SQUID APPLICATIONS TO GEOPHYSICS

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Edited by

HAROLD WEINSTOCK

Office of Naval Research and
Illinois Institute of Technology
Chicago, Illinois

WILLIAM C. OVERTON, Jr.

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

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PREFACE

The Workshop on SQUID Applications to Geophysics was held at the Los Alamos Scientific Laboratory, June 2-4, 1980. The aim of this Workshop was to enhance understanding between cryogenic physicists and geoscientists of (1) the capabilities and limitations of SQUIDs, (2) the state-of-the-art in conventional geophysical measurements, (3) techniques in which SQUIDs are being used to advance geophysical exploration and (4) new applications made possible through SQUID and other superconducting technology.

The SQUID, or Superconducting QUantum Interference Device, is an extremely sensitive magnetic field sensor based on the Josephson junction, with a basic sensitivity some 10,000 times greater than that of the best conventional magnetometers. In a Josephson junction, electron pairs tunnel across a thin insulating barrier between two superconductors. Brian Josephson was awarded a Nobel prize for his 1962 predictions of the quantum nature of the current-voltage relation and the radio frequency emission of a superconducting tunnel junction. Experimental verification of these predictions and the development of the SQUID concept followed within two years. Over the past decade, several companies have begun to produce SQUIDs commercially. Two of the papers (by Falco/Schuller and Clarke/Goldstein) in these proceedings describe how the Josephson effects have led to the evolution of ac and dc SQUIDs, while the bulk of the remaining papers describe their use in active electromagnetic (EM) and passive magnetotelluric (MT) exploration methods, in gravity studies and in magnetic anomaly detection. One paper deals with archeological exploration of ancient village sites by a conventional proton magnetometer. We include this because SQUID gradiometers can be adapted to give great improvement in such small-area explorations.

Many of the 26 papers in these proceedings are tutorial and review in nature, in order to facilitate communication between geoscientists and cryogenic physicists. We hope this will aid both groups in appraising the potential of and developing ideas for the use of SQUIDs in geophysics.

We wish to express our appreciation to our sponsors, the Office of Naval Research (ONR) and the Los Alamos Scientific Laboratory (LASL) for their assistance, encouragement and financial support, without which the Workshop and its proceedings could not have been brought to fruition. Specifically, financial support was provided by ONR's Earth and Environmental Physics Program, LASL's Physics Division and its Basic and Applied Geosciences Division. We would like particularly to thank Jack Heacock of ONR for his continued interest and assistance; LASL's Sue Wooten, Ed Stein and Floyd Archuleta for their work on behalf of the program; and our diligent session chairmen, George V. Keller, Charles M. Swift, John C. Wheatley, Robert S. Andrews and Grant Heiken, for maintaining a stimulating atmosphere while adhering to a tight schedule.

We acknowledge, as well, the invaluable aid we received from the other two members of our organizing committee, George V. Keller of the Colorado School of Mines and Charles M. Falco of the Argonne National Laboratory. Additionally, George Keller graciously hosted our two organizing committee meetings. Finally, we wish to thank the Society of Exploration Geophysicists for its willingness to publish these proceedings and its fine cooperation throughout our endeavors.

While these proceedings were in preparation, the name of the host institution, the Los Alamos Scientific Laboratory, was changed to the Los Alamos National Laboratory. Since many of the papers herein were prepared prior to the change, we have decided not to make editorial corrections at the many points of reference to the old name.

Harold Weinstock
Office of Naval Research
Chicago, Illinois

William C. Overton, Jr.
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

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MAGNETOMETERS FOR GEOPHYSICAL APPLICATIONS

BY SHELDON BREINER*

ABSTRACT

Magnetometers are used for a variety of geophysical measurements, including mobile measurements for airborne, marine, satellite and ground surveying, and for fixed-point monitoring for magnetospheric and subsurface research. The principal instruments in use today are the proton precession, optically-pumped, fluxgate and induction coil magnetometers. These conventional instruments, their sensitivity and characteristics are discussed as a base-line reference, as it were, for applications where SQUID magnetometers might be more advantageous.

