SEA GRAVIMETER SYSTEM OF THE ICEBREAKER 'SHIRASE'

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Abstract: The gravimeter system of the SHIRASE is the NIPRORI-1 sea gravimeter which was transferred from the icebreaker FUJI. In installing this gravimeter on the SHIRASE some changes for adaptation as well as some improvements for enhancing the capabilities were made. The main differences of the gravimeter installed on the SHIRASE are as follows:

1) The gravity sensor unit and the data processing unit were installed in separate rooms.

2) An air-cushioned board was placed in the gravity sensor room in order to reduce vibration of the floor caused by the engines.

3) The data processing unit was expanded, and computers and floppy disks were doubled.

4) Temperature regulation of the gravimeter was improved, so that it became possible to detect the tidal variation of gravity by the use of the existent gravity sensor.

5) Software for data processing was improved in two points; one concerned with the operation by interrogation and the other with the refinement of noise filtering.

1. Introduction

The NIPRORI-1 sea gravimeter manufactured in 1980 (SEGAWA *et al.*, 1981, 1982, 1983) was in use on board the icebreaker FUJI from 1980 to 1982. A new icebreaker SHIRASE which is approximately twice as large as the FUJI was launched at the end of 1982, and she replaced the FUJI with a mission of transporting the Japanese Antarctic Research Expedition party as well as surveying the sea around Antarctica. The NIPRORI-1 sea gravimeter installed on FUJI was then transferred to the SHIRASE for the 25th Japanese Antarctic Research Expedition (1983–1984).

The SHIRASE is better equipped than the FUJI: The gravity sensor room was prepared almost at the center of the ship's motion where the magnitude of motion is the smallest. A laboratory for data processing was built separately on the upper floor. Information of navigation is almost perfect; continuous outputs of the ship's position, velocity, water depth and so on from an integrated navigational aid are available in digital form at all of the laboratories. Electric power of the new icebreaker was much improved, as it comprises the power of 60 Hz, 115 V and 50 Hz, 100 V, in addition to the 400 Hz, 115 V, 3-phase power. The 50 Hz power was prepared particularly for the instruments of precise measurement.

Because of such significant changes of environment it became necessary for the NIPRORI-1 gravimeter to be changed in part and added with some new apparata not only for fitting the gravimeter to the new environment but also for enhancing its capabilities. This paper reports various points of improvement of the NIPRORI-1 gravimeter as well as some new findings about its performance.

2. Installation of Gravimeter

The NIPRORI-1 sea gravimeter can be divided into the sensor unit and the data processing and storage unit. They were transferred and installed separately in two rooms of the SHIRASE (Fig. 1). In the room at the center of the ship were in-

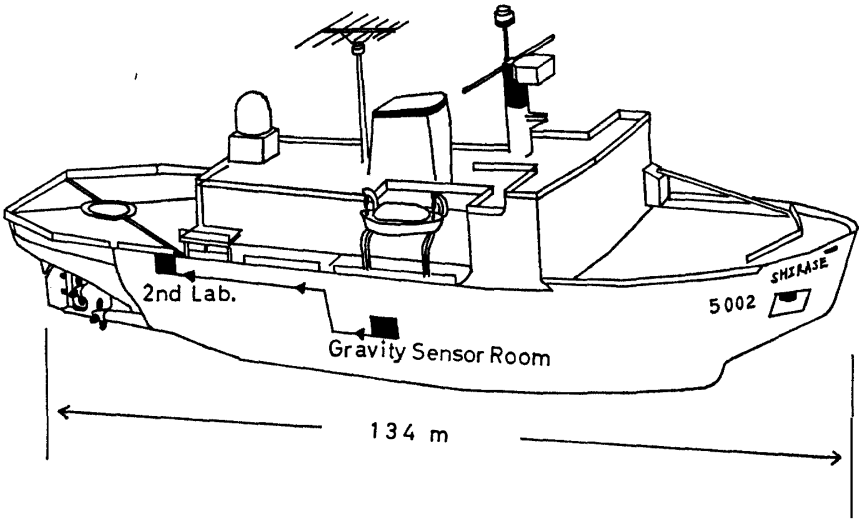

Fig. 1. The icebreaker SHIRASE showing the location of the gravity sensor room and the 2nd laboratory. The arrow indicates a cable line interconnecting the two rooms.

stalled the gravity sensor and the related hardwares. The data processing units were installed in the '2nd laboratory' located at the stern-side on the main deck. The data obtained in the gravity sensor room are sent to the 2nd laboratory at a distance of about 35 m by means of 100 twisted pairs of cable (polyethylene-insulated braided cable, JIS MTTEYCS-50×2, 0.78 mm in diameter, specific resistance 51.6 Ω/km). The length of the cable spanning between the two rooms is approximately 40 m, yielding a DC electric resistance of about 2 Ω for each wire.

