Development of Magnetic Prospecting System with HTS SQUID Gradiometer for Exploration of Metal Resources

Akira Tsukamoto*,1, Tsunehiro Hato[1], Seiji Adachi[1], Masayuki Motoori[2], Masaki Sugisaki[2], Keiichi Tanabe[1]
[1]SRL-ISTEC, [2]JOGMEC
[1]Minowa-cho,Kohoku-ku,Yokohama, Kanagawa 223-0051, Japan
[2]Toranomon, Minato-ku, Tokyo 105-0001, Japan
tsukamot@istec.or.jp

***Abstract*— We have developed a magnetic prospecting system with HTS SQUID gradiometers for exploration of metal resources. The SQUID gradiometer consists of a flux transformer chip made of a YBCO thin film and a SQUID gradiometer chip which is stacked on the transformer chip. The SQUID gradiometer chip was fabricated by using an HTS multilayer and ramp-edge junction technology at ISTEC. Their effective volume and the balance estimated by using a Helmholtz coil were approximately 3 x 10^{-9} m^3 and 1/500, resulting in the gradiometric field noise of 7 pT/m/$Hz^{1/2}$ at 10 Hz. Two assembled SQUID gradiometers which measure dB_z/dx and dB_z/dy field gradients were cooled with liquid nitrogen in a cryostat of the magnetic prospecting system. The cryostat was suspended from the frame of the system and its attitude was self-controlled by gravity. The magnetic prospecting system with the HTS SQUID gradiometers, flux-gate sensors, a GPS module, and a gyro sensor was also tested in a field near an old mine.**

Keywords—HTS-SQUID; gradiometer; mineral exploration; flux transformer;

I. INTRODUCTION

Magnetic prospecting is one of the popular geophysical prospecting methods for exploration of metal resources. Underground metal resources are magnetized by the Earth field and generate an induced magnetic field around them. Since the induced field is superimposed on the earth's magnetic field measured at the ground surface, one can find metal resources by precisely measuring the earth's field and detecting the magnetic anomaly due to the induced field.

Although the earth's field varies from hour to hour, it is possible to compensate the variation of the earth's field by measuring the field gradient. In addition, it is important to maintain the attitude of a sensor system to the earth's field. We have developed a magnetic prospecting system with HTS SQUID gradiometers. In our system, a main body including two SQUID gradiometers is suspended from a frame of the system to keep the vertical axis along the gravitational direction. Two gradiometers measure orthogonal two tangential gradient field components (dBz/dx and dBz/dy).

II. HTS SQUID GRADIOMETERS

A. Fabrication

The gradiometer consists of a flux transformer chip made of a commercially available YBCO thin film formed on a 2-in. diam. MgO substrate (THEVA). The transformer consists of parallel gradiometric pickup coils with the size of 20 mm square and the baseline of 20 mm, and a single-turn gradiometric input coil which matches the size of the pickup coil of the SQUID gradiometer chip as shown in Fig. 1(a). A directly-coupled thin film gradiometer with pickup coils of 5 mm square and baseline of 5mm was fabricated on the SQUID chip by using the ISTEC HTS-mutilayer process including fabrication of ramp-edge Josephson junctions, crossover structures and superconducting contacts [1]. The SQUID gradiometer chip was stacked on the transformer chip as shown in Fig. 1(b).

The flux transformer and SQUID chip were mounted on a printed circuit board. A chip resistor (100 ohms) was fixed on the SQUID chip as a heater element for detrapping. After wire bonding, the assembled SQUID was hermetically sealed with a plastic cap. The mutual inductance between the input coil of the flux transformer and SQUID was estimated to be approximately 0.022 nH. The distance between the input coil and SQUID gradiometer was 0.6 mm.