I. INTRODUCTION

Geophysical applications in the context of this paper refer to measurements of the earth's magnetic field (or extraterrestial fields) generally on the order of several tens or up to 10^5 nanotesla (1 nT = 1 gamma = 10^{-5} oersted ≈ 10^{-5} gauss). The characteristics of conventional magnetometers are described herein with respect to such geophysical applications and also relative to the superconducting Josephson junction type magnetometer commonly referred to as a SQUID (superconducting quantum interference device). Many of the characteristics and sensitivities of the various magnetometers for these applications are described with particular emphasis on possible advantages or limitations vis-a-vis the SQUID for each geophysical application.

To characterize the applications, it is convenient to describe them as either fixed point monitoring or mobile survey measurements. The former usually involves the recording of temporal variations as the objective and the latter spatial variations although there are several examples of overlapping objectives.

The various types of magnetometers in use for geophysical applications include fluxgate, proton, optically pumped, induction, mechanical, SQUID, and miscellaneous other tyes. As a crude estimate, geophysical applications utilize these instruments in the following percentages, respectively: 16%, 60%, 4%, 12%, 5%, 1%, and 2%.

Each of these instruments tends to offer, for a given application, a specific advantage be it sensitivity, cost, stability, mobility, ease of operation, frequency response, type of measurement, or dynamic range, to name a few. The nature of the measurement may be vector or scalar, variation or absolute, value at a point or differential, time rate of change or some combination of these. Notwithstanding its use in magnetotelluric arrays and laboratory measurements of rock magnetism, the SQUID is sufficiently new in its development, unique in specifications, or complex in its operation and maintenance, that as an instrument it is still seeking its place in geophysics.

Fixed point monitoring applications include at least the following and perhaps others not mentioned: investigations and measurements for the magnetosphere, magnetotellurics, secular change, base-station-fixed reference for magnetic surveys, paleomagnetism, piezomagnetism, and archeomagnetism. Survey applications include ground, airborne, marine, and borehole surveys for geological information for natural resource exploration and geological research, mapping of the terrestial and planetary magnetospheres and internal magnetic field sources, mapping of the Curie point isotherm for geothermal research, archeological and search prospecting, atmospheric studies, and mapping of the magnetic component of natural and artificial electric currents for natural resource exploration and solid earth research. Not included here but closely related are such security or military applications as antisubmarine warfare, mine detection, harbor defense, and weapons detection (as presently used in airports) and medical and biological research as in measurement of the magnetic field of the heart and other organs.

II. MAGNETOMETER DESCRIPTIONS

A very brief description of the principal characteristics of each of the magnetometers is useful to compare their relative merits for each of these uses. These characteristics are generalized to include the various models and versions of these instruments but is intended to refer to instruments that have been actually used in practice at this time. The sensitivity of each instrument is described with respect to the inherent sensor and not in combination with added flux collectors or similar enhancement devices that can be used with any sensor to increase sensitivity but decrease other operating characteristics. A more detailed explanation of any one instrument is readily available in the literature. The order in which these instruments are described is chronological with respect to their original development and is presented in this way because of the trend, albeit slow, towards increased utilization of the newer instruments at the expense of the older types.

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* EG&G Geometrics
Sunnyvale, CA

A. Mechanical Magnetometer

Used in mineral exploration for almost 400 years, mechanical magnetometers are basically a magnetic dipole suspended horizontally or vertically on a variety of jewelled, torsion fiber, or mechanical bearing suspensions, the more common types being the Schmidt type, recording variometers, torsion, QHM, dip needle, Hotchkiss super dip, and other specialized types usually developed and manufactured by companies specializing in precision optical devices. Taken at their best specifications, these instruments exhibit a temperature dependence, have a sensitivity of several up to tens or hundreds of nT, and measure a vector component of the magnetic field usually horizontal or vertical. The measurements usually obtained on a stable tripod for point measurements in ground survey applications and in a special enclosure on a pier for continuous recording for magnetic observatory observations. Use of these instruments has diminished significantly with the development of electronic or electromechanical instruments over the past two decades, largely because the sensitivity, accuracy and/or rate of survey coverage is much lower than that obtained with electronic magnetometers.