Figure 2 shows the arrangement of gravimeter units in the gravity sensor room. This room is 3500 mm long and 2775 mm wide, located on the floor just above the

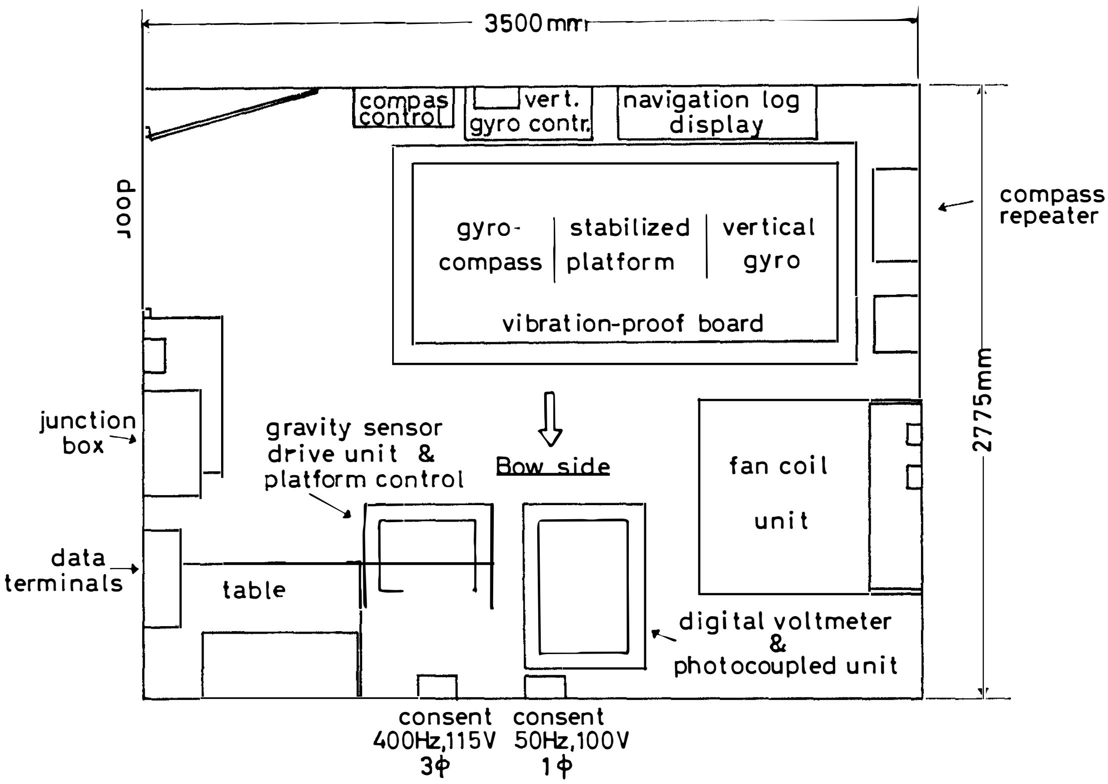

Fig. 2. Arrangements of the gravity sensor and the related hardwares in the gravity sensor room of the SHIRASE.

engine room and somewhat (3 m) aside from the ship's median line towards the starboard side. Since this room is close to the engine the floor is mounted on rubber sheets so as to reduce vibration. The efficacy of the rubber sheets is not satisfactory because the vibration of the engine is too strong. As seen from Fig. 2 the main mechanical units of the gravimeter, *i.e.*, vertical gyro, stabilized platform with a gravity sensor and gyrocompass, were mounted together on an air-cushioned steel-board with a thickness of 3 cm. This vibration-proof board works not only for reducing the ship's floor vibration but also for unifying the three mechanical units firmly, because the verticality of the platform is basically determined by a geometrical relationship with the vertical gyro and the gyrocompass.

The gravity sensor drive unit, the platform control, the vertical gyro control, the gyrocompass control and the compass repeater were also arranged in this room. The digital voltmeter which converts the analog output of the gravity acceleration into digital data has to be placed close to the sensor in order to avoid undesirable electric interference. Digital data of gravity acceleration are then sent to the data processing units. Since the data processing units were installed far from the gravity sensor room, a problem arose in telemetering digital signals: It happens sometimes that the electric voltage level of a ship's ground, *i.e.*, ship's body, varies significantly from place to place, or from time to time. Therefore, if two instruments are grounded separately in different places, the ground voltage level with one instrument might differ from that with another, making it impossible to exchange electric signals. In order to avoid such an adverse situation the ground of the gravity sensor room and that of the 2nd laboratory were electrically separated by means of photo-coupling devices. The photo-coupled unit (photo-coupled driver) shown in Fig. 2 converts the electric signals into photometric signals by the use of photo-diodes, and then inverts them to electric signals which are fed to the twisted-paired cables through data terminals.

The gravity sensor room is equipped with a fan-coil unit, by which the room temperature can be regulated.

