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GRAVIMETRIC TIDAL FACTORS AT SYOWA STATION OBTAINED FROM THREE-YEAR OBSERVATIONS WITH A SUPERCONDUCTING GRAVIMETER

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Abstract: Gravity change observations with a superconducting gravimeter started in March 22, 1993 at Syowa Station, Antarctica. The observations have been continuing almost four years until now. In this paper, the first three years of data are investigated for the purpose of obtaining detailed tidal constants for diurnal, semidiurnal and terdiurnal waves. The observed tidal constants show rather large δ factors of 1.2 and of 1.5 for diurnal and semidiurnal tides, respectively. Those apparent large δ factors could be explained by large ocean tide loading. After applying several corrections to the observed tidal parameters, the ocean-tide corrected tidal factors were compared with theoretical ones by an elastic, ellipsoidal, rotating Earth model. Finally, the obtained tidal factors are consistent with theoretical ones within the discrepancy of 1% for principal constituents. More detailed discussion, for example, to see the latitude dependency of tidal factors, awaits accurate calibration of the scale constant of the gravimeter.

key words: earth tide, gravity, superconducting gravimeter, ocean tide loading

1. Introduction

Gravity change observations with a superconducting gravimeter (SG) started from the 34th Japanese Antarctic Research Expedition (JARE-34) in 1993 at Syowa Station, Antarctica. The observations have been carried out to observe gravity tide change in high latitude, Earth's free oscillations as well as seismic core modes, core undertones which originate from inertia-gravity waves in fluid core, secular gravity change, etc. The first data from the SG were obtained on March 22, 1993, and observations have been continuing for more than four years.

There were several previous gravity tide observations at Syowa Station using spring type gravimeters before the installation of the SG. OGAWA *et al.* (1991) analyzed gravity tide data which were obtained by using a LaCoste & Romberg G477 gravimeter for about two months in 1987, integrated with an electrostatic feedback system. KANAO and SATO (1995) observed the gravity tide in 1992 by using a LaCoste & Romberg D73 gravimeter which was modified to an electrostatic feedback type. The observations with the D73 gravimeter were extended to 1993 and 1994 to provide a scale factor for the SG.

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The installation of the SG and the analysis of the first one year of data were described by SATO *et al.* (1995). The diurnal and semidiurnal tides for the first two years of SG data were discussed by SATO *et al.* (1996a), while SATO *et al.* (1997) also discussed long period tides at Syowa Station. In this paper, we investigate the stability of gravity tide observations with three year of data, and obtain more detailed δ factors and phases for diurnal, semidiurnal and terdiurnal tides.

Syowa Station is located close to the ocean, hence the observed gravity tidal factors and phases are largely affected by ocean tide loading effects. Therefore, global problems cannot be discussed if their effects are not adequately corrected for. To compare observed results with the Earth model, recent ocean tide models (MATSUMOTO *et al.*, 1995) which are developed by using TOPEX/ POSEIDON altimetry data are used to estimate ocean tide loading effects at Syowa Station.

2. Gravity Tide Observations

A superconducting gravimeter (GWR Instruments, model TT70, #016) was installed in a Gravity Observation Hut (GOH) at Syowa Station in 1993. The GOH was designed to be used for absolute gravity measurements and for continuous gravity observations with the SG and LaCoste & Romberg gravimeters. The GOH is located at 39°35.'7 E, 69°0.'4 S and 24 m above sea level, and at about 300 m distance from the nearest coast (Fig. 1). The GOH is constructed on a bedrock area. The level of microseisms is comparable to that of an ordinary domestic observation site. In winter time, the microseism level becomes lower since the ocean surrounding Antarctica is covered with extended thick sea ice which suppresses ocean waves.

The SG has characteristics of high sensitivity, high stability and low drift rate. It has enough sensitivity to detect 0.01 μ gal (10^{-10}ms^{-2}) gravity changes if they are periodically coherent. The sensor unit of the SG consists of a superconducting niobium sphere about 2.5 cm in diameter which is levitated by magnetic forces created by superconducting currents. The position transition of the sphere yielded by the gravity acceleration change can be detected as a gravity change signal (PROTHERO and GOODKIND, 1968). The sensor unit must be cooled by liquid helium to 4 K to maintain the superconducting currents. The SG high stability comes from the high stability of superconducting currents. Actually, the recent drift rate after four years of operation has been less than 1 μ gal per month (1 μ gal=10^{-8} ms^{-2}), which is one hundredth that of the D73 gravimeter.