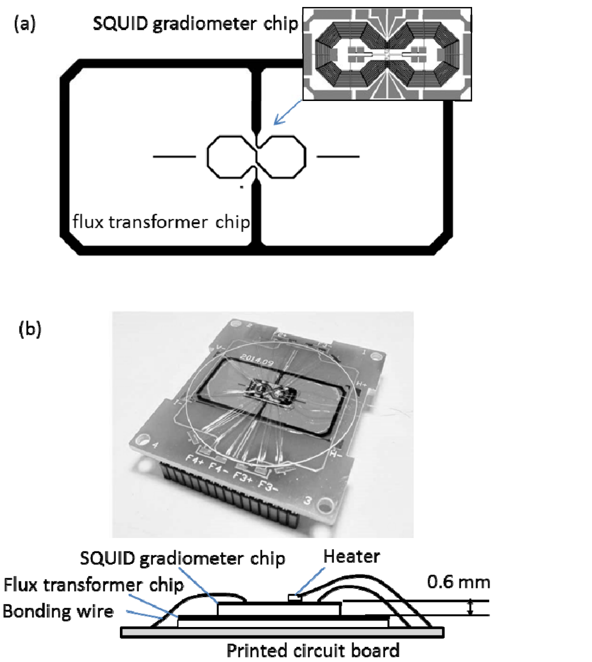

Fig.1. SQUID gradiometer chip and flux transformer chip. (a) CAD patterns and (b) photograph of the assembled gradiometer.

This work is a part of mineral exploration renovating program conducted by Japan Oil, Gas and Metals National Corporation (JOGMEC) and is fully funded by Ministry of Economy, Trade and Industry, Japan.

B. Characterization

Gradiometer imbalance was evaluated by applying a uniform field B_z using a square Helmholtz coil with a side length of 1 m. The effective area for uniform field (A_{eff}^M) is defined by

$$A_{eff}^M = \Phi_s / B_z \qquad (1)$$

where Φ_s is the flux signal transferred to the SQUID. Gradient sensitivity was evaluated by applying a gradient field G_{zx} ($=dB_z/dx$) using a planar gradient coil. The effective volume (V_{eff}) is defined by

$$V_{eff} = \Phi_s / G_{zx} = A_{eff}^G \cdot b \qquad (2)$$

where A_{eff}^G is the effective area for gradient field and *b* is baseline length. Then, the gradiometer imbalance is given by the ratio, A_{eff}^M / A_{eff}^G. The results are listed in TABLE I. The effective volume is approximately 3×10^{-9} m^3 which is about 8 times larger than that of the SQUID gradiometer chip alone.

Figure 2 shows the noise spectra of the assembled gradiometer measured by using FLL with dc and ac bias scheme. The left and right axes correspond to the flux noise and gradient field noise, respectively. Low-field noise level was dramatically reduced by ac bias scheme, resulting in the gradiometric field noise of 7 pT/m/$Hz^{1/2}$ at 10 Hz.

TABLE I. Characteristics of SQUID gradiometers with the flux transformer.

Sensor	SQUID 1	SQUID 2
A_{eff}^M (mm^2)	0.000257	0.000287
V_{eff}(m^3)	2.35E-09	3.28E-09
b(mm)	20	20
A_{eff}^G(mm^2)	0.118	0.164
imbalance	0.00219	0.00175
imbalance(fraction)	1/457	1/571

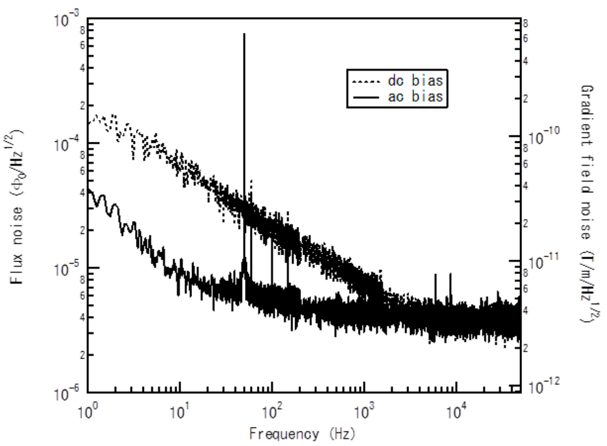

Fig.2. Noise spectra of an assembled SQUID gradiometer with a flux transformer measured by dc and ac bias mode.