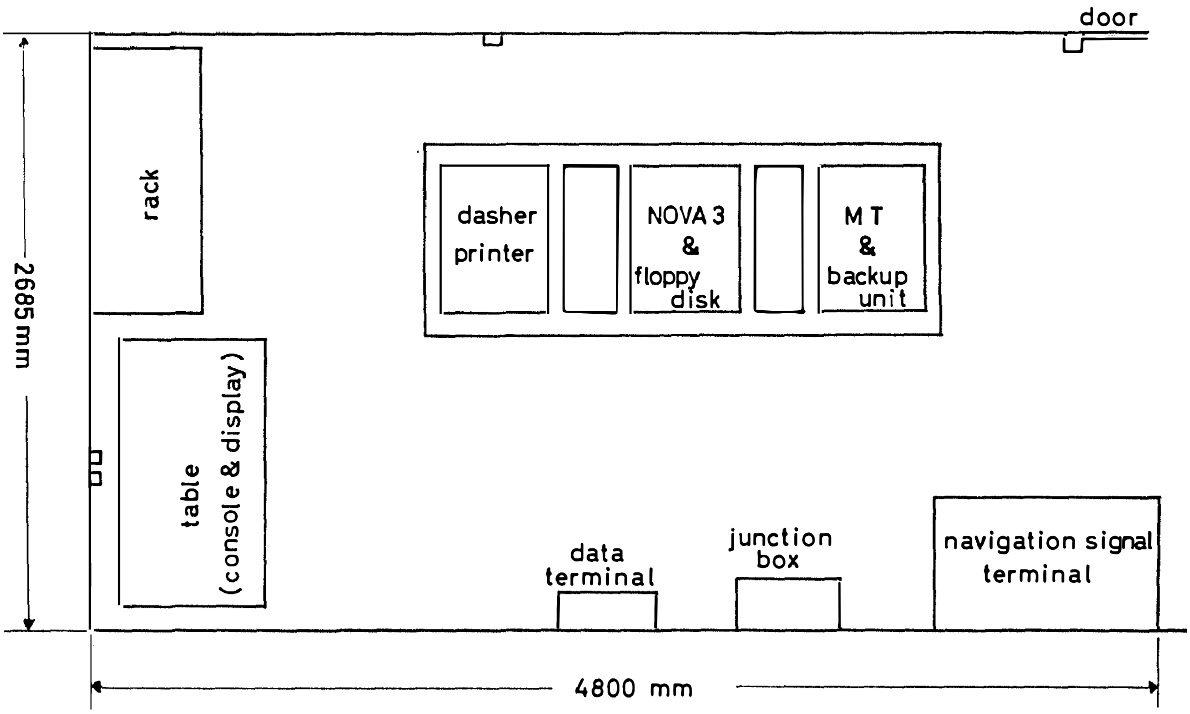

Fig. 3. Arrangements of the data processing units in the 2nd laboratory of the SHIRASE.

Figure 3 shows the arrangement of the data processing units. These units occupy a corner 4800 mm wide and 2685 mm long, where two sets of mini-computer NOVA-3 systems including a console and CRT display, floppy disks, a magnetic tape recorder and a dasher printer were installed. Although not shown in the figure, a time-code generator, an interfacing device and a photo-coupled receiver are also equipped in this corner. Digital data of gravity acceleration sent by the photo-coupled driver in the gravity sensor room are acquired by the photo-coupled receiver from the data terminals of this room. The data together with the time code are fed to the NOVA-3 system.

The navigation log displays are equipped in both the gravity sensor room and the 2nd laboratory. In the 2nd laboratory the navigation signal terminals are equipped in addition to the navigation display. These terminals make it possible to process gravity data in real time with necessary navigational corrections, although the function is not fully used at present. Figures 4 and 5 show photographs of the gravity sensor room and the 2nd laboratory. It is seen from Fig. 4 that the vibration-proof board (d) of the gravity sensor room is suspended by rubber balls (e) pressurized by

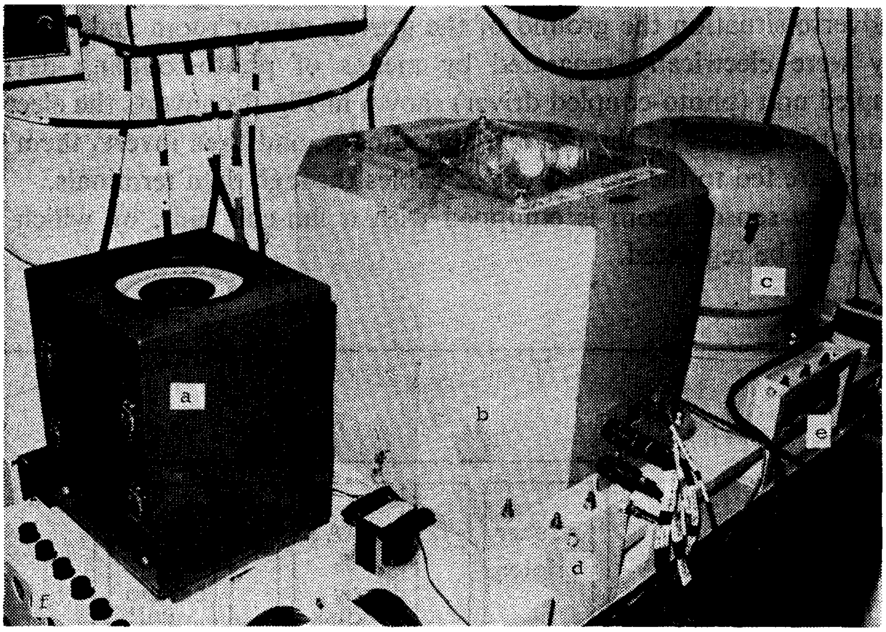

Fig. 4. Photograph showing part of the gravity sensor room of the SHIRASE. *a. Gyrocompass. b. Stabilized platform. c. Vertical gyroscope. d. Vibration-proof board. e. Rubber balls (cushions). f. Dials for pressure regulation.*