B. Induction Coil Magnetometers

The induction coil magnetometer is only briefly covered here inasmuch as it is the subject of other papers in this publication and is defined by some as an electromagnetometer, i.e., the magnetic component detector for the more rapidly varying natural or artificial signals. Commonly comprised of a thousand or more turns around an air, ferromagnetic or ferrite core, an induction coil measures the rate of change of magnetic field with respect to time and is particularly used for magnetic field changes in such frequency ranges as 100 Hz to 1 kHz, 1 Hz to 100 Hz, or 0.001 Hz to 10 Hz. However, the signal amplitude varies directly with the frequency so that signals in the very low, near dc frequency, are measured with very low sensitivity. If one wished to obtain measurements in nT, the signal that is a time-derivative must be integrated over time as required.

The principal applications of an induction coil magnetometer are for magnetotellurics, measurement of micropulsations, or magnetic detection for airborne and ground-based electromagnetic surveys for natural resources such as electrically-conductive massive sulphide deposits. An induction coil for high sensitivity measurements is very large and heavy, exhibits motion sensitivity, (because it measures the rate of change in field even if generated by movement in the earth's field), is a vector component instrument requiring orientation stability in the frequency band of interest, and measures the rate of change rather than the field itself. Typical sensitivities for a ferrite core coil are 10^{-1} nT/Hz, 5×10^{-4} nT/Hz, 7×10^{-5} nT/Hz and 10^{-4} nT/Hz at periods of 0.001 Hz, 0.1 Hz, 10 Hz, and 100 Hz, respectively.

C. Fluxgate Magnetometers

The fluxgate magnetometer was originally developed in the 1940's for use in antisubmarine warfare. Immediately after World War II, it was adopted for airborne geophysical surveys for natural resource exploration. In its various configurations, the instrument is known as a 2nd harmonic, ring core, thin film, or oriented fluxgate magnetometer, etc., and usually consists of a series of windings on a ferromagnetic core in which the permeability is a function of field strength. The sensitivity is enhanced through the use of an ac driving signal that is used to drive the core through saturation around the hysteresis loop. The effect of the ambient field adds to the induction in one direction and subtracts in the other, creating a difference in the interval of saturation, detectable at twice the driving frequency. This rectified signal is proportional to the vector component of the field in the direction of the axis of the ferromagnetic core. A dc current used to null the ambient field is a source of some instability at long periods but allows sensitivity of perhaps 0.05 nT is recently developed instruments, 0.1 nT in some of the airborne and monitoring versions and up to several nT for handheld portable instruments.

All fluxgate magnetometers measure a relative rather than absolute value of the magnetic field and as such must be calibrated in some way such as being used to reoccupy measurements points or referenced to absolute measurements using other magnetometers. This is common in airborne, satellite, and some ground survey applications. Since the fluxgate measures a vector component of the field, survey applications require that the instrument be referenced to some spatial coordinate system such as vertical, as in the case of ground portable surveys, or electromechanically oriented along the earth's field for airborne surveys. These oriented fluxgate systems utilize three mutually orthogonal fluxgate sensors that are continuously oriented by a remote motor so that two of the sensors measure zero field. The third or primary sensor thus measures the maximum vector, otherwise referred to as total magnetic intensity. The precision of the sensors and the electromechanical orientation system are some of the principal limitations on sensitivity or resolution, particularly on a rapidly moving platform. Some satellite, a very few airborne research survey aircraft, and some borehole probes utilize three mutually orthogonal fluxgate sensors referenced to an inertial or other spatial coordinate system in order to obtain vector information of the field.

