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OBSERVATION OF EARTH TIDES AND EARTH'S FREE OSCILLATIONS WITH A SUPERCONDUCTING GRAVIMETER AT SYOWA STATION (STATUS REPORT)

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Abstract: Superconducting gravimeter (SCG) observation is believed to offer high sensitivity and high resolution data for study of the Earth's core dynamics. We describe the importance of SCG installation at Syowa Station at high southern latitudes (69.0°S) for weak signal detection of fluid core resonance, core undertones, Slichter mode, etc. In order to assess the SCG capability as a long-period seismometer, parallel observations using a Streckeisen seismometer and a LaCoste & Romberg type-D gravimeter with the same data acquisition systems are planned. Although leakage of liquid helium from the SCG dewar during the installation procedure in the 33rd Japanese Antarctic Research Expedition (JARE-33: February 1992) delayed the start of the SCG observation, a retrial was performed during JARE-34 (February 1993). The installation proved successful, although fine tuning may still be required.

1. Introduction

As part of the 5 year program "Synthetic observations and monitoring of dynamic behavior of the Earth's crust", a type TT70 superconducting gravimeter (GWR Instruments: SCG016) at Syowa Station was installed during the summer operations of the 33rd Japanese Antarctic Research Expedition (JARE-33: February 1992). This installation was basically a joint project between the National Astronomical Observatory of Mizusawa (NAOM) and the National Institute of Polar Research (NIPR), and several other scientists also participated in the framework of the "Study of the Earth's deep interior (SEDI)".

Due to the leakage of liquid helium (LHe) from the SCG dewar, we could not start the observation from 1992. In this report, project objectives, characteristics of the SCG, installation plan at Syowa Station, observation conditions at Syowa Station, collocation with the Fairbanks data, and status of retrial are briefly outlined.

2. Outline of Project Objectives

During these two decades, seismological studies for the structure of the Earth's interior have made great progress in both theory and observation. We now have several standard models of a layered structure of the Earth, and can predict the eigen-frequencies of the Earth's free oscillations with an accuracy better than 0.1 or 0.2% (*e.g.*, GILBERT and DZIEWONSKI, 1975; DZIEWONSKI and ANDERSON, 1981). It has become possible to infer three dimensional inhomogeneity of the mantle, to derive the shape of the core-mantle boundary (CMB) and discuss physical processes occurring there (MORRIS *et al.*, 1987) by applying tomography to the world-wide seismometer network data.

There have also been remarkable developments in the geodetic approach. VLBI (Very Long Baseline Interferometer) measurements or SCG observations can detect displacements or gravity changes in frequency bands much lower than those detected by seismometers (*e.g.*, HERRING *et al.*, 1991; CROSSLEY and SMYLIE, 1975). These new techniques provide observation data of higher accuracy by one or two orders of magnitude than conventional geodetic techniques, thus give us important data for the study of the Earth's deep interior.

Because the retardation force of the fluid core motion is mainly determined from the density distribution within the fluid core, the core undertone may be driven by much weaker force than that for the Earth's free oscillations. Then the motion of the fluid core may be characterized by much lower frequencies than those of the Earth's free oscillations, which are mainly determined from the strength of the mantle. An SCG observation is expected to cover the required low-frequency range and to detect the following weak and long-period signals, as noted by *e.g.*, CROSSLEY and ROCHESTER (1980), and NEUBERG *et al.* (1987).

(1) Fluid core resonance (24 hours period) may reflect degree of inertial coupling between the mantle and the core (CMB).

(2) The core undertone (13 hours period) may reflect gravitational waves in the fluid core, and provide information on the mechanical structure and associated temperature distribution in the fluid core.

(3) The Slichter mode (3 hours period, SLICHTER, 1961) may be characterized by translational motion of the inner core, or a degree of departure of the outer (fluid) core from the symmetrical layered structure.

(4) Core modes (10–30 min period) are characterized by the strength of the inner core and the associated elastic oscillations.

Moreover, the Mf tide (14 days period) is expected to give important information on frequency-dependent rheological properties of the Earth.

The gravity change related to each phenomenon described above is considered small, on the order of 10–30 nGal (1 nGal $= 10^{-11}$ m/s^2). Although the signal-to-noise (S/N) ratio may be less than 1, even in SCG observations, there must be some regularity in spatial distribution of both amplitude and phase and/or in the positions of spectrum peaks. It thus becomes important to observe weak signals simultaneously using a global SCG network.

