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GEOPHYSICAL APPLICATIONS OF SQUIDS

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Introduction

Magnetic and electromagnetic fields are among the few probes available to geophysicists for studying the geological history of the earth and for determining properties of the earth deep below the surface. Thus, the development of high sensitivity, reliable magnetic field sensors has been and continues to be of vital importance. When SQUID magnetometers first became commercially available in the mid-1970's, it was hoped that these instruments would lead to significant improvements in the quality of geomagnetic data and perhaps open new areas of research, not accessible with conventional magnetometers.

While the popularity of SQUIDS in geophysics is increasing rapidly, many researchers have been reluctant to use SQUIDS because they require cryogenics, and because they have not always been as reliable and easy to operate as other devices. Thus, the use of SQUIDS has been limited largely to two areas: laboratory measurements or remnant magnetization and magnetic susceptibilities of rocks, and to magnetotellurics. In this paper we discuss these topics in more detail, giving particular attention to magnetotellurics, since it is here that SQUIDS have had the most profound influence. Finally, we discuss the criteria that SQUID magnetometers must satisfy to be useful in geophysics and make suggestions for improving the reliability of the instruments.

Laboratory Measurements with SQUIDS

Approximately half of the SQUID magnetometers in geophysics are used in the laboratory to measure the magnetic susceptibilities of rocks as functions of temperature and pressure, and to determine remnant magnetization in ore bodies for geological dating (paleomagnetism). Magnetic susceptibilities vary widely, spanning the range 10^{-2} to 10^{-5} CGS cm^{-3} , while the remnant magnetizations of interest fall in the range 10^{-2} to 10^{-6} CGS cm^{-1} . In most instances conventional mutual inductance bridges have sufficient sensitivity to measure the magnetic susceptibilities. However, SQUID magnetometers have proven themselves to be a reliable and very convenient alternative. Furthermore, SQUID susceptometers, whose resolution may approach 10^{-13} CGS cm^{-3} , allow measurements to be made on much smaller samples than was previously possible.

To measure remnant magnetizations, torsional fiber magnetometers with sensitivities as high as 0.2nTHz^{-1} suffice in most instances. However, for magnetizations in the range 10^{-6} CGS cm^{-3} spinner magnetometers have previously been required. These instruments are difficult to calibrate and are time consuming to use. With SQUIDS, remnant magnetizations in this range can now be determined routinely in a matter of minutes.

Magnetotellurics

In magnetotellurics one measures the electromagnetic surface impedance of the earth as a function of frequency using the natural electromagnetic fluctuations of the upper atmosphere and ionosphere as a broadband source of radiation. Electromagnetic waves propagate into the earth to a distance determined by the skin depth. Thus, measurements of the surface impedance as a function of frequency can in principle be mathematically transformed into a measurement of electrical conduc-

tivity as a function of depth. The conductivity of the ground is dominated by the water content of the rocks, which in turn depends on pore sizes, salinity and temperature. Magnetotelluric measurements are therefore of particular interest to geophysicists exploring for geothermal sources and oil deposits. Resistivities of the earth generally lie in the range $1\Omega\text{m}$ to $10^4\Omega\text{m}$, and depths of interest range from 100 meters to a few tens of kilometers. The skin depth, δ , in kilometers is approximately given by

$$\delta = 0.5 (\rho/f)^{1/2} \quad (\text{km}), \quad (1)$$

where ρ is the resistivity in Ωm and f is the frequency in Hz. Therefore, the usual range of frequencies in magnetotellurics is $10^{-3}\text{Hz} < f < 10^2\text{Hz}$.

Because of the high contrast in electrical conductivity between earth and air, and because of the large distance between the ionosphere and the earth's surface, the electromagnetic waves can be thought of as normally incident plane waves. These waves induce screening currents in the ground that are detected by measuring the voltage between pairs of buried porous ceramic electrodes containing a solution of CuSO_4 . The electric fields are typically 10mVkm^{-1} . To obtain the surface impedance one has to measure, simultaneously, the horizontal components of magnetic field $H_x(t)$ and $H_y(t)$ and the horizontal components of the electric field $E_x(t)$ and $E_y(t)$. The impedance $\underline{Z}(\omega)$ at an angular frequency ω relates the fourier components of the fields according to the equations

$$E_x(\omega) = Z_{xx}(\omega) H_x(\omega) + Z_{xy}(\omega) H_y(\omega) \quad (2)$$

$$E_y(\omega) = Z_{yx}(\omega) H_x(\omega) + Z_{yy}(\omega) H_y(\omega) \quad (3)$$

