I. INTRODUCTION

Currently the major application of low-Tc superconducting quantum interference devices (SQUIDs) is for magnetoencephalogram (MEG) to detect extremely small magnetic fields in the order of ~100 fT generated from a human brain [1]. We have developed 160-channel systems for human brain research and clinical diagnosis, which can help brain researchers and medical doctors investigate brain functions without harming patients [2]. In this case, SQUIDs are operated in a magnetically shielded room (MSR) to prevent environmental noise.

While being widely applied for MEG systems, SQUIDs have also been expected to function as promising sensors for geophysical applications. In particular, the unrivaled sensitivity in the range of extremely low frequency (ELF), lower than ~1 kHz, enables one to obtain more detailed properties of the earth deep below the surface. In 1980’s, J. Clarke et al. proposed remote-reference magnetotellurics (MTs) by using SQUID magnetometers and indicated their availability for geological survey [3]-[5]. Besides the use in MT methods, SQUIDs have a big potential in geophysics. Recently, some geophysicists have observed electromagnetic phenomenon related to seismic and volcanic activities [6]-[7].

II. INSTRUMENTATION

A. SQUID magnetometers and a Flux Locked Loop (FLL)

Considering geophysical applications, not only high sensitivity but also large dynamic range and high slewing rate are necessary in order for a SQUID to work stably in the fields where SQUIDs are exposed to large artificial magnetic noises or the earth fields. A relaxation oscillation SQUID (ROS) is adopted as a magnetometer, because it has 2-3 times larger output voltage and typically more than 10 times larger magnetic field-to-voltage transfer function, compared to those of a standard dc SQUID used for MEG working inside a magnetically shielded room (MSR) [8-9].

A ROS magnetometer is integrated on a silicon substrate by thin-film technology using niobium as a superconductor. It has more than 100 µV of voltage modulation and 5-10 mV/Φ_o of transfer function. Thanks to the large output voltage and the large transfer function, the output signal is read directly with a preamplifier without any transformer matching, which is helpful in designing an uncomplicated FLL circuit. In addition, the preamplifier-attributed noise can be negligible, which means that the 1/f noise of a preamplifier can be reduced, and the closed loop gain can be decreased to obtain a wide frequency bandwidth.

The chip is mounted on a PCB (printed circuit board) (1 cm ⊗ 1 cm) and is bonded to the terminals with aluminum wires. A small resistor is placed adjacent to the chip to heat up if the SQUID is trapped with magnetic noise while cooling.
The chip and the resistor are covered with epoxy glue to be preserved. Three PCB chips are fixed perpendicular to each other on a GFRP (Glass-Fiber Reinforce Plastic) block. In order to eliminate radio frequency (rf) noise which degrades the properties of a SQUID, a small RC filter at about 3 MHz is connected to the SQUID. To reduce helium consumption, stainless-shielded wires are used from RC filters to a connector attached to the top of a probe at room temperature.

Compact electronics, 30 cm 20 cm 8 cm, is developed for easy carrying. Sixteen sensors are driven at one time. An FLL is realized with a simple direct readout technique. High and low pass filters, band elimination filters and amplifiers of various magnification are prepared for each channel.

In designing an FLL for a SQUID magnetically unshielded, the maximum feedback field and the slewing rate, which mean the allowed detectable field and the frequency response, are important parameters. They have been determined by optimizing a preamplifier gain, the time constant of an integrator, and the feedback resistor consisting FLL in consideration of the SQUID parameters. So far, the frequency response extends from dc to 100 kHz. The output gain in the magnetic field is set to be 24 nT/V.

B. Properties of a magnetometer

Fig. 1 shows the magnetic field resolution of a magnetometer measured with FLL operation, being magnetically shielded with a superconductive tube. Resolutions of 10 fT/√Hz (10 µγ/√Hz) at 1 kHz and 20 fT/√Hz (20 µγ/√Hz) at 1 Hz are achieved. These values are 10³ smaller compared with those of a commercially available fluxgate magnetometer. The property at lower frequency is confirmed by measuring the dc fluctuation, which is mainly due to the thermal fluctuation of a preamplifier. Lower fluctuation than 1 pTpp/hour is achieved.

The maximum feedback field and the slewing rate are shown in Fig. 2. More than 100 µT/s (1 10⁵ γ/√Hz) is realized at 10 kHz, which is expected to be large enough for geophysical measurements in rural areas. At frequency lower than 4 Hz, the maximum feedback field is limited by the voltage of the power supply, corresponding to 360 nT (360 γ). This value is large enough compared to the diurnal variation in the earth field. A dynamic range of 10⁷ in a 1 Hz bandwidth and 10³ in a 1kHz bandwidth are obtained.

C. Liquid helium cryostat

A probe with three SQUID magnetometers was inserted into a liquid helium cryostat, and connected to driving electronics. Two types of cryostat were prepared. One was made of aluminum, 0.8 m in height and 0.26 m in diameter for low frequency measurements. It contains 10 liters of liquid helium, which keeps the SQUIDs in a superconductive state for a week. This cryostat functions as an rf shield because of the eddy current effect. For measurements of high frequency signals, we have developed a GFRP cryostat 1 m in height and 0.3 m in the diameter, which has the capacity of 35 liters of liquid helium, and the liquid helium consumption of about 1 liter per day. It enables one to use SQUID magnetometers for a month without further supply of liquid helium.

III. MEASUREMENT RESULTS AND DISCUSSION

We operated the three SQUID magnetometers in the alu-
minimum cryostat in our laboratory and measured the variation in the earth fields for one night. Since some other electrical equipment is working and people go into and out of the room opening the door made of iron in the day time, the measurements were done during the night. Signals are filtered at 10 Hz by low pass filters, and 60 Hz from the power line is eliminated by band elimination filters. Measured data recorded with a time recorder are shown in Fig. 3. The horizontal axis represents the Japanese Standard Time (JST) and the vertical axis is the variation in magnetic field, corresponding to 12 nT (12 \( \gamma \)) per division. H, D, Z mean the direction of each component of the field in terms of geophysical notation, where H and D are the direction of north to south, and east to west respectively, and Z is the direction perpendicular to the surface of the earth. It is indicated that the system is working stably. No lock-off and no flux jump can be seen, where a flux jump per flux quantum (\( \Phi_0 \)) corresponds to 1/5 division. We have also confirmed the SQUID magnetometers work stably in the GFRP cryostat without rf shield.

In field operation, a SQUID magnetometer is exposed to unexpected large and high frequency noises, which might cause flux jumps and lock-offs at outputs because of the finite frequency bandwidth and the slewing rate of the feedback loop. In a practical use, SQUID magnetometers should be carefully shielded from rf noise. For detection of low frequency signals ranging from dc up to about 10 Hz, a metal cryostat made of aluminum or stainless steel with the thickness of \(~1\) cm are available. A GFRP cryostat is used for detection of higher frequency signals. In this case, SQUID magnetometers should be shielded with metal mesh or foil. The thickness of the shielding metal determines the cut-off frequency. The interval between SQUIDs and the shielding metal should be long enough to reduce thermal noise from the metal.

For confirmation of a longer-term stability of the system, we are planning to bury the three-axis SQUID magnetometer developed here under ground and attempt to measure the earth field for a month.

IV. CONCLUSION

We have developed a low-Tc three axis SQUID magnetometer with large dynamic performance using relaxation oscillation SQUIDs for geophysical applications. Magnetically unshielded operation of the magnetometer was demonstrated.

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