As illustrated in Fig. 1, SCG observations are currently made at 11 sites in the

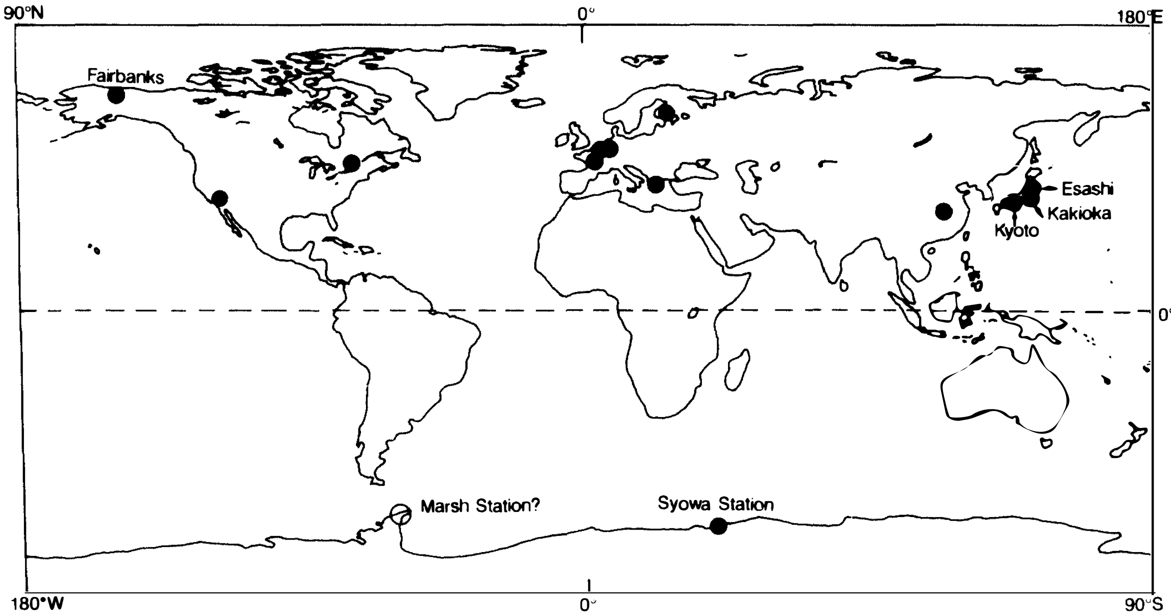

Fig. 1. Global SCG observation sites. The status of installation at Marsh Station? (open circle) by the German expedition is not known to the authors.

world (R. WARBURTON, personal communication, 1993). We find that the observation sites are concentrated in a narrow zone bounded by latitudes 30°N and 50°N including three Japanese sites (Esashi, Kakioka and Kyoto). This geographically biased distribution of the SCGs restricts the resolution of the detected core motion only in the east-west direction. However, the gravity signals caused by the core motion may be affected by the shape of the CMB or the dynamical ellipticity of the core; they must be dominant in the north-south direction. Thus installation of SCGs in high latitudes of both hemispheres is required to detect small signals related to the core motion.

3. Characteristics of the SCG

The principle of the SCG relies on the Meissner effect (GWR INSTRUMENTS INC., 1985). A gravity force acting on the superconducting sphere as a proof mass can be balanced with a magnetic force produced by superconducting currents. We can precisely measure fine displacements of the superconducting sphere from its balanced position due to changes of the Earth's gravitational force by controlling superconducting currents. With the benefit of long-term stability of superconducting current, the typical zero drift of the SCG is on the order of 100 μGal/year. This stability cannot be realized with a conventional gravimeter using a metal spring (PROTHERO and GOODKIND, 1972). Moreover, since the sensing unit of the SCG is operated in an environment of cryogenic temperature (4 K), the sensor noises (thermal noises) can be suppressed very low. The slow drift and low thermal noise let us measure such small gravity changes with a high resolution at a level of 0.1 nGal or better.

Since 1988, tidal gravity observations have been carried out at the Esashi Earth Tides Station of NAOM using the type TT70 (GWR Instruments: SCG007) gravimeter. From analysis of the obtained data, we find that the SCG has the following characteristics. (1) the noise level in the frequency band from 1/2 to 1/3 cph (cycle per hour) is less than 10 nGal, (2) the S/N ratios for diurnal and semi-diurnal tides are more than 70 dB, and (3) the observed amplitude is consistent with the theoretically predicted amplitude within 10%.