III. Magnetic Prospecting System

Figure 3(a) shows a photograph of the magnetic prospecting system. The two-story outer frame with 350 x 350 x 700 mm dimensions has transparent acrylic doors for windshield. The main body covered with a gold-colored aluminum case having RF shielding function is suspended from an aluminum beam by a free joint. Therefore, the direction of the vertical z-axis of the main body is self-controlled by the gravity. Figure 3(b) shows a top view of the inside of the aluminum case. A 3-axis fluxgate magnetometer (Bartington, Mag-628T) and gyro compass with GPS unit (Sumitomo precession, NAV440), FLL electronics (Magnicon, SEL-1), and batteries are mounted on the aluminum flange. A glass Dewar and SQUID probe are under the aluminum flange as shown in Fig. 3(c). Two SQUID gradiometer can measure orthogonal two tangential gradient field components (dB_z/dx and dB_z/dy). A wireless communication unit including ADC, a diver circuit of the fluxgate, an amplifier-filter-amplifier unit, antennas and batteries are housed within the upper room of the outer frame. The system is controlled by software on the note PC. The measured signals are digitized and transferred to a note PC by wireless communication using a ZigBee protocol.

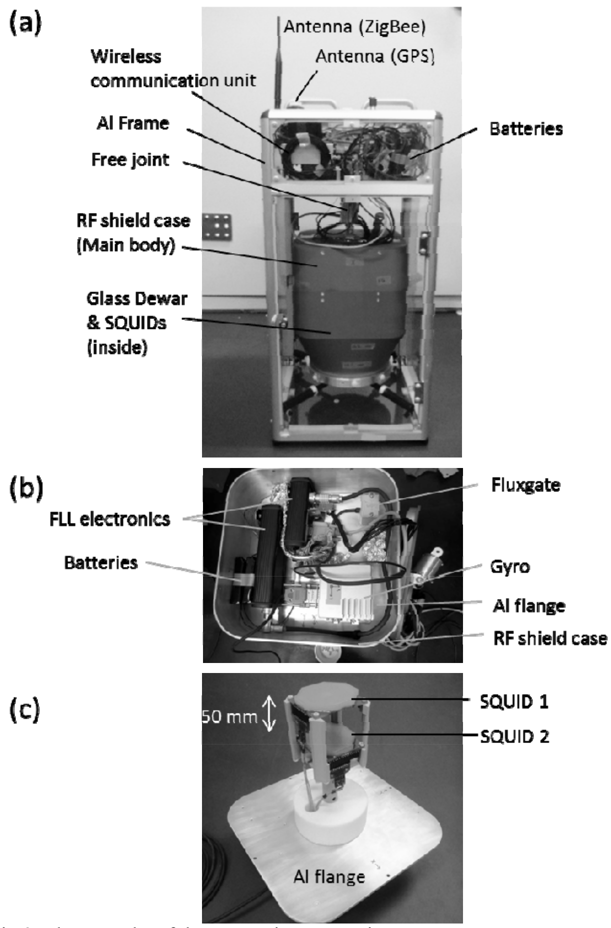

Fig.3. Photographs of the magnetic prospecting system.
(a) overview, (b) inside view of the main body, and (c) SQUID probe with two gradiometers.

The weight of the system shown in Fig. 3(a) is approximately 25 kg. The weight of the main body (suspended part) is 11.7 kg. A long bar can be attached to the top of the frame to carry the system by two persons as shown in the inset of Fig. 4. The capacity of liquid nitrogen is about 1 litter. This corresponds to a cooling period of approximately 5-6 hours, though the period strongly depends on the degree of shake of liquid nitrogen during motion.

IV. Field Test at Old Mine

First field test of the magnetic prospecting system was performed near Nakakosaka old magnetite mine located at Shinmonita-cho, Gunma prefecture, in Japan. Figure 4 represents a geological map around the test area. The magnetite ore is formed in the vicinity of the boundary between "Nanjyai layer" (North-east area) and "Heikatsu-kakougan layer" (South-west area) shown by the dashed curve. Therefore, a large variation of the induced magnetic field can be expected near the boundary. The solid curve in Fig. 4 indicates the survey line which starts in front of the entrance of mine area and extends along a downward slope across the boundary. The system was carried by two persons. Another person controlled the system using a note PC.