The gravity signals and atmospheric pressure data are measured at every two second interval by using a 7.5-digit A/D converter. Other environmental data such as room temperature and tilt of the SG are measured every 5 min. For details of the data acquisition system, see SATO *et al.* (1995).

The adopted sensitivity constant of the SG is –57.965 μ gal/volt throughout three years of data. This value was determined by comparing tidal factors obtained by the LaCoste & Romberg D73 gravimeter with those obtained by the SG during the parallel observations in 1993. The scale constant of the SG at the Esashi Earth Tides Station of National Astronomical Observatory, Mizusawa was determined similarly. In this case, the LaCoste & Romberg G457 gravimeter was used for parallel gravity tide observations. Recently, the scale factor of the SG at Esashi was calibrated by using an absolute

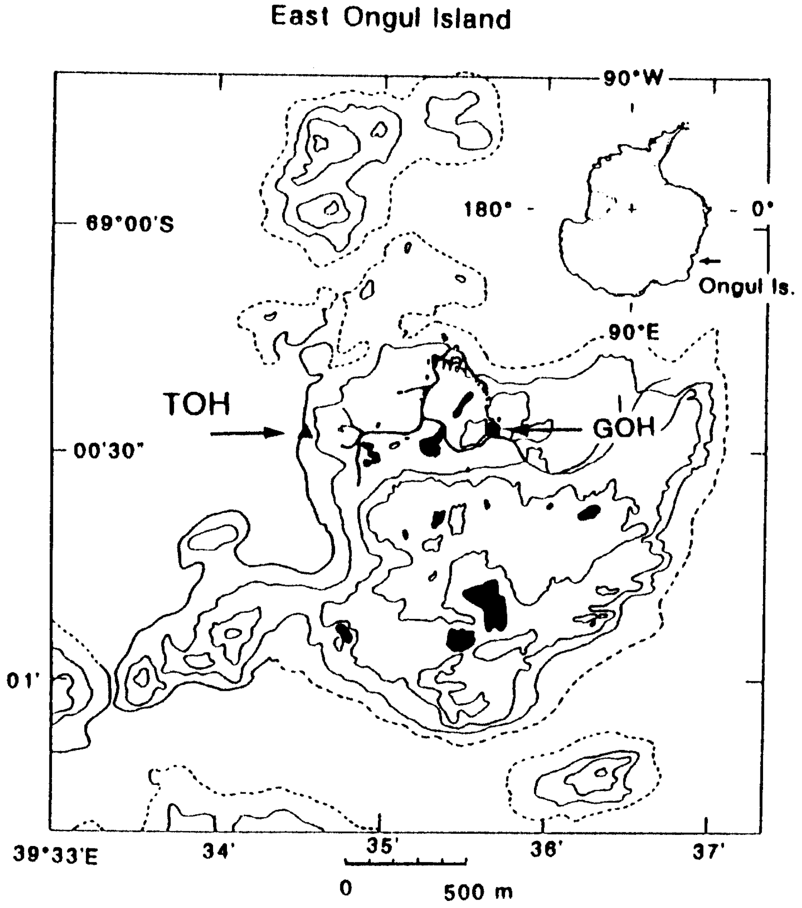

Fig. 1. Location of gravity observation hut (GOH) at Syowa Station, Antarctica. TOH is ocean tide observation hut.

gravimeter FG5 (Sato *et al.*, 1996b), and the above two scales coincided each other within 0.2% discrepancy. Supposing no systematic scale error in the absolute gravity measurements, we infer that, similar to the Esashi Station, the adopted scale value of the SG at Syowa Station has an error on the order of 0.2%.

3. Tidal Analysis

A digital low-pass filter was applied to the original 2 s sampling data and the hourly sampled data were created for the tidal analysis. The filter is an even filter and has no phase shift for tidal periods. The filter length is 361 points, that is, the data during 6 min before and after true hour were used to generate hourly sampling data. The filter is also designed to remove high frequency (higher than 0.01 Hz) noises such as microseisms and instrumental noises.