From the above consideration it is highly possible that we can detect weak signals related to the core dynamics by SCG observations as obtained by the IDA network data (*e.g.*, FUKAO and SUDA, 1989).

4. Installation Plan at Syowa Station

At Syowa Station, observation of tidal gravity with a LaCoste & Romberg type-D gravimeter (D-73) was started in January 1992, while observation by broad-band Streckeisen seismometer (STS) was initiated in 1988. Therefore, SCG observations will give us data from three different types of instrument.

The sampling interval will be every 2 s for all three instruments after analog-to-digital (A/D) conversion to a dynamic range of 7.5 digits. In order to correct for environmental effects on the observed gravity change, both the room temperature and atmospheric pressure changes are acquired with the same sampling interval. We also use a low-pass filter for the D-73 gravimeter, which has the same frequency characteristics as those of the TIDE/MODE filter used in the SCG (GWR INSTRUMENTS INC., 1985). This TIDE/MODE filter is the same as that used in the world-wide accelerometer network IDA (International Deployment of Accelerometers; AGNEW *et al.*, 1986).

Although there are few SCG applications to the study of Earth's free oscillations, SCG may have a capability as a very long-period seismometer. Comparison of the SCG data with the STS data in the IRIS (Incorporated Research Institutions for Seismology; *e.g.*, SMITH, 1986) standard and with the LaCoste & Romberg gravimeter data in the IDA standard will clarify its capability.

5. Observation Conditions at Syowa Station

Figure 2 illustrates the main facilities at Syowa Station; the SCG will be installed in the Gravity Observation Hut where a concrete pier to support the SCG dewar was constructed in February 1991 (JARE-32). By detaching the concrete base from the floor, vibration of the hut under high-winds is suppressed. The hut is air-conditioned with temperature kept at $15^\circ \pm 5^\circ$C, which assures stabilized operation of the sensor and the recording devices.

Overall, the ground noise is in the range of 10–20 μkine ($1\text{–}2\times10^{-7}$ m/s) under calm weather conditions. However, the ground noise attains 1–3 mkine ($1\text{–}3\times10^{-5}$ m/s) in the frequency bands of 2–30 Hz during blizzards. This does not have significant effect on tidal gravity observations.

One disadvantageous observation condition at Syowa Station is ocean waves striking Ongul Islands. The packed sea ice in Lützow-Holm Bay was sometimes blown away; then the ground noise attained 10–30 mkine ($1\text{–}3\times10^{-4}$ m/s) in the