Below a few Hz the spectrum of the magnetic fields varies roughly as f^{-3} with a typical spectral density of $10^{-6}(\text{nT})^2 \text{Hz}^{-1}$ at 10 Hz. The only conventional instruments with sufficient sensitivity to detect the magnetic signals are induction coils which typically consist of 30,000 turns of copper wire on a molypermalloy core 2m long and 10 cm in diameter². The intrinsic

noise of coils near 1 Hz is on the order of $10^{-3} \text{ nT Hz}^{-1/2}$, and on days of low spheric or ionospheric activity, can exceed the signal level. In contrast to coils, a typical three-axis SQUID magnetometer is much less bulky and has a sensitivity approaching $10^{-5} \text{ nT Hz}^{-1/2}$. The magnetic field sensitivity of both rf and dc SQUIDS³ can in principle be enhanced by another order of magnitude with a suitable superconducting flux transformer, but this has not yet been necessary.

One of the major problems in magnetotellurics has been to obtain reliable estimates of $\underline{Z}$ when there is noise in the measurements. The usual solution⁴ has been to find the $\underline{Z}(\omega)$ that minimizes $|\overline{\underline{E} - \underline{Z}\underline{H}}|^2$ in the least squares sense. Here the bar denotes an average over data records and/or a narrow band of frequencies. This leads to a set of four simultaneous equations for the elements of $\underline{Z}(\omega)$. For example, for Z_{xx} and Z_{xy} one has

$$\overline{E_x H_x^*} = Z_{xx} \overline{H_x H_x^*} + Z_{xy} \overline{H_y H_x^*} \quad (4)$$

$$\overline{E_x H_y^*} = Z_{xx} \overline{H_x H_y^*} + Z_{xy} \overline{H_y H_y^*} \quad (5)$$

where * denotes complex conjugate. These equations are readily solved provided the incident field has at least two distinct polarizations.

Unfortunately, the least squares method has a major flaw in that the estimate of $\underline{Z}$ depends on the autopowers $\overline{H_x H_x^*}$ and $\overline{H_y H_y^*}$. This means that noise in the magnetic fields will never average to zero, and therefore that the estimate of $\underline{Z}$ will be biased by the noise power. As we will show below, the bias errors can be enormous.

One of the initial motivations for using SQUID magnetometers for magnetotellurics was, in fact, to reduce the bias errors, by virtually eliminating sensor noise. We used SQUID magnetometers for numerous magnetotelluric surveys and found that, contrary to our hopes, the bias errors were still substantial.

Thus, through the use of SQUID magnetometers, we concluded that environmental, rather sensor, noise often dominates the accuracy of the estimate of $\underline{Z}(\omega)$, and that a new method of magnetotellurics is required if the bias errors are to be eliminated. In 1977 we developed a new method known as remote reference magnetotellurics^{5,6}.

In remote reference magnetotellurics one makes an independent measurement of the plane wave signals with a second magnetometer located several kilometers from the base station. The signals, $\vec{R}$, from this reference magnetometer are telemetered to the base and are recorded simultaneously with the local $\vec{E}$ and $\vec{H}$ fields. The impedance tensor is then obtained by cross correlating the fields in Eqs. (2) and (3) with $R_x(\omega)$ and $R_y(\omega)$. For example, Z_{xx} and Z_{xy} are given by

$$\overline{E_x R_x^*} = Z_{xx} \overline{H_x R_x^*} + Z_{xy} \overline{H_y R_x^*} \quad (6)$$

$$\overline{E_x R_y^*} = Z_{xy} \overline{H_x R_y^*} + Z_{yx} \overline{H_y R_y^*} \quad (7)$$

The idea here is that the plane wave signals will be correlated over long distances whereas noise, which in a general sense is any electromagnetic disturbance that is not a plane wave, will not be correlated between the two sites. Thus, the noise in each of the average cross powers in Eqs. (6) and (7) will tend to zero with increasing number of data records, and the estimate of $\underline{Z}(\omega)$ will be unbiased.