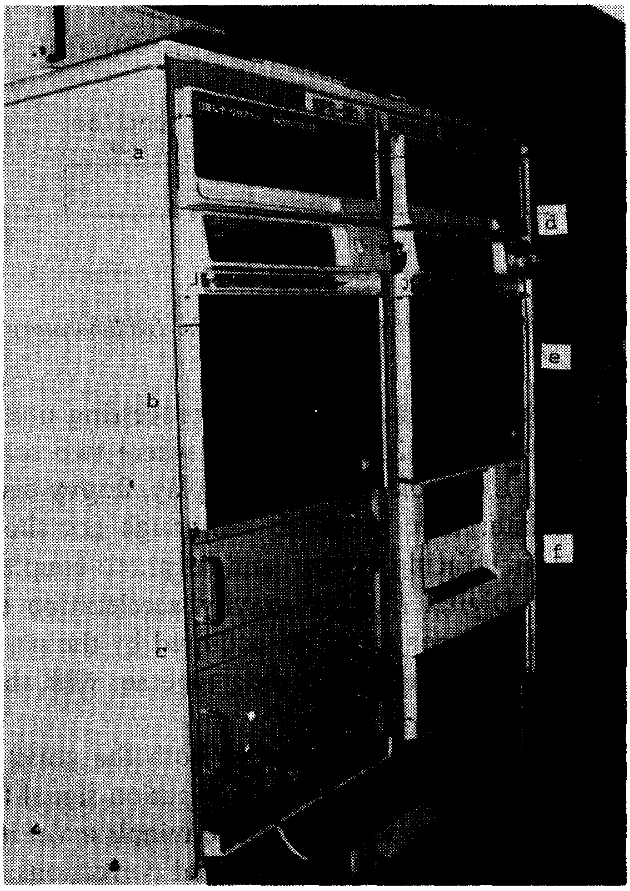

Fig. 5. Photograph showing part of the 2nd laboratory of the SHIRASE. *a. Mini-computer NOVA-3 (main). b. Floppy disk device (main). c. Interfacing unit which transmits data to mini-computer. d. Mini-computer NOVA-3 (spare). e. Floppy disk device (spare). f. Magnetic tape device.*

an air compressor. Internal air pressure (1 to 2 bars) of the balls is controlled by pressure regulators which are manually adjusted by the dials (f). The two sets of the NOVA-3 computer devices compose the main device and its spare. The double systems were employed because the Antarctic expedition continues longer than 5 months.

3. Gravimeter Assembly and Data Processings

Figure 6 shows a diagram of the whole assembly of the NIPRORI-1 gravimeter installed aboard the SHIRASE. The gravity sensor composed of a precise servo accelerometer is mounted on the stabilized platform, which is controlled by the platform control using the signal from the vertical gyroscope and the gyrocompass. Digital

