

We compare the results obtained by the AGRVP with those obtained by the NAOM #2 in the same period as the AGRVP and with those obtained by the Sakuma-type absolute gravimeter of the Geographical Survey Institute (GSI-Sakuma) in January 1992. The results of the NAOM#2 and the GSI-Sakuma are shown in Table 1 together with those of the AGRVP (Fujiwara *et al.*, 1993 ; Tsubokawa and Hanada, 1994). These values are

Table 1. Comparison of ablsolute gravity values obtained at Syowa Station.

Gravimeter	Mean	Number	S.D.	Period
AGRVP (A)	982524.113	43	0.040	Jan. 3–10, Feb. 4–5, 1993
AGRVP (B)	982524.345	304	0.065	Dec. 29, 1992–Feb. 4, 1993
NAOM#2	982524.152	276	0.040	Dec. 27, 1992–Jan. 26, 1993
GSI-Sakuma	982524.252	834	0.030	Jan. 4–28, 1992

1) AGRVP (A) and (B) mean the results of groups A and B obtained by the AGRVP, respectively.
2) The Honkasalo correction is not included in the mean gravity values.
3) Mean and S.D. are expressed in mGals (10^{-5} ms^{-2}).

directly comparable since the measurement points for three absolute gravimeters were within the 1.5 m×2.5 m pier, and two LaCoste & Romberg gravimeters could not detect any horizontal gravity gradient there. Among the mean gravity values obtained by the different kinds of absolute gravimeters, group B of the AGRVP shows an exceptional value; the other three mean values are within 1.4×10^{-6} ms^{-2} (140 μGals). The difference between the AGRVP(A) and the NAOM#2, 4.0×10^{-7} ms^{-2} (40 μGals), is not very large compared with the standard deviations and is also not very large compared with the differences in the Third International Comparison of Absolute Gravimeters (BOULANGER *et al.*, 1991). There might be something wrong in group B although the number of data was more than that in group A, since the standard deviation of group B was the largest among them and the mean value was exceptional. According to the record of the experiments, we replaced the whole of the falling object with a spare on January 10, 1993 on account of breakage of the ruby sphere attached to the top of the object. The ruby sphere broke again on February 3, 1993, and we replaced the whole of the falling object with that used before January 10 having a new ruby sphere. It is possible that the difference in the mean values of groups A and B is attributable to the difference in the characteristics of the falling object. It was not ascertained whether the optical center of the corner cube prism coincided with the center of gravity in the spare falling object and also whether the ruby sphere was on the central axis of the spare object, since there was no special equipment for adjustment at Syowa Station. A falling object with an eccentric axis and with an optical center not on the center of gravity can give incorrect gravity values.

When an optical element drops freely in vacuum, the distance between the interferometer and its center of gravity will quadratically decrease due to the acceleration of gravity. If the falling object rotates around the horizontal axis during the drop, the optical path length deviates from the normal quadratic change. The effect of rotation upon a measured gravity value is approximately proportional to the square of the angular velocity and to the distance between the optical center and the center of gravity. The condition for absolute gravimetry of 10^{-9} accuracy can be approximated by the relation,

$$\omega \cdot d < 5.8\times10^{-7}\ \mathrm{ms}^{-1}, \tag{1}$$

where ω is the angular velocity and d the distance (HANADA, 1988). The situation becomes worse if rotation around the horizontal axis is superimposed on horizontal movement in the direction perpendicular to the axis. The falling object, which rotates around the horizontal axis passing through the center of gravity and moves horizontally at a constant velocity, is equivalent to that rotating around the other axis at a distance from the center of gravity if we observe it from a fixed point. The distance between the center of gravity and the point where the apparent axis of rotation passes can be expressed as:

$$d = v/\omega, \tag{2}$$

where v is the horizontal velocity. A very long distance d, perhaps on the order of cm or 10 cm, is possible depending on the combination of the values of v and ω. For example, angular velocity of 2.9×10^{-3} rad s^{-1} (10 arc min/s) and horizontal velocity of 10^{-3} ms^{-1}, which are not impossible values, cause the distance d to be 0.34 m ; the product of ω and d then becomes 10^{-3} ms^{-1}. This value is three orders of magnitude larger than that required for absolute gravity measurements of 10^{-9} accuracy. However, we cannot completely exclude other possibilities such as the effect of the ion pump, the effect of bugs in the computer program, and environmental changes.

We compared the result obtained by the AGRVP with that by the NAOM#2 at the Esashi Gravity Station, Esashi, Iwate, Japan and also with the results obtained by the NAOM#2 and the GSI-Sakuma at the GSI, Tsukuba, Ibaraki, Japan after we came back to Japan in order to investigate the cause of the difference in the measured gravity values. Special attention was paid to these comparisons to keep the condition of the gravimeters as constant as possible. The results are shown in Table 2 for Esashi and Table 3 for Tsukuba, respectively. Only a small number of data was obtained by the AGRVP since the bugs in the computer program were not removed in the period of the experiments. The difference between the mean values obtained by the AGRVP and the NAOM#2 at Esashi, 3.0×10^{-7} ms^{-2}, is not very large compared with the standard deviations. Although the difference which appeared in the experiments at Tsukuba is larger than that at Esashi, it is insignificant for other reasons. The GSI is located near a highway, and the ground is always vibrating due to traffic. The dominant period of the vibration is about 0.15 s and is close to 0.17 s, the falling time of the AGRVP. It is, therefore, impossible to thoroughly separate the vibration signal of a sinusoidal wave from the gravity signal of a quadratic curve. The effect of ground vibration was larger than 2×10^{-4} ms^{-2} (20 mGals)

Table 2. Comparison of absolute gravity values obtained at Esashi.

Gravimeter	Mean	Number	S.D.	Period
AGRVP	980121.766	39	0.049	June 2–24, 1993
NAOM#2	980121.736	198	0.061	May 20–June 20, 1993

1) The Honkasalo correction is not included in the mean gravity values.
2) Mean and S.D. are expressed in mGals (10^{-5} ms^{-2}).

Table 3. Comparison of absolute gravity values obtained at Tsukuba.

Gravimeter	Mean	Number	S.D.	Period
AGRVP	979951.063	69	0.336	June 29–July 2, 1993
NAOM#2	979951.168	61	0.085	June 29–July 2, 1993
GSI-Sakuma	979951.221	58	0.053	June–July 1993

1) The Honkasalo correction is not included in the mean gravity values.
2) Mean and S.D. are expressed in mGals (10^{-5} ms^{-2}).
3) The result of GSI-Sakuma is not the final one (Akiyama, private communication).

for the AGRVP; an effect of larger than 2×10^{-6} ms^{-2} (200 μGals) might remain uncorrected in the measured gravity values even if we corrected the effect of vibration with an accuracy of 1 %. It is interesting that the trend of decreasing values of gravity in the three types of absolute gravimeters at Tsukuba is similar to that at Syowa Station. As a result of the domestic comparisons, exceptionally large gravity values as seen in group B of the Antarctic experiments did not reappear.

4. Concluding Remarks

Absolute gravity measurements obtained by employing the AGRVP at Syowa Station gave two solutions which differ by about 2.3×10^{-6} ms^{-2} (230 μGals). According to comparison with other absolute gravimeter measurements at Syowa Station, Esashi and Tsukuba, the solution with the lower value seems to be reasonable. Its mean value is about 4.0×10^{-7} ms^{-2} (40 μGals) smaller than that obtained with NAOM#2. One possibility of the cause for the difference between the two solutions is misalignment of the falling object. The gravity value at GOH in Syowa Station will be fixed more definitely if another experiment is performed in the future.

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