A harmonic analysis method BAYTAP-G (Tamura *et al.*, 1991) was used for data pre-processing and tidal analysis. BAYTAP-G dose not assume an explicit time function (ex. polynomial or sinusoid) for the drift model but only defines linearity (smoothness) of the drift. Each hour drift d_i is regarded as an unknown parameter to be solved. It is estimated under the constraint of,

$$d_{i-1} - 2d_i + d_{i+1} \fallingdotseq 0. \tag{1}$$

The above restriction can be controlled by a hyperparameter D (the parameter V in TAMURA *et al.*, 1991). If a large D value is adopted in the analysis, the fluctuation of the drift will be controlled within a small magnitude and *vice versa*. Too large a D value brings too large residuals in the analysis, and too small a D value brings instability in the parameter estimation and poor resolution between long period waves and drift term. The optimum value of D can be selected by referring to the information criterion ABIC (AKAIKE, 1980) automatically in the program.

Before the tidal analysis, hourly sampling data were pre-processed to remove large irregular data caused by maintenance of the observation instruments or by distant large earthquakes. With this pre-processing, about 4% data were eliminated. This percentage is comparable to the SG observation at Esashi in Japan (TAMURA, 1997).

Since BAYTAP-G does not deal with long period tides such as fortnightly Mf and

Table 1. Results of tidal analysis for the period from July 29, 1993 to January 28, 1996. The phase lag is taken to be positive. The corrections for phase delay caused by analogue low-pass filter, for ocean tide loading and for inertia are not carried out in this table in order to compare our results with previous works immediately.

Symbol	δ Factor (rms)	Phase (rms) degree	Amplitude (rms) μ gal
Q_1	1.2931±0.0019	−2.13±0.08	5.151±0.008
O_1	1.2671±0.0004	−0.66±0.02	26.361±0.008
M_1	1.2510±0.0049	−0.36±0.22	2.047±0.008
π_1	1.2076±0.0102	−1.10±0.48	0.684±0.006
P_1	1.2133±0.0006	−0.12±0.03	11.746±0.006
S_1	1.2169±0.0308	−8.55±1.45	0.279±0.007
K_1	1.1983±0.0002	−0.05±0.01	35.063±0.006
φ_1	1.2653±0.0234	1.63±1.06	0.290±0.005
ϕ_1	1.2185±0.0133	0.17±0.62	0.508±0.006
J_1	1.2032±0.0032	−0.63±0.15	1.969±0.005
OO_1	1.1903±0.0080	−2.06±0.39	1.066±0.007
$2N_2$	1.3136±0.0041	−5.64±0.18	0.321±0.001
N_2	1.4240±0.0009	−0.81±0.03	2.632±0.002
M_2	1.3983±0.0002	−0.57±0.01	13.500±0.002
λ_2	1.4012±0.0217	−1.53±0.89	0.100±0.002
L_2	1.5142±0.0097	−3.37±0.37	0.413±0.003
T_2	1.4732±0.0064	−2.07±0.25	0.387±0.002
S_2	1.4975±0.0004	1.43±0.01	6.726±0.002
K_2	1.5146±0.0016	0.86±0.06	1.849±0.002
M_3	1.0815±0.0144	21.60±0.76	0.074±0.001
S. D.	0.081 μ gal		
Hyperparameter D	2.0		
Pressure response	−0.367±0.003 μ gal/hPa		

monthly Mm tides, long period tidal components have to be subtracted from pre-processed data by assuming a priori tidal factors before the final analysis. By removing them from the pre-processed data set, the estimations of drift term and offset values became steady.

In the initial four month data in 1993, there was trouble in the data acquisition system and the noise level was several times higher than in the remaining period, as mentioned in SATO *et al.* (1995). Thus we used homogeneous 2.5 years of data from July 29, 1993 to January 28, 1996. In Table 1, the obtained detailed δ factors and phases are listed. The δ factor is defined as the ratio of the observed amplitude to the theoretical one on the rigid elliptical Earth, while the phase is similarly defined as the observed phase delay against the theoretical one (the observed phase delay is taken to be positive in this paper). The response parameter of the gravity change to atmospheric pressure change is listed in Table 1. We found an insignificant phase delay in atmospheric pressure response, therefore only a simple proportional coefficient was evaluated in our analysis.