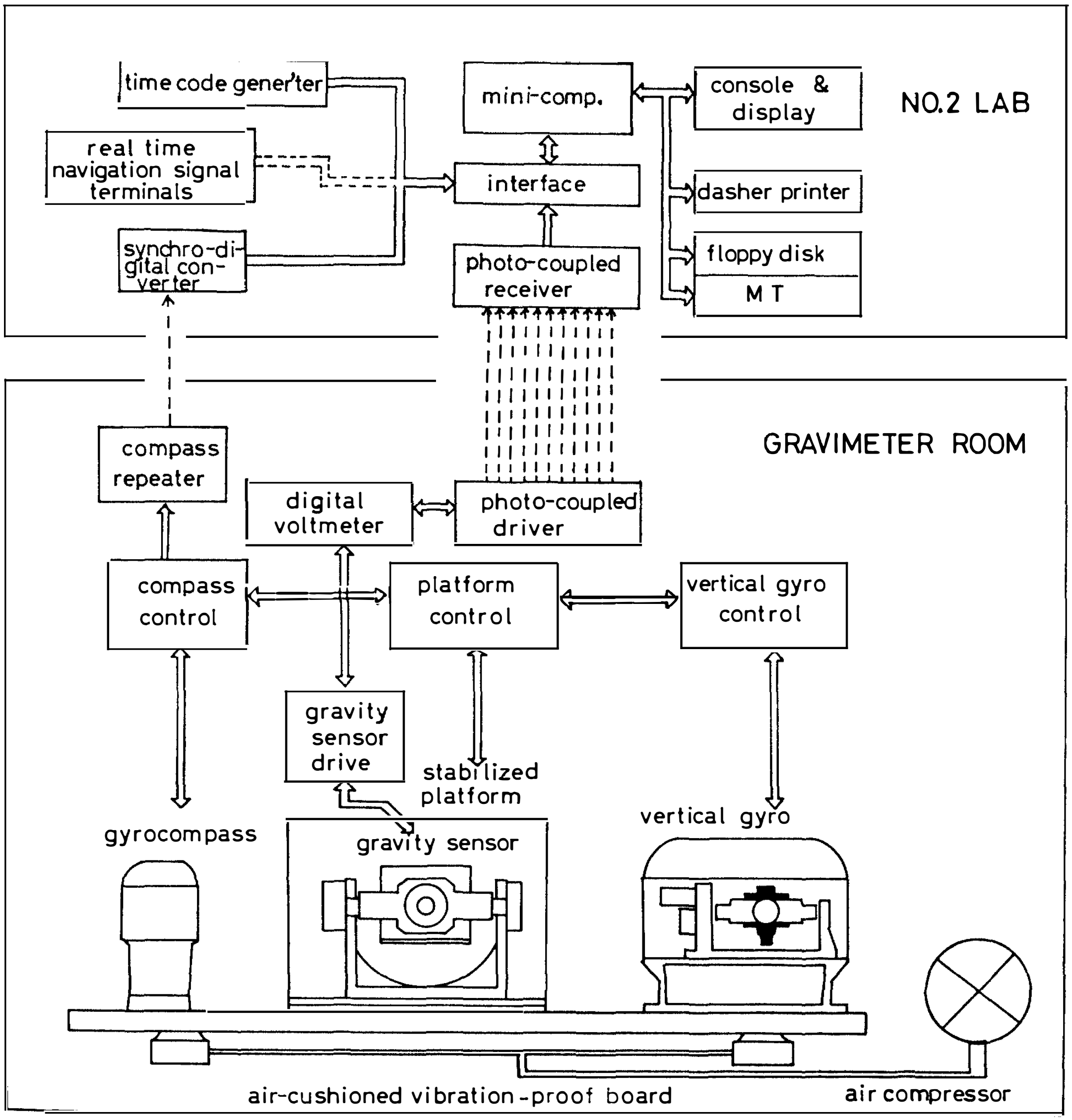

Fig. 6. A diagram showing the whole assembly of the NIPRORI-1 gravimeter installed aboard the SHIRASE.

signals of gravity acceleration are sent to the computer system in the 2nd laboratory with the aid of the photo-coupled driver and receiver through interconnecting cables. The ship's heading measured by the gyrocompass in the gravity sensor room is conveyed to the 2nd laboratory through another interconnecting cable. The heading (or the azimuth) transmitted by a synchro-transmitter in the compass repeater is converted into a digital value by a synchrodigital converter to be supplied for the computer system.

The mini-computer NOVA-3 system is initialized by manual inputs from a keyboard which is monitored by a CRT display. The initial set and the monitoring of computation proceed by interrogation scheme. So, all the inputs from the keyboard are guided by the instruction on the CRT display. Computed results are printed out and stored in both floppy disks and magnetic tapes. The real time navigation signals are not used at present, but when used in future a real time calculation to obtain the Eötvös correction and gravity anomaly may become possible.

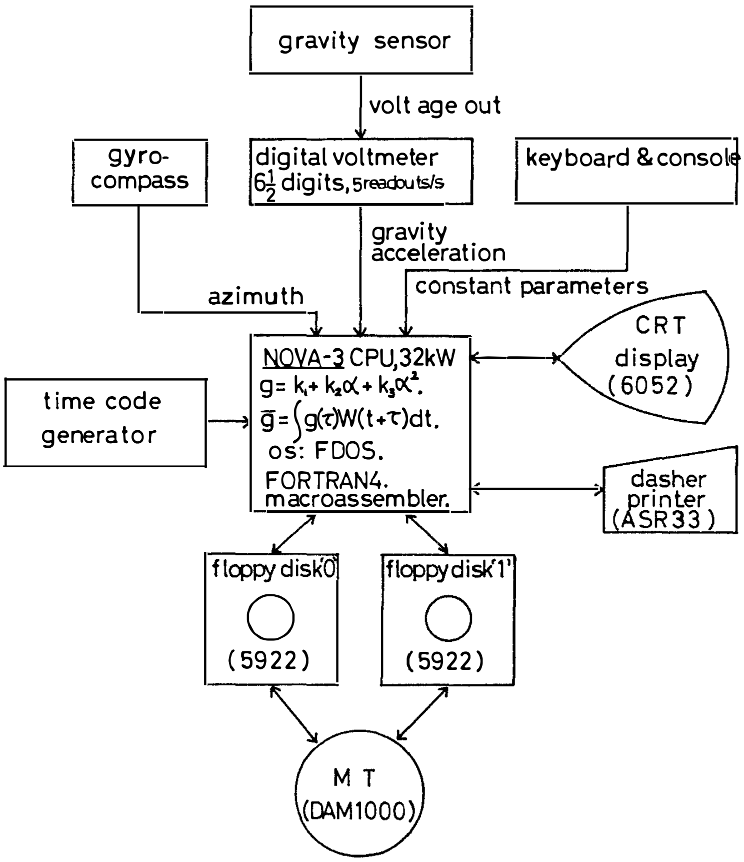

Fig. 7. A brief diagram of data flow in the NIPRORI-1 gravimeter installed aboard the SHIRASE.