D. Proton Magnetometers

The proton magnetometer was developed in the mid 1950's as an outgrowth of research involving nuclear magnetic resonance. The proton magnetometer, also called a nuclear precesion, proton precession, or proton free precession magnetometer, consists of a coil of wire surrounding a fluid containing hydrogen atoms such as water, kerosene, etc. The proton or nucleus of the hydrogen atom is itself a spinning magnetic dipole that can be polarized or aligned by a momentary

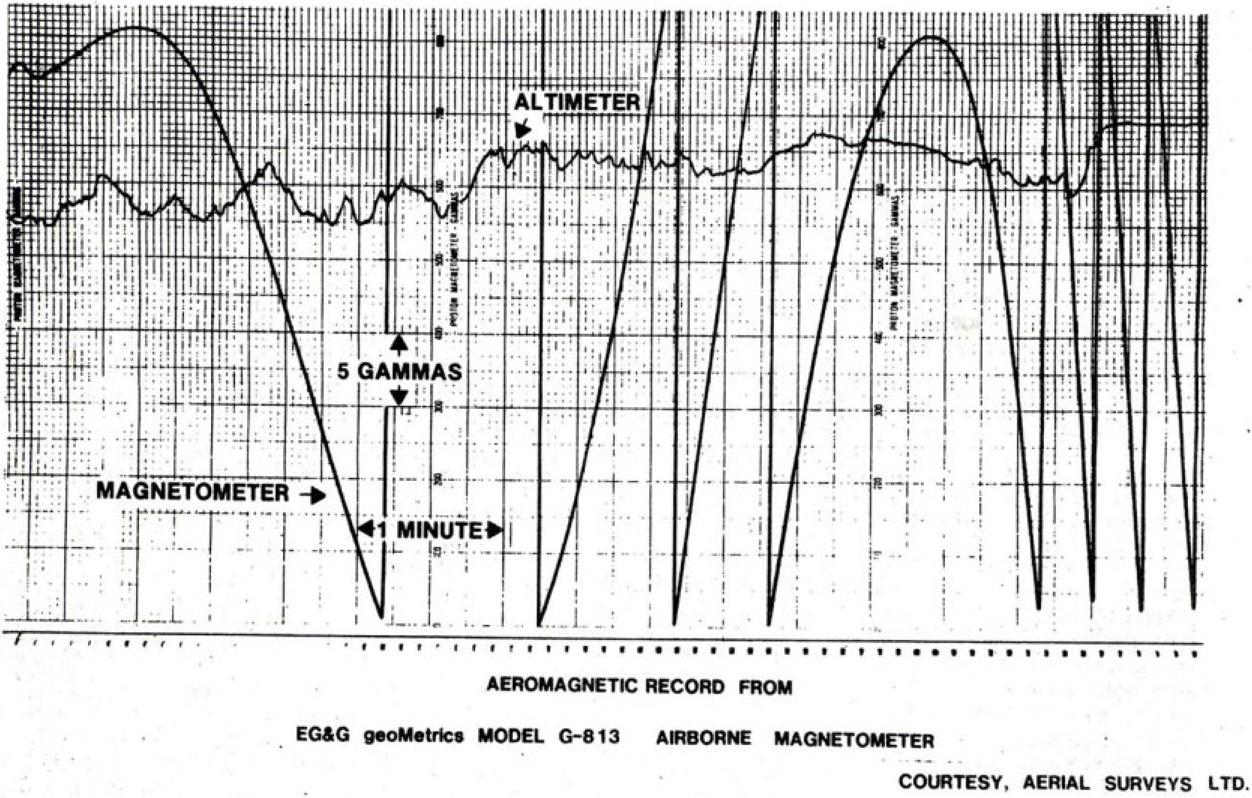

Figure 1: Aeromagnetic record of a stinger-mounted proton magnetometer. Courtesy, Aerial Surveys, Ltd.

application of a uniform magnetic field produced by a dc current in the coil surrounding the sample. After the current in the coil is abruptly terminated, these spinning protons precess about the direction of the ambient, or earth's magnetic field, at a frequency that is proportional to the field intensity and independent of the direction of the sensor or the direction of the earth's field. The precessing protons induce a signal, typically 2 kHz, in the polarizing coil. The polarization usually decays in a matter of a few seconds, requiring a repolarization between measurements, and the measurements are thus discontinuous at a rate up to 10 readings per second.

