Development of a TDEM Data Acquisition System Based on a SQUID Magnetometer for Mineral Exploration

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Abstract We report on the research and development of a TDEM data acquisition system (SQUITEM) by JOGMEC using a highly sensitive high-temperature superconductor (HTS) SQUID vector magnetometer cooled by liquid nitrogen, which is suitable for mineral exploration. JOGMEC has achieved stable operation of all three channels during field tests. SQUITEM meets high requirements for slew rate (6.8 mT/s), dynamic range (100 dB) and bandwidth (DC – 100 kHz). It offers deeper penetration of depth than the conventional induction coil system because it can record the step response that decreases with time slower than the impulse response of the induction coil system. SQUITEM also performs horizontal gradient observations that can provide much better resolution of shallow conductive targets than conventional TDEM observations. We have obtained good reproducibility of SQUID data and correlation between the output signals of the reference induction coils and the derivatives of the SQUID signals in TDEM field tests.

Keyword HTS SQUID, TDEM, mineral exploration

1. Introduction

Time domain electromagnetic (TDEM) method is one of the geophysical methods to investigate the ground, and is widely used in petroleum, mineral and groundwater exploration. Fig. 1 shows the typical setup of a TDEM survey. In TDEM measurements, a strong direct current is usually passed through an ungrounded loop (electric wire) by a transmitter. At time t=0, this current is abruptly interrupted. According to Faraday’s law of induction, the rapid change in the primary magnetic field during current-on will induce eddy currents in the ground. During the current-off periods, the weak secondary magnetic field generated by induced eddy currents in the ground is measured by the magnetometer put on the ground. Shallow parts of the ground can be investigated by the early time data from interruption of the current, and deep parts can be interpreted by the late time data because induced eddy currents diffuse from the surface into the ground with time. 2-D or 3-D distribution of electrical property in the ground can be investigated by measuring the secondary magnetic field from early time to late time after current interruption at the various positions of the magnetometer.

All commercial TDEM data acquisition systems are based on an induction coil magnetic sensor to acquire the response from the ground. An induction coil outputs a voltage proportional to the time derivative of the magnetic field (db/dt). Therefore, large responses will come from rapidly decaying magnetic fields and small responses from slowly decaying fields. Because the targets of interest in base metal exploration are generally conductive with slow decays, TDEM method using an induction coil sensor is considered to have an inherent weakness for this purpose. Concretely, the induction coil data are biased towards detection of less conductive and more rapidly decaying conductors. Therefore, a magnetometer (to measure the magnetic field) will be more suitable for the detection of conductive targets in the presence of a conductive overburden (weathered surface layer) because it does not have this bias. Furthermore, the slower decay of the magnetic field compared with db/dt ensures better resolution at later time moments and therefore a large depth of investigation.

There are three solutions to improve detectability of more conductive targets and the signal-to-noise ratio at later time moments in TDEM methods. The first solution is to obtain the equivalent magnetic field response by integrating the transmitter waveform such as UTEM system[1]. The second approach is to acquire the data measured with an induction coil and to deconvolve them to obtain the equivalent step response. However, this may be an unstable computation because the spectrum of the transmitter waveform does not have information at certain frequencies. Concretely, because an induction coil receiver cannot measure the whole waveform, it is impossible to determine the constant of integration (DC shift) which must be applied to the integrated data. We have obtained good reproducibility of SQUID data and correlation between the output signals of the reference induction coils and the derivatives of the SQUID signals in TDEM field tests.
Electric Hightechs Co., Ltd., SQUITEM can measure three components of the magnetic field or the horizontal gradient of the one-component magnetic field in order to achieve higher resolution of shallow part of the ground. In this paper, we present the outline of the SQUITEM and some results of field tests to check its performance and practicality.