In order to check time variability of δ factors and phases, we divided the data set into four data periods and compared the results. Each period had 7.5 months of data without overlapping. The obtained δ factors and phases for O_1, K_1 and M_2 waves of four different periods are illustrated in Fig. 2. The δ factors have a common time variation

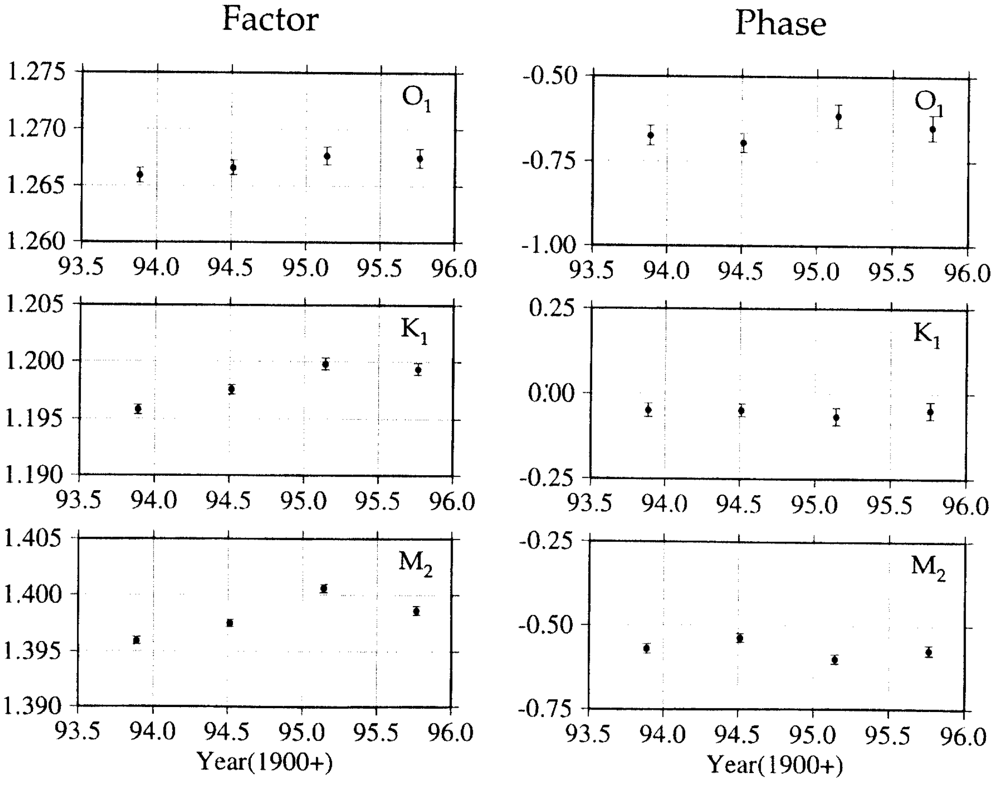

Fig. 2. Time variation of δ factors and phases for O_1, K_1 and M_2 waves. The data set from July 29, 1993 to January 28, 1996 are divided into four data periods. Each analysis period has a same data length of seven and half months without overlapping.

pattern; this will be discussed in Section 5.

4. Corrections

The δ factors and phases in Table 1 and Fig. 2 are those with no correction applied, but they can be compared directly with the previous results of Table 1 in Sato *et al.* (1995) and Table 1 in Sato *et al.* (1996a). These values can be used to predict the synthetic tidal component and extract it from the observed gravity changes to discuss nontidal gravity changes. To discuss global phenomena, it is required to apply several corrections; (1) the characteristic of the analogue low-pass filter which is build in the electronic circuit of the SG, (2) inertial change (Parysky and Pertsev, 1978), and (3) ocean tide loading effects.

The tidal gravity signal from the SG is low-pass filtered with a cutoff period of 50 s, and the associated linear phase delay of 0.1558 degree/cpd must be corrected for. The gain of the filter can be accepted as flat in the tidal frequency bands.

The inertia correction I is to correct for the additional gravity acceleration change caused by the dynamic vertical motion of the observation site due to the sinusoidal tidal displacement, where I can be expressed using the Love number h, Earth's radius r, gravity acceleration g and angular velocity ω (measured in radians per second) of tidal component considered as,

$$I = -h\frac{\omega^2 r}{2g} = -1.966 \times 10^5\,\omega^2. \tag{2}$$

The magnitude of this correction is roughly –0.001 and –0.004 for diurnal and semidiurnal δ factors, respectively.