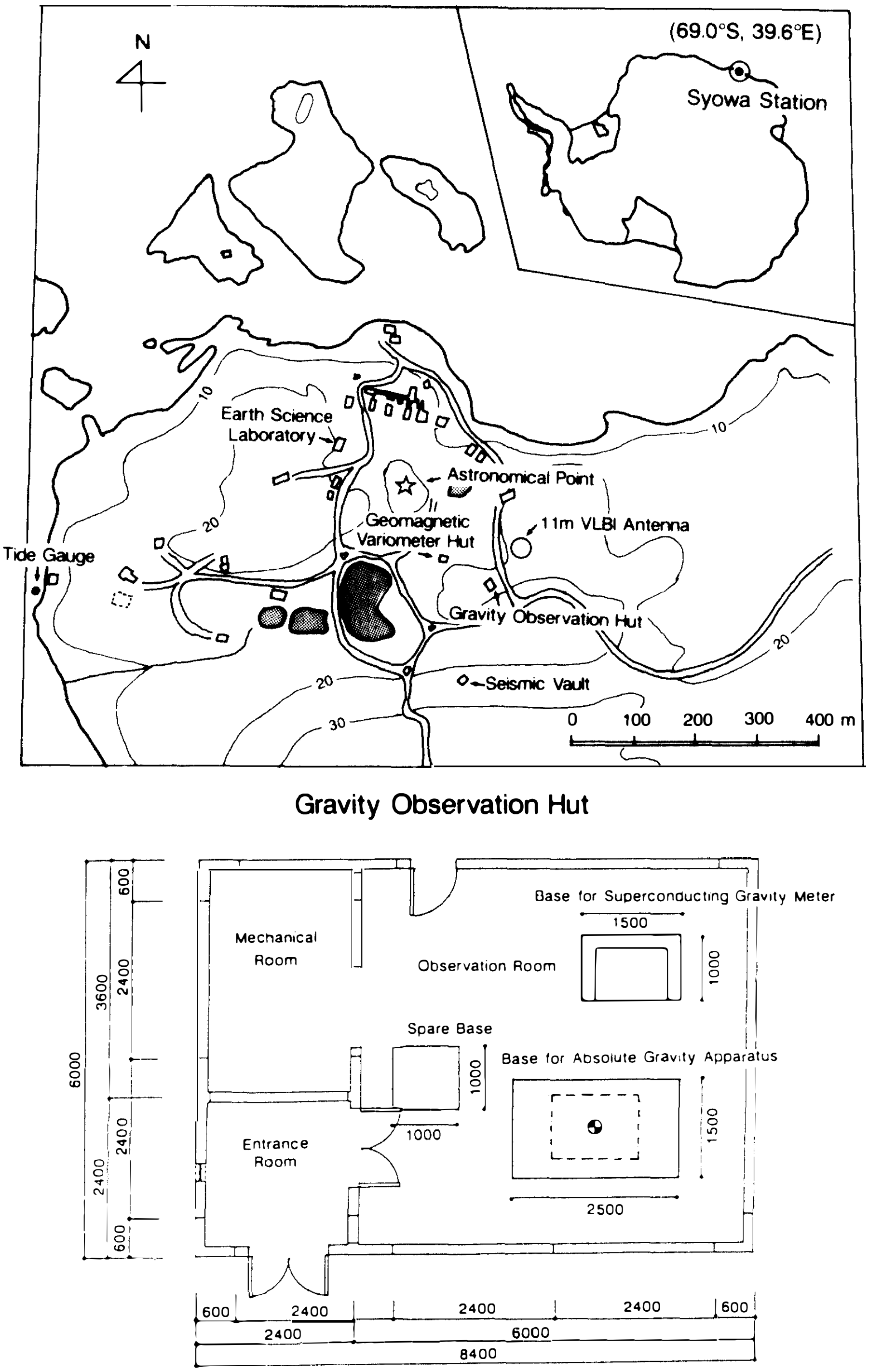

Fig. 2. Facilities at Syowa Station, and the plain view of the Gravity Observation Hut. There is a concrete pier and base to support the SCG dewar, and another marble base for installing the absolute gravity apparatus.

frequency band of 0.05–1 Hz due to the effect of the ocean tide. This high ocean-wave condition may last a month, for example from March to April, though its appearance changed from year to year in the previous expeditions. Since the dominant frequency of ocean tides is close to that of MODE data observed by the

SCG, long-period seismic data are certainly degraded by high ocean wave conditions, though the effect has to be estimated carefully.

6. Collocation with the Fairbanks SCG Data

In order to detect weak signals related to core motion, large latitudinal aperture of the SCG baseline is required. The disadvantageous geographical distribution of SCGs discussed in Section 2 may partly be solved by the start of observations at Fairbanks, Alaska (see Fig. 1) in September 1992 by the National Geodetic Survey (NGS, U.S.A.; W. CARTER, personal communication, 1992).

Figure 3 shows the latitude dependence of tidal gravity amplitude (MELCHIOR, 1983). The diurnal waves have maxima at 45° and minima at both poles and the equator. For semidiurnal waves, amplitude maxima appear at the equator while both poles are nodes of the waves. As inferred from Fig. 3, there are three advantages to observations at high latitude such as Syowa Station at 69°S. We can observe the Mf tide with very high S/N ratio as compared with the observations at middle latitude. The amplitudes of diurnal waves at Syowa Station are about 70% of the corresponding maximum value; thus the fluid core resonance in the diurnal tides is less suppressed. The amplitudes of semidiurnal tides at Syowa Station are less than 10% of the corresponding maximum value; thus we may have a reasonable chance to detect core undertones with a comparatively higher S/N ratio than in mid latitudes, because the core undertone has a strong spectrum peak at period between 12 and 13 hours. These geographical advantages hold true for observations at Fairbanks, at 64°N.

It should furthermore be noted that Syowa Station and Fairbanks are nearly at antipoles (173° separation along the great circle). This is favorable for detection of the Slichter mode because the gravity increase at Syowa Station should correspond to the gravity decrease at Fairbanks, and *vice versa*.