2. Numerical Tests

It is difficult to detect low resistivity targets (orebodies) by the conventional TDEM survey to measure db/dt in mineral exploration if the targets are covered with the weathered surface layer which typically has low resistivity. In such a case, the magnetic field measurement in TDEM might be able to obtain the response from orebodies because the magnetic field decays more slowly than db/dt. We checked this superiority of the magnetic field measurement over the db/dt measurement with respect to the depth of investigation in TDEM by carrying out 1-D modeling. Fig. 2 shows the three-layered resistivity model. The size of a squared loop on the surface is 200 m $\times$ 200 m. The weathered surface with low resistivity is expressed as the first layer with 10 ohm-m and 50 m thick. The second layer has the resistivity of 100 ohm-m, average resistivity of the subsurface in Japan. The bottom layer with 10 ohm-m is placed 200 m, 400 m or 600 m below the surface. The responses (magnetic field) at the center of the transmitter loop are computed by varying the depth of the bottom layer (200 m, 400 m and 600 m) in order to check at what time moment difference of the response between the two-layered model (without the bottom layer) and the three-layered model appears (Fig. 3, 4). The three-layered response which starts to depart from the two-layered response includes information on the bottom layer from which we can grasp the depth of investigation at the corresponding time moment. The magnetic field curves in Fig. 3 indicate that SQUITEM can obtain information on resistivity even below 600 m from the surface because the magnetic field for the 600 m case around its departure from the two-layered curve is larger than the system noise envelopment of SQUITEM. On the other hand, the conventional TDEM equipment cannot obtain information even on 400 m below the surface because the system noise envelopment of the conventional TDEM equipment is larger than the magnetic field for the 400 m case around its departure from the two-layered curve. This numerical check demonstrates that the magnetic field measurement can investigate deeper than the db/dt measurement. Therefore, the SQUID magnetometer is highly sensitive, it may be possible to acquire the space difference of the magnetic field in order to raise resolution (detectability) of TDEM survey. We also conducted 3-D modeling in order to check how high the resolution of db/dx is by comparing with the magnetic field and db/dt. Fig. 5 shows a 3-D model. A horizontal plate with 100 m $\times$ 100 m $\times$ 50 m in size and 1 ohm-m is placed 200 m below the center of the 200 m $\times$ 200 m transmitter loop. The resistivity of the background is 100 ohm-m. We computed the anomalous rates of db/dt, magnetic field, and db/dx defined as the rates of the responses from an inhomogeneity to the responses from a homogeneous half-space, and compared their resolutions because an anomalous rate is an indicator of resolution of the ground. Fig. 6 shows anomalous rates of db/dt and the magnetic field. The responses around the peaks of the anomalous rate have much information on the conductive plate. Fig. 6 and Fig. 7 show that the peaks of the anomalous rates on db/dx are tens of percent to more than a hundred percent, which are much larger than those of the magnetic field and db/dt. This 3-D modeling demonstrates that resolution of db/dx is higher than the magnetic field and db/dt.

Fig. 1 Configuration of the conventional TDEM survey. A strong direct current is usually passed through an ungrounded loop by a transmitter. At time t=0, this current is abruptly interrupted. According to Faraday’s law of induction, the rapid change in the primary magnetic field during current-on will induce eddy currents in the ground. During the current-off periods, the weak secondary magnetic field generated by induced eddy currents in the ground is measured by the magnetometer put on the ground.

Fig. 2 Three-layered resistivity model to demonstrate the depth of investigation of the magnetic field and db/dt. Two black dots on the surface show the locations of the loop. The magnetic field and db/dt are computed at the center of the loop shown by a triangle.
in Fig. 2 after the current interruption. Solid line shows the magnetic field for the two-layered model without the bottom layer of 10 ohm-m. The magnetic field for three-layered model with the bottom layer 200 m below the surface is shown by the wider broken line. 400 m case and 600 m case are shown by the shorter broken line, and the dotted line, respectively. The horizontal dotted line indicates the system noise envelopment of SQUITEM.

Fig. 4 $db/dt$ for the three-layered resistivity model shown in Fig. 2. Each curve is computed by the same model as the magnetic field case in Fig. 3. The horizontal dotted line indicates the system noise envelopment of the conventional TDEM equipment.

Fig. 5 Three-dimensional resistivity model to check resolutions of the magnetic field, $db/dt$ and $db/dx$. The origin of the coordinate is the center of the loop. $x$ and $y$ are horizontal directions. Anomalous rates of the magnetic field and $db/dt$ are computed at (10 m, 0 m), (20 m, 0 m) and (30 m, 0 m). The anomalous rates of $db/dx$ between the center and the point 10 m, 20 m and 30 m away from the center are also computed.

3. SQUITEM

SQUITEM is a three-channel system to measure three components of the magnetic field simultaneously or one-component magnetic fields at two points and their horizontal gradient for ground-based TDEM application (Fig. 8). SQUITEM has three SQUID magnetometers, one of which is the vector magnetometer, and the others are for horizontal gradient measurement. SQUITEM is characterized by the specification in Table.1. The SQUID magnetic field resolution is about $100 \text{fT/Hz}$ above 10Hz in the field. The 3.3-liter dewar for three-component measurement has a dimension of 589 mm high and 190 mm in outer diameter (Fig. 9). The 2-liter dewar for gradient measurement has a dimension of 353 mm high and 190 mm in outer diameter (Fig. 8). All the dewars permit more than 9-hour continuous operation without liquid nitrogen refilling. The slew rate of the SQUID electronics (6.8 mT/s) is sufficient to accurately respond to square-wave primary-field variation. The dynamic range of about 100 dB and the frequency bandwidth from DC to 100 kHz provides
Conceptionally, a FLL is a feedback mechanism that attempts to maintain the output voltage of the SQUID (flux passing through the SQUID hole) at a constant value by application of a compensating field generated by a feedback coil. If the external magnetic field exceeds the feedback magnetic field, the SQUID will slip into the next period of the flux voltage characteristic and produce a jump in the FLL output signal. In order to prevent this flux jump, the FLL needs to have a slew rate enough to maintain the feedback signal to follow any change of the external magnetic field. For an idealized noise-free system, the slew rate of the SQUID system can be improved by increasing the bandwidth of the FLL electronics. However, because the SQUID is not noise-free, the achievable bandwidth of a FLL, and hence the maximum achievable slew rate, is determined by the level of noise of the SQUID\(^2\).