The ocean tide loading effects have just the same frequencies as those of the solid earth tides. Consequently, these effects cannot be distinguished in tidal observations. To estimate these effects, the global convolutional integral method is required using both global ocean tide models and loading Green function models. For our analysis, recent global ocean tide models of MATSUMOTO et al. (1995), developed by assimilation technique of empirical and dynamic modeling, were used. The convolutional integration method GOTIC developed by SATO and HANADA (1984) was applied to estimate ocean tide loading effects. The calculation results for principal constituents are listed in Table 2. The estimation results in Table 2 slightly differ from those of SATO et al. (1996a) though the present estimation method is essentially the same as theirs. This is mainly because the adopted coordinates of the GOH are revised to more appropriate ones in this paper. The effects for diurnal tides reach almost 10% of solid tides, while those of semidiurnal tides attain 20% of solid tides.

In Table 3, the final δ factor and phase of principal tides after completing the above corrections are listed. Theoretical δ factors for elastic, ellipsoidal, and rotating Earth model at the latitude of Syowa Station (69°S) are also listed in Table 3 for comparison (Dehant and Zschau, 1989).

Table 2. Ocean tide loading effect for principal constituents are estimated based on Matsumoto *et al. (1995) ocean tide models. In this study, the station coordinates are revised to more appropriate ones.*

Symbol	This study Amplitude (μ gal)	Phase (degree)	Sato *et al.* (1996a) Amplitude (μ gal)	Phase (degree)
Q_1	0.65	336.19	–	–
O_1	2.63	347.02	2.63	346.99
P_1	0.70	359.26	–	–
K_1	2.07	358.13	2.08	358.11
N_2	0.47	342.26	–	–
M_2	2.34	349.88	2.35	349.73
S_2	1.71	358.69	1.72	358.59
K_2	0.48	358.62	–	–

Table 3. Final δ factors and phases after correcting phase delay by low-pass filter, inertia effect and ocean tide loading effects are listed. In Sato *et al. (1996a), the filter characteristic and the station coordinates are uncorrected. Theoretical δ factor is based on* Dehant *and* Zschau *(1989) for an elastic, elliptical, uniformly rotating Earth model.*

Symbol	This study δ factor	Phase (degree)	Sato *et al.* (1996a) δ factor	Phase (degree)	Dehant and Zschau (1989) Theoretical δ factor
Q_1	1.142	0.75	–	–	1.152
O_1	1.143	0.53	1.144	0.66	1.152
P_1	1.139	-0.25	–	–	1.147
K_1	1.127	-0.10	1.127	0.04	1.132
N_2	1.179	2.43	–	–	1.158
M_2	1.156	1.06	1.157	1.41	1.158
S_2	1.111	1.95	1.111	2.34	1.158
K_2	1.161	1.09	–	–	1.158

5. Discussion

The data length used in Table 1 is about three times longer than that of Table 1 by Sato *et al.* (1995; we call this hereafter the previous study), making it possible to obtain tidal constants for minor constituents. The estimation errors for semidiurnal and terdiurnal tides in Table 1 become smaller than those in the previous study because of the increase of data length, while those of diurnal tides are not significantly improved. This may seem peculiar in an ordinary least squares estimation procedure, but this paradox can be explained by the constraints in the drift model adopted by BAYTAP-G. The selected hyperparameter D in our present analysis is 2.0, while that in Sato *et al.* (1995) was 4.0 (this value is not given explicitly). In other words, the linearity constraint to the drift in our present analysis is weaker than that of the previous one. For this reason, the estimation errors of longer period diurnal waves become relatively worse as compared with those of shorter period semidiurnal waves. If we select a larger D value in a trial, we could reduce the estimation errors of the diurnal tide, but the mean residuals would increase and the estimated drift would deviate from the real drift.

The diurnal δ factors are almost the same as those in the previous study, while the semidiurnal δ factors are about 0.3% larger. The variability of the δ factors will be discussed later in this section. The results in the previous study are *not* corrected for ocean tide effects although the effects were corrected for based on SCHWIDERSKI's (1980) ocean tide models. In addition, the definition of the sign of the phase is opposite to our definition.