Figure 7 shows a brief diagram of data flow. Gravity accelerations are digitized by a 6 1/2 digit digital voltmeter at a rate of 5 samples per second (0.2 s interval). An instantaneous gravity value $g(t_n)$ at time t_n is calculated using calibrated constants k_1, k_2 and k_3, as follows (SEGAWA *et al.*, 1981).

$$g(t_n)=k_1+k_2\alpha(t_n)+k_3\beta^2(t_n)\ , \tag{1}$$

where k_1 is a bias gravity determined at a port of departure, k_2 a constant of proportion that converts the voltage output $\alpha(t_n)$ into gravity value, and k_3 a constant which corrects for minor nonlinearity of the sensor proportional to the variance of gravity accelerations $\beta^2(t_n)$. The values $g(t_n)$ are obtained every 0.2 s. To successive values of $g(t_n)$ is applied digital filtering using a symmetric weight function $W(t)$, where $W(t)$ is a normal filter expressed by

$$W(t)=\exp(-0.5t^2/\sigma^2)\,, \tag{2}$$

with a constant σ. Let $S(\omega)$ be Fourier transform of $W(t)$, where ω is an angular frequency, then we have

$$S(\omega)=\sigma\exp(-0.5\sigma^2\omega^2) \tag{3}$$

or

$$=S(0)\exp(-0.5\sigma^2\omega^2)\,. \tag{4}$$

By the use of this filter a weighted average is taken according to the following equation:

$$\widetilde{g(\tau_n)}=\frac{\sum_{P=-N}^{N} g(\tau_n+t_p)W(t_p)}{\sum_{P=-N}^{N} W(t_p)}\,, \tag{5}$$

where $\widetilde{g(\tau_n)}$: smoothed gravity at time τ_n,
$g(\tau_n+t_p)$: instantaneous gravity at time (τ_n+t_p),
$W(t_p)$: weight value at time t_p,
N: a number limiting a spread of a weight function over which the average is taken.

τ_n is selected normally with the interval of either 1, 2 or 5 minutes. t_p is sampled every 0.2 s. The characteristics of the normal filter shown by eq. (2) depend significantly on the value σ. As soon understood from Fourier transform in eqs. (3) or

Table 1. Weight function $W(t)$ and its normalized Fourier transform $S(\omega)/S(0)$ as a function of time t in second and angular frequency ω in rad/s, respectively. (σ=30 s)

$\|t\|$	$W(t)$	ω	$S(\omega)/S(0)$
0	1.000000	0	1.000000
1	0.999445	0.005	0.988813
2	0.997780	0.010	0.955997
5	0.986207	0.020	0.835270
10	0.945960	0.050	0.324652
20	0.800739	0.100	0.011109
40	0.411116	0.200	0.000000
60	0.135338	0.300	$<10^{-8}$
80	0.028567	0.400	$<10^{-8}$
100	0.003866	0.500	$<10^{-8}$
120	0.000335	0.800	$<10^{-8}$
140	0.000019	1.000	$<10^{-8}$
150	0.000004	2.000	$<10^{-8}$

(4), gravity signals which are to be measured are weakened when σ is too large and disturbing accelerations caused by the ship are poorly removed when σ is too small. The value σ used for the filter of the NIPRORI-1 gravimeter is 30 s which seems to optimize the balance between noise elimination and signal conservation. Table 1 shows the value of $W(t)$ and $S(\omega)/S(0)$ as a function of either t or ω. Although the weight function $W(t)$ is a continuous function of t which can be defined from $-\infty$ to ∞, the value approaches zero rapidly when $|t|$ increases; for $t=\pm 150$ s $W(t)$ is of the order of magnitude 10^{-6} when σ is 30 s. So, the number N which limits the spread of the weight function is taken as 750, corresponding to 150 s when t_p is sampled with the interval of 0.2 s. The denominator of eq. (5) is a simple sum of the weight function which is necessary to normalize the weight function.

Final outputs from the NIPRORI-1 gravimeter that are displayed, printed and stored in memories consist of the filtered gravity acceleration, time of measurement, ship's heading and variance of gravity acceleration. Programing was performed in FORTRAN IV language using the FDOS operating system of the NOVA computer.

4. Nature of Vibration-Proof Board

The servo accelerometer used for the gravity sensor of the NIPRORI-1 gravimeter is the one that is comparatively immune to external vibration. However, when there are strong vibrations on the floor where the gravimeter is placed, some amount of shift in gravity occurs due to slight nonlinearity of the sensor. The floor vibration is not desirable to the vertical gyroscope and the stabilized platform either.

Floor vibrations caused by the ship's engines with 30000 HP were examined by the shipbuilding company soon after the ship was fully equipped. The results show that the amplitude of the vertical vibration of the floor in the gravity sensor room is smaller than 4 cm/s^2 with a predominant frequency of 15 Hz when the ship cruises at a speed of 15.3 kn, and that it is smaller than 14 cm/s^2 with a frequency of 22.5 Hz when the ship cruises at a speed of 19.8 kn. This was the official result provided by the shipbuilder. Similar examination was made by the present authors mainly for the sake of checking the performance of the vibration-proof board. Figure 8 shows the results. Vibrations of the floor and those of the vibration-proof board were measured by means of a vertically sensitive piezoelectric accelerometer. The ship's speed was 12 kn when the measurement was made. Figure 8A is the spectrum of vertical acceleration caused by the ship's vibration which was obtained when the accelerometer was directly placed on the floor. The abscissa of the graph shows the frequency of vibration and the ordinate shows the amplitude in dB unit, where 0 dB corresponds to 10 cm/s^2. Figures 8B and 8C are both the spectra of vertical acceleration obtained on the vibration-proof board. Rubber cushions supporting the board are attached to in two ways; 6 cushions out of 12 suspend the board vertically upwards, and the rest 6 cushions support the board sideways so that the board might not slip out of the normal position. Figure 8B shows the amplitude distribution when the board was supported both upwards and sideways, while Fig. 8C shows the distribution when the board was suspended upwards only, the lateral cushions having been left slackened.