Another proton magnetometers, referred to as the Overhauser/Abragam magnetometer, can also be polarized by a radio frequency exciting field in an organic fluid containing a free radical to provide a continuous precession and measurement of the field. Though the Overhausen/Abragam magnetometer provides a continuous measurement, the exciting field somewhat influences the absolute measurement of the field.

The maximum sensitivity of either type of proton magnetometer is generally 0.01 nT. The absolute accuracy of the free precession magnetometer, however, is approximately 0.1 nT, (limited primarily by the magnetic properties of the sensor, accuracy of the frequency counting circuits and known precision of an atomic constant), and represents the most accurate measurement of the absolute value of the earth's magnetic field of the various types of conventional magnetometers. The frequency response of the proton magnetometer within the time of active precession is dc to frequencies of up to at least several hundred kHz. However, since most precession proton magnetometers obtain one measurement per polarization cycle, the frequency response is limited by the highest cycle rate (dc to less than 10 Hz for free precession and nearly dc thru several hundred kHz for Overhauser/Abragam). The majority of portable ground magnetometers now being utilized are proton magnetometers, some with a sensitivity of 0.25 nT and absolute accuracy of approximately 1 nT.

Proton magnetometers, and for that matter the optically pumped magnetometers, share this spin precession characteristic that makes them the most suitable of all magnetometers for survey applications on a moving platform, such as an aircraft or ship, since they do not contain any moving parts and provide a measurement of magnetic field independent of orientation (see Figure 1). They provide a measurement of the total magnetic intensity, a scalar, much as the oriented fluxgate sensor but do not require orientation or inertial reference. Proton magnetometers will not operate in extremely high gradients, though, which limits their use in some ground surveys over iron formations.

The spin precession magnetometers, however, can also be utilized to obtain vector component measurements. The sensor can be operated within a coil system designed so as to cause the ambient field within the coil system to represent the desired component of the earth's magnetic field.

With the knowledge of the currents and coil geometries, the scalar magnetometers can thus be utilized for vector measurements, which is now in common use in magnetic observatory systems and a few research directed survey aircraft.

E. Optically Pumped Magnetometers

The optically pumped magnetometer was first used for geophysical measurements in 1957. This magnetometer takes advantage of optical pumping to cause atomic or electron spin precession in very much the same way as the principles of nuclear magnetic resonance are applied to take advantage of proton precession. The optically pumped magnetometer utilizes a population of electrons in alkali vapor gas such as rubidium or cesium (sometimes potassium or sodium) or in metastable helium to obtain a continuous measurement of the scalar field intensity at sensitivities better than 10^{-3} nT. The typical optically pumped magnetometer utilizes a lamp containing the alkali metal or helium whose light is passed through a glass cell containing the vapor of the same element and focused on a photo detector on the other side of the vapor cell. The output of the photo detector is connected through an amplifier to a coil surrounding the vapor cell. This electro-optic system, through resonance absorption and reradiation of energy, constitutes an oscillator whose frequency is directly proportional to the scalar magnetic field intensity in much the same way as the proton precession magnetometer. The optically pumped magnetometer, however, operates with a continuous signal at frequencies considerably higher - on the order of several hundred kHz for the alkali metals and two MHz for helium.

The sensitivity of a cesium magnetometer, as typical of optically pumped instruments, has been shown to be 5×10^{-4} nT in a band width of approximately 0.1 Hz thru 10 Hz and possibly 10^{-3} nT between 10^{-3} Hz and 10^{3} Hz. (See Figure 2.) The absolute accuracy of a conventional optically pumped magnetometer, however, is generally one to several nT due to the complexity of various resonant lines on which it operates that in turn are a function of orientation in the earth's magnetic field and several operating characteristics of the exciting lamp and amplifier. The frequency response of all optically pumped magnetometers exceeds several MHz inasmuch as the precession frequency responds to changes even much shorter than a single cycle of precession.

F. SQUID Magnetometers

The SQUID magnetometer, its characteristics, applications and limitations, are described extensively elsewhere in this publication. Therefore, this information is omitted in the context of descriptions of conventional magnetometers.