The SQUID sensors were cooled at a space along a major road, and confirmed correct operation. However, after moving to the survey line, the feedback operation of the SQUID became unstable. We speculated that the trapped flux caused by motion in the earth's field coupled with weak electro-magnetic signal from wireless communication and generated a magnetic signal transferred to the SQUID. It was difficult to return the SQUID to its stable state by detrapping using the chip resistor as a heater element probably due to a small heating area around the SQUID ring at the center of the gradiometer chip. As a result, the measurement along the survey line was performed using one SQUID gradiometer.

The measurement was performed by a step measurement sequence in which motion of the system was stopped at every 25 m and then data were collected. An averaged value in several seconds after reducing the oscillation of the suspended main body was used as a representing value.

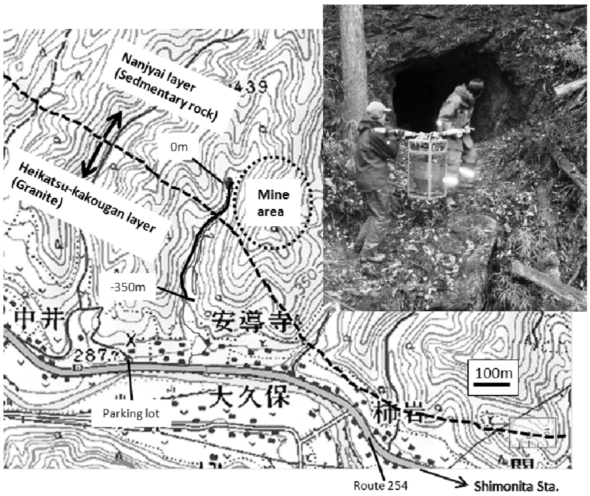

Fig.4. Geological map around the Nakakosaka old magnetite mine. The dashed curve represents the boundary where the magnetite ore is formed. The solid line shows the survey line.

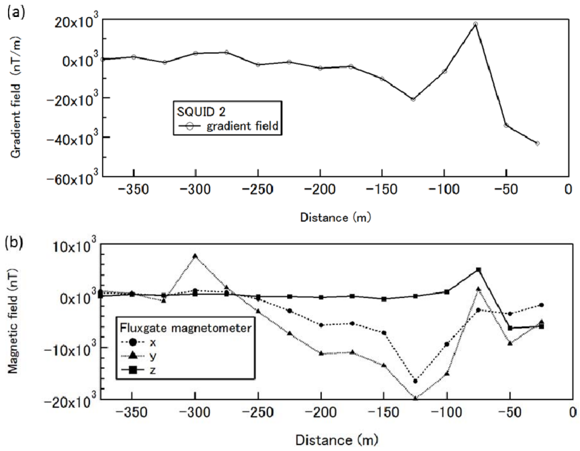

Fig.5 Dependence of (a) the gradient field and (b) magnetic field on the distance from the starting point of the survey line.

During the measurement, unlocking of the feedback operation of the FLL electronics should be avoided, since the SQUID measures only relative change from the initial value obtained when feedback operation starts. When unlocking occurred during motion in the test, the system returned to the previous measurement site, measured a gradient field again, and moved to next measurement site to keep a continuity of the relative change of the gradient field.

Figures 5(a) and 5(b) show the dependence of the gradient field and magnetic field on the distance from the starting point of the survey line, respectively. The plotted data were relative values based on the values at -350 m. The gradient field values were obtained by subtracting the error signal due to the imbalance of the gradiometer from the data measured by the SQUID gradiometer. The error signal was estimated from the change of B_z and the imbalance factor of the gradiometer. Large signal changes are observed around at -75m in both gradient field and magnetic field. This point seems to be close to the boundary on the geological map shown in Fig. 4, indicating that the magnetic anomaly caused by the magnetite ore can be detected successfully. However, more improvement and evaluation should be necessary to confirm advantages of our system.

V. Summary

We have developed a magnetic prospecting system using HTS-SQUID. The SQUID gradiometer coupled with the transformer shows about 8 times larger effective volume than the bare gradiometer chip, resulting in the gradient field noise of 7 $pT/m/Hz^{1/2}$ at 10 Hz. In a field test at an old magnetite mine, a magnetic anomaly could be detected, although several problems were found.

References

[1] S. Adachi *et al*., IEICE Trans. Electron. Vol. E95-C, No. 3 (March 2012), pp.337-346.