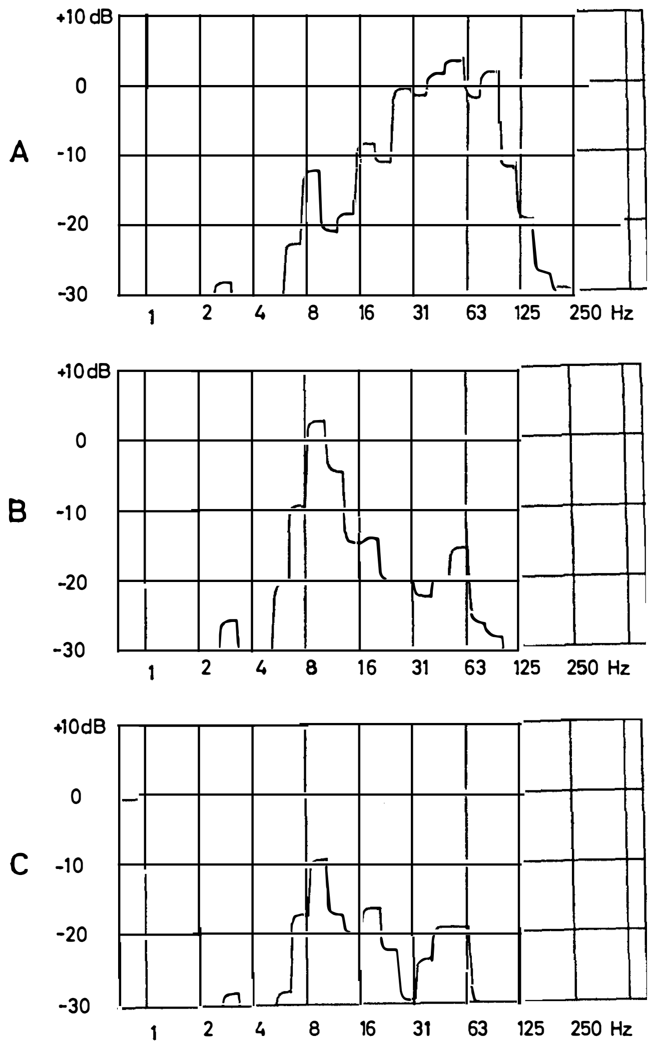

Fig. 8. Amplitude distributions of vertical accelerations caused by vibration of the floor in the gravity sensor room of the SHIRASE. *0 dB correspond to 10 cm/s². A. Record on the floor of the gravity sensor room. B. Record on the vibration-proof board when the board was supported by both vertical and lateral cushions. C. Record on the vibration-proof board when the board was suspended by vertical cushions only.*

It is found from Fig. 8A that the predominant vibration of the floor is of the frequency of 50 Hz and with a magnitude of 15 cm/s^2. From Fig. 8B, on the other hand, a clear peak of amplitude is found at a frequency of 8 Hz, which is larger than the amplitude of the same frequency observed in Fig. 8A. This suggests that the resonant frequency of the board supported both upwards and sideways is nearly 8 Hz. When the cushions pressing the board sideways were slackened, the vibration of the board was much reduced, as seen from Fig. 8C. In this case the maximum amplitude of vibration on the board was -10 dB, that is, approximately 3 cm/s^2. It was concluded from a comparison of the three results that on the vibration-proof board the ship's vibration decreased significantly as long as its frequency was higher than 16 Hz, but that in the frequency range between 6 and 15 Hz the board was not effective, or rather even magnified the accelerations.

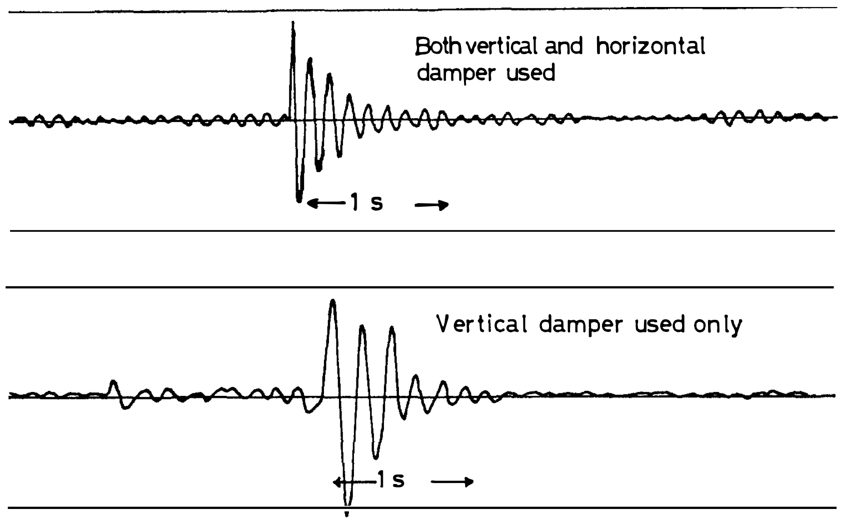

Fig. 9. Oscillation of the vibration-proof board and its decay observed when the board was forcibly hit in the vertical direction. Upper: Record when both the vertical and lateral cushions were used. Lower: Record when the vertical cushions only were used.