In the previous results in Table 3 of SATO *et al.* (1996a), only four constituents were compared with the theory by WAHR (1981). In this paper, eight principal constituents are listed in Table 3 after the corrections mentioned in Section 4, and they have been compared with the theory by DEHANT and ZSCHAU (1989). There are only 0.1% or less differences in the δ factors between our present results and the previous ones by SATO *et al.* (1996a), while the phases disagree about 0.°1–0.°4. These differences in phase mostly come from the phase delay correction associated with the analogue filter in the SG. This correction was not included in SATO *et al.* (1996a), and the phases in our results come closer to zero except for the K_1 wave. As for the theoretical δ factor to be compared, the WAHR (1981) model has a larger latitude dependency while the recent theory by DEHANT and ZSCHAU (1989) has a smaller one.

For the time variation of tidal constants shown in Fig. 2, a common variation pattern is shown in the δ factors. The δ factors are slightly increasing year after year, and maximum peaks seem to appear early in 1995. For the O_1 and K_1 phases, the time variation is not so clear considering their comparable estimation errors. The variation of M_2 phase exceeds its estimation error, but this change is not so large as compared with that of the M_2 δ factor. The data length of each period is taken as 7.5 months, which is long enough to resolve principal tidal constituents but is not too long to smooth out the time variation. The small phase changes and common variation pattern of the δ factors in Fig. 2 may suggest the existence of sensitivity change of the SG during the observation period which is caused by the change of mean output voltage level of the gravity signals, and by the tilt changes of the gravity sensor unit. However, both causes are rejected because we cannot find any change of the δ factor before and after the levitation operation (adjustment of the position of the sensor superconducting sphere) which yields the change of mean output level, and because no substantial tilt changes are monitored in that period. We kept the scale of the SG constant throughout the three years, because it is yet too early to try to include the sensitivity scale variation model in our present analysis. There is no reasonable explanation of these variations yet, but we may see one possibility from the time variations in the oceanic tides. Since the ocean tide loading effects attain 10–20% of solid tide amplitudes, they might cause about 0.1–0.2% variation of the δ factor seen in Fig. 2, if the amplitude of ocean tides around Syowa Station is modulated 1%.

In the previous gravity tide analyses at Syowa Station (OGAWA *et al.*, 1991; KANAO and SATO, 1995; SATO *et al.*, 1995), large observed δ factors are reported, especially for semidiurnal waves. Also in this paper, large δ factors are obtained as in Table 1. Although the observed δ factors of diurnal tides are almost 1.20, the corresponding semidiurnal factors are fairly large, around 1.40–1.50, as compared with the theoretical Earth model factors of 1.15–1.16. These large observed δ factors can be explained by the ocean tide loading effects, because after all corrections mentioned in Section 4, final δ factors agree well with theoretical values (Table 3). OGAWA *et al.* (1991) could not explain large apparent semidiurnal δ factors even after the correction for ocean tides. This was because they used the ocean tide model by SCHWIDERSKI (1980) which had few constraints by tide gauge data around the Antarctica and whose precision in the Antarctic Sea is considered not so high, and because the mesh size of the adopted digital map was still too coarse as compared with the topography of East Ongul Island (SATO *et al.*, 1996a).

There is uncertainty in the scale constant of the SG on the order of 0.1%, as was determined by the parallel observations with the LaCoste & Romberg D73 gravimeter in 1993. Although the δ factors after the correction for the ocean tide loading effect (Table 3) show rather good agreement with theoretical values, they appear to be systematically smaller, on the order of 0.3–0.6%, for the diurnal band. This systematic discrepancy may be attributed partially to the uncertainty of the scale constant of the SG, and partially to the errors in the global ocean tide models. Although the uncertainty of the scale value of the SG is not a serious problem for studies of free oscillation of the Earth, core under tone or secular change of gravity, it is a critical obstacle in discussing the latitude dependence of δ factors whose magnitude range is around 0.1% or 0.2%.

The SG itself dose not have an absolute calibration system to determine its own scale constant, so that calibration with an other instrument is required. In the summer expedition of JARE-36 in 1995, the Geography Survey Institute carried out absolute gravity measurements with an FG5 gravimeter beside the SG in the GOH (YAMAMOTO, 1996), but unfortunately, accurate determination of the scale factor of the SG by comparison with the absolute gravity measurements could not be done, partly because the tidal observation by the SG itself was disturbed several times during maintenance work in the summer field season. In order to obtain an accurate scale constant for the SG, operation of the absolute gravimeter parallel with the SG entirely during winter is required.

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