### 4. Field Tests

We have conducted field tests several times since 2002 in order to check performance and practicality of SQUITEM. Here, we introduce the results of three field tests at Kamikawa and over two metal deposits inside Japan in 2003.

Fig. 10 and Fig. 11 represent an example of the SQUID data and a comparison between the SQUID and the coil transient signals, respectively, which were recorded over Kannondo deposit (Kuroko-type deposit) at the northern part of Japan (Akita Prefecture) in November, 2003. In Fig. 11, a good agreement is found between the time derivative of the SQUID data and the reference coil data. Notice that the SQUID magnetometer provides better signal-to-noise characteristics at later time moments than the induction coil, illustrating the advantage of the SQUID magnetometer over the coil receiver to increase the depth of investigation.

The function of electronic differentiation between two SQUID magnetometers was installed in order to obtain the horizontal gradient of the magnetic field between two points (db/dx) in the summer of 2003. Fig. 12 shows the horizontal gradient of x-component magnetic field acquired by the electronic differentiation (solid line) and those computed from the magnetic fields measured at two points (30m spacing) simultaneously (open circle) at Kamikawa (Saitama Prefecture) in October, 2003. The purpose to measure db/dx is to achieve higher resolution at the shallow part of the ground. Our numerical test suggested that db/dx at about 1 msec would be necessary to detect the target placed about 200 m below the surface more distinctly than the induction coil data if the resistivity of the ground is 100 ohm-m, typical resistivity in Japan. However, the horizontal gradient data reach the system noise floor at about 0.2 msec in Fig. 12. To obtain the horizontal gradient data until about 1 msec, the system noise floor must be reduced to one bit resolution by 10 times amplification.

Fig. 13 represents the reconstructed resistivity distribution by 1-D inversion computation of the SQUID data acquired over Uwamuki No.4 deposit located at the Kuroko-area in the green tuff region at the northern part of Japan (Akita Prefecture). Uwamuki No.4 deposit is a kuroko-type deposit (volcanogenic massive sulfides) of middle Miocene age, and placed about 300 m deep below the surface. The thickness of the surface Quaternary volcanic ash fall is 80 m to 100 m. Neogene volcanics and pyroclastics is located 300 m to 400 m below the surface. The intrusive rhyolite occupies the left part of the section. The host tuff breccia and the foot wall dacite are intensively altered around the orebody which is already mined out located at the right side below the intrusive rhyolite\(^3\). The reconstructed distribution almost matches well to the known geology by drilling, the result of the DC resistivity logging, and the 2-D resistivity distribution reconstructed from the DC resistivity tomography data. The Quaternary volcanic ash fall shows higher resistivity in the upper layer and lower resistivity in the lower layer. The intrusive rhyolite precisely corresponds to the high resistivity zone. The low resistivity at deeper portion might be due to presence of intensively altered part around the orebody.
Fig. 10 The magnetic field by SQUITEM over Kannondo deposit placed about 50 m below the surface. The signal-to-noise ratio by the SQUID data is better than the reference coil data shown in Fig. 11.

Fig. 11 Comparison between the time derivative of the SQUID data in Fig. 10 (Δ) and the reference coil data (o) over Kannondo deposit. A good agreement is found between them.

Fig. 12 Horizontal gradient of z-component magnetic field acquired by the electronic differentiation (solid line) and those computed from the magnetic fields measured at two points simultaneously at Kamikawa. A good agreement between the electronic differentiation and the computed differentiation suggests the electronics of differentiation operated well. However, dB/dx reach the system noise floor at about 0.2 msec, which is not enough to investigate 200 m below the surface.

Fig. 13 The reconstructed resistivity distribution (vertical section) by 1-D inversion computation of the SQUID data acquired over Uwamuki No.4 deposit. The SQUID data were acquired at a 10 m spacing by four transmitter-loops. The orebody was placed just below the intrusive rhyolite. There is a low resistivity zone corresponding with argillic alteration.

5. Conclusions and future works

JOGMEC has been developing a three-channel TDEM data acquisition system using the SQUID magnetometer (SQUITEM) for mineral exploration. SQUITEM has two measuring modes for simultaneous data acquisition of three-component magnetic field, and simultaneous measuring of one-component magnetic fields at two points and the horizontal gradient between them. In several field tests, good agreements were found between the time derivatives of the SQUID data and the reference coil data from early time to late time. The SQUID data generally have better signal-to-noise characteristics at later time moments than the induction coil data, representing the advantage of the SQUID magnetometer over the induction coil receiver with respect with depth of investigation.

However, we could not acquire the horizontal gradient data of the z-component magnetic field at time moments which included information around 200 m deep in the field tests. This is because the gradient data were so small that they reached the system noise floor faster than the magnetic field.

JOGMEC will make an effort to make SQUITEM more robust in the field, and to reduce the period to adjust SQUID in order to raise its acquisition efficiency.

References


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