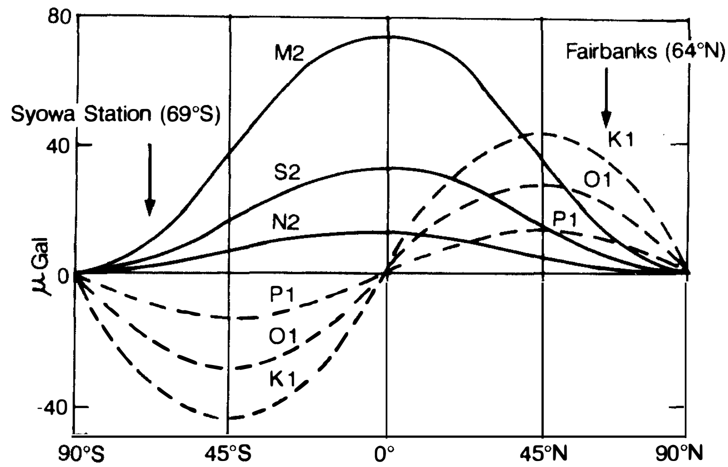

Fig. 3. Latitude dependence of tidal gravity amplitude, after MELCHIOR (1983). Solid curves for semidiurnal waves and dashed curves for diurnal waves, respectively.

7. Status of Retrial

Since it is impossible to transport LHe to Syowa Station by the icebreaker "SHIRASE", which carries the expedition members and supplies, we installed nitrogen and helium liquefiers during the summer operations of JARE-33 (February 1992). The installation procedure of the SCG includes the following 11 steps. 1) install a thermal leveler for tilt compensation and hang the LHe dewar on the leveler, 2) produce 70 liters of liquid nitrogen (LN2) and 100 liters of LHe to cool down both the gravimeter sensing unit (GSU) and the dewar, 3) transfer LN2 to the dewar, 4) discharge LN2 from the dewar after pre-cooling, 5) pre-cool GSU with LN2, 6) transfer LHe to the dewar, 7) insert GSU into the dewar and demagnetize it, 8) levitate the superconducting sphere, 9) iteratively adjust the superconducting sphere position by adjusting the superconducting currents which produce the balancing force in the created magnetic field, 10) set the GSU to a tilt-insensitive position, and 11) fine tilt tune the leveler to determine the position of the superconducting sphere.

The installation procedure during the JARE-33 summer season reached step (6). However, abnormal evaporation of LHe from the dewar occurred at step (7) and subsequent procedures had to be abandoned. The dewar was then returned to the manufacturer. Inspection showed that the abnormal evaporation of LHe resulted from a so-called "cold leak". This cold leak did not occur at LN2 temperature but occurred at LHe temperature, and must have resulted from a molecular-size defect of the inner vacuum bottle. It is suspected that roll and pitch of "SHIRASE" during 40 days' cruise and/or helicopter (S61-A) vibration during the transport between "SHIRASE" and Syowa Station might have damaged the SCG dewar.

We are going to pay special attention to transport the dewar for retrial by JARE-34. We prepared a spare dewar (RD-143HD) which has harder mechanical strength than the previous dewar RD-200 for insurance. Special shock absorption mounts (Barry Cupmounts NC-2040) were prepared for both of the dewars, and they will be transported on a sledge pulled by an oversnow vehicle from the anchoring site of "SHIRASE" to the Gravity Observation Hut (500 m distance). Heli-borne transportation will not be used because three-component acceleration observations on the helicopter S-61A (Tateyama, 31 August 1992) showed maximum vertical vibrations of ± 0.8 G (18 Hz predominant frequency) at the hovering stage (~ 30 s duration) for landing.

Training for SCG installation was performed twice (April and August in 1992) at NAOM using the GSU which was brought back from Syowa Station and the replaced RD-200 dewar. The test observations (August-September 1992), which followed the start-up training, resulted in high quality records; the GSU proved strong enough to be transported as standard cargo by "SHIRASE".

8. Note Added after Submission

After the above transport and start-up procedures, continuous observation by the model TT70 superconducting gravimeter (SCG016) started in the Gravity Observation Hut at Syowa Station on March 19, 1993. Figure 4 illustrates the SSTV