The differences of the resonant frequency of the board and the time constant of damped oscillation were examined as seen from Fig. 9. In this experiment the vertical vibration of the board was measured by forcibly moving the board to cause vibration. The upper figure shows a damped oscillation of the board when both the vertical and horizontal cushions were used. This case shows that the resonance occurs with a frequency of 7.5 Hz, and the time constant of half amplitude is approximately 0.3 s. The lower figure is the case when the vertical cushions only were used. The resonance occurred with a frequency of 4.5 Hz, and the time constant of half amplitude was nearly 0.5 s.

After considering the results of experiments described here it was recommended that the vibration-proof board, which is 3 cm thick and about 800 kg in weight, is used with the vertical cushions pressurized only when the sea state is not too rough, and that when sea is rough the lateral cushions are used at the same time for the sake of safety.

5. Problem of Temperature Regulation

Taking into account the knowledge obtained so far, the temperature regulation of the gravity sensor and the gravity sensor room of the SHIRASE was improved in several respects. One improvement is that a room air-conditioner (the fan coil unit of Fig. 2) which works independently of the other rooms was attached to the gravity sensor room. Although the air-conditioner is not an automatic regulator and has to be adjusted manually, it is possible to keep the room temperature at an desired value with a fluctuation of ± 3°C. The other improvement is that the gravity sensor was insulated thermally using a better insulator and that the manner in which the electric current to the heater winding of the sensor is controlled was changed so that the ripple of temperature was reduced.

The effect of these improvements on the actual sea measurement has not been

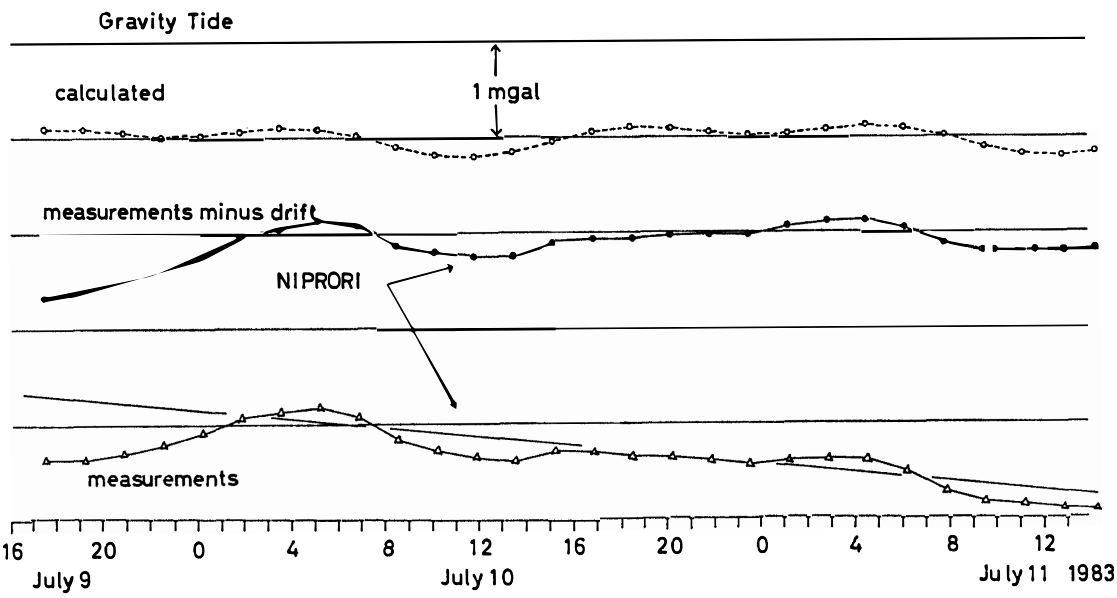

Fig. 10. Gravity tide measured by the NIPRORI-1 gravimeter in a laboratory on land. Sample interval is 100 min. Lower: Profile of actual gravity measurements. Middle: Profile of measured gravity minus drift of the meter with time. Upper: Profile of theoretical (calculated) gravity tide obtained according to a formula.

confirmed yet, because the SHIRASE is still at sea now. However, there is a result from an experiment on a land laboratory that might indicate plausibility of the improvement. Figure 10 shows a record of the earth gravity tide successfully measured by means of the gravity sensor modified for the SHIRASE. The period of this record coincided with that of a full tide when the largest gravity change with an amplitude of about 0.3 mgal *p-p* value was expected. This measurement continued for two days from 9 to 11 July 1983. The lowest profile in Fig. 10 shows the measurements of gravity change sampled every 100 min. A drift of gravity with a rate of about 0.5 mgal/day is found together with the record of tidal variation. The middle profile is the record in which the drift of gravity has been subtracted from the measurement shown in the lowest profile. The upper profile is a theoretical gravity tide. When the upper and the middle profiles are compared the gravity variation with time is almost the same except for a portion during the first 10 hours.

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