The remote reference method was first tested in 1977 near Hollister, California using two three-axis SQUID magnetometers. To illustrate the results, it is convenient to introduce apparent resistivities which are defined by

$$\rho_{ij} = 0.2f^{-1} |Z_{ij}|^2 \quad (i, j = x, y). \quad (8)$$

Figure 1. shows the apparent resistivities ρ_{xy} and ρ_{yx} as a function of period that were obtained both for the conventional

Fig. 1. Apparent resistivities versus period for standard analysis. Dashed lines indicate remote reference results.

least squares analysis and for the remote reference analysis. In this test all fields were recorded simultaneously, the only difference being that for the standard analysis Eqs. (4) and (5) were used to compute $\underline{Z}$ while for the remote reference analysis Eqs. (6) and (7) were used. It is readily apparent from the figure that the curves for the standard analysis are much more jagged than those for the remote reference analysis and that they are consistently lower because of the bias errors. Near 10s period the downward bias is by more than two orders of magnitude for ρ_{xy} . In the figure, the actual data points for the remote reference are not shown. Therefore, it is important to point out that the dashed curves actually pass through each of the data points without smoothing. In several regions of the spectrum the confidence limits for the remote reference method for random errors⁶ are smaller than 1%. The remote reference technique has proven to be so successful over the last two years that it is rapidly becoming

the standard technique for magnetotelluric surveying.

An additional advantage of the remote reference method is that one can estimate for the first time the signal and noise power in each component of $\vec{E}$, $\vec{H}$, and $\vec{R}$. For example, the signal power $\overline{H_x H_x^*}$ and $\overline{H_y H_y^*}$ can be calculated from Eqs. (4) and (5) using the values of Z_{xx} and Z_{xy} obtained from Eqs. (6) and (7). The noise power is simply the difference between the measured power and the predicted power. The ability to isolate signal and noise power is of current interest, because it is still not understood what the major sources of noise are. It would be particularly interesting to determine if there is electromagnetic noise associated with geothermal sources. To test this one would need to carry out surveys in which the background noise is the signal. For this type of survey, SQUID magnetometers would be essential, since these are the only instruments with sufficient resolution.

Requirements for SQUID Magnetometers

Through the use of SQUIDS in magnetotellurics several criteria, apart from high sensitivity, have been found necessary to make SQUID magnetometers viable field instruments for geophysics. First, the instruments must be extremely rugged to withstand the mechanical shocks to which they are subjected in the field. Also, they must be lightweight and portable. The present commercially available three-axis rf SQUID magnetometers, as well as our dc SQUID magnetometers, are extremely robust and have never been mechanically damaged, despite several mishaps in which the magnetometers have fallen over. Furthermore, since all three sensors are in one fiberglass dewar that is typically 1m and 20 cm in diameter, and weighs about 20 kg, the units are considerably less bulky than a set of three 2m long induction coils. It is also interesting to note that a complete three-axis SQUID magnetometer with a 25ℓ He⁴ dewar, which holds

He^4 for about two and one-half weeks, may be several thousand dollars less expensive than a set of three, high quality induction coils, with their associated electronics.

Virtually all of the difficulties in making SQUID magnetometers fieldworthy instruments have been in the design of readout electronics that can cope with the broad spectrum of magnetic and electromagnetic signals to which the SQUIDS are exposed. The problems are accentuated by the fact that the SQUIDS are always incorporated in a feedback loop which, whenever broken, results in flux jumps (dc steps) at the output because of the periodic dependence of the SQUID signal on applied flux. Any signal that cannot be tracked by the feedback electronics produces flux jumps. Thus, the instruments must be carefully shielded from rf interference. Furthermore, the full dc output range must be at least $\pm 100 \text{ nT}$ to track the diurnal variations in magnetic field without saturating the electronics. For an instrument with a sensitivity of $10^{-5} \text{ nT Hz}^{-1/2}$ this implies a dynamic range of $10^7 \text{ Hz}^{-1/2}$. Even though most signals of interest in magnetotellurics are below 100 Hz, the electronics must be able to respond at high frequencies to track transients generated by lightening. In practice we have found that the electronics must have a bandwidth of almost 20 kHz and a slew rate approaching 10^5 nT s^{-1} at 1 kHz.