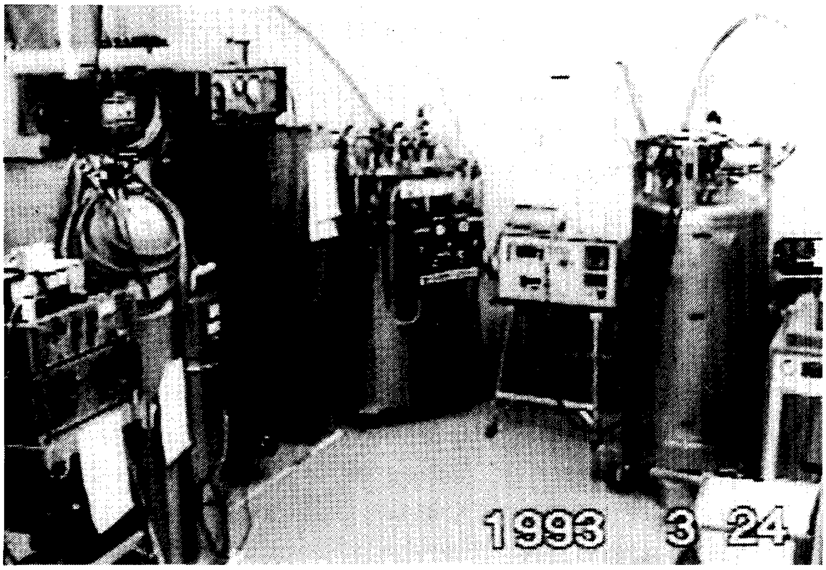

Fig. 4. Observation instruments in the Gravity Observation Hut. Concrete pier and the RD143HD dewar hung from the thermal leveler can be seen at left, while the LaCoste Romberg D-73 gravimeter (covered by the polyurethane box) is seen in the lower-right corner.

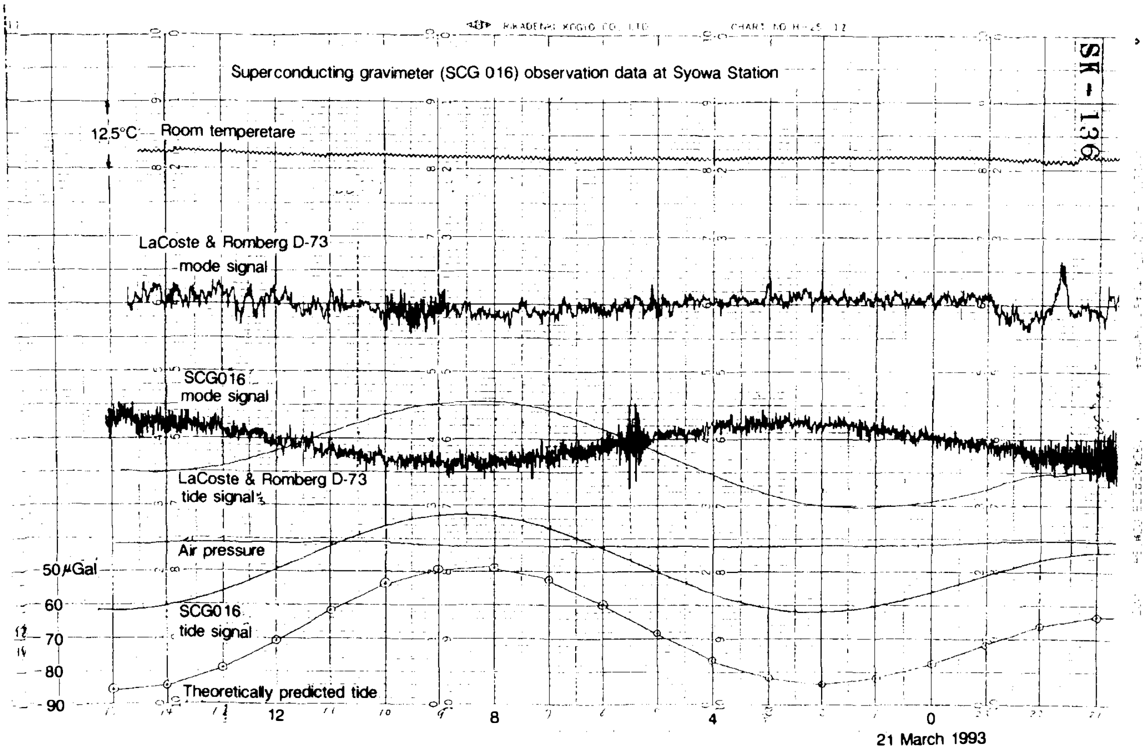

Fig. 5. Monitoring data of the SCG output 2 days after the levitation procedure. See explanation on the figure.

scene of the observation instruments. The monitoring data in Fig. 5 show that the installation was successful, although fine tuning may still be required.

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