The maximum possible bandwidth and slew rate are limited by intrinsic noise in the electronics, which when fed back to the SQUID can produce spontaneous flux jumps, even in the absence of external perturbations. Thus, the present SQUID magnetometers are inherently unstable since there is always a finite probability that a transient that cannot be tracked will be produced, either externally or internally. This is, in fact, one of the main reasons why many geophysicists think that SQUID magnetometers are not yet sufficiently reliable. Our experience has been that SQUID magnetometers can sometimes be used for days without a single flux jump, but that at other times flux jumps may occur every few minutes. In magnetotel-

lurics the amplitude of a flux jump may be orders of magnitude larger than the signals. Therefore, it is important that the rate of flux jumps be less than about one per hour, so that they will not interfere with data collection at the longest periods of interest ($\sim 10^3$ sec).

To deal with the problem of flux jumps we have recently designed and tested an electronic circuit that automatically detects and compensates for flux jumps on a time scale of $10\mu\text{s}$. The circuit works by detecting the rapid step of a flux jump by differentiating the output signal. The output of the differentiator triggers a dual comparator which in turn fires one channel of a dual one-shot. The one-shot produces a $3\mu\text{s}$ long square pulse that closes an FET switch connected to the integrator of the feedback electronics. When the FET switch is closed, charge flows from a dc power supply onto the capacitor of the integrator to compensate the charge that was gained or lost when the flux jump occurred. Thus, the net effect of a flux jump is to produce a short pulse ($10\text{--}20\mu\text{s}$ long) rather than a dc step. This pulse is readily filtered out and is sufficiently short that it has no effect at the frequencies of interest. We feel that once a flux jump compensator, either of this kind or some other design, becomes a standard part of the SQUID electronics that there is no reason why SQUID magnetometers should not be as reliable, or even more reliable than induction coils or other types of magnetometers.

Discussion

SQUIDS have now been in use in geophysics for about five years. In that short time they were directly responsible for the development of remote reference magnetotellurics. Magnetotellurics has, in a sense, been a proving ground for SQUID magnetometers, since it is through the work in magnetotellurics that virtually all of the design criteria for fieldworthy super-

conducting magnetometers were established. The improvements in the electronics with regard to slew rate, dynamic range and frequency response, together with the rugged design of fiberglass cryostats have already resulted in a very reliable, compact package, with sensitivity below 1 kHz higher than that of any other instrument. Once some type of automatic flux jump compensation is incorporated into the electronics, there is no reason why SQUIDS should not be as trouble-free and easy to use as any other conventional magnetometer.

Already, interest in SQUIDS is spreading to other areas of geophysics. For example, there is considerable enthusiasm for designing superconducting gradiometers for aerial surveys for ore bodies, and for fabricating magnetometers suitable for measurements in boreholes and undersea. In these new areas there are additional complications resulting from the need for liquid He^4 . In magnetotellurics, He^4 is usually one of the smallest concerns, except in very remote locations where there may be difficulty in acquiring the liquid. In these new applications the He^4 bath must undergo considerable pressure variations. Consequently, means must be found for properly venting the dewar so that the operating temperature of the sensor remains near 4.2K. Ideally one wants a cryogenic magnetometer that requires no liquid coolant. The work of Zimmerman⁷ on closed cycle refrigerators is particularly exciting since he has already demonstrated a very compact refrigerator that reaches 6K and has successfully operated a SQUID at this temperature using the refrigerator. The idea of a SQUID magnetometer with a built-in refrigerator that operates simply by connecting a power supply is enormously appealing. Further technological developments in this and other areas in the next few years should prove to be very exciting and should lead to the use of SQUIDS in geophysics on a much larger scale.

References

1. Lindsley, D. H., Andreasen, G. E., and Balsley, J. R.: Memoir 97 of the Geological Society of America, Inc., Handbook of Physical Contents, Section 25, Sydney P. Clark, Ed., 544-552 (1966).
2. Vozoff, K.: Geophysics 35, 98-141 (1972).
3. Clarke, J., Goubau, W. M., and Ketchen, M. B.: J. Appl. Phys. 25, 99-144 (1976).
4. Sims, W. E., Bostick, F. X., Jr., and Smith, H. W.: Geophysics 36, 938-942 (1971).
5. Goubau, W. M., Gamble, T. D., and Clarke, J.: Geophysics 43, 1157-1166 (1978).
6. Gamble, T. D., Goubau, W. M., and Clarke, J.: Geophysics 44, 53-68 (1979).
7. Gamble, T. D., Goubau, W. M., and Clarke, J.: Geophysics 44, 959-968 (1979).
8. Zimmerman, J.: Second International Conference on Superconducting Quantum Interference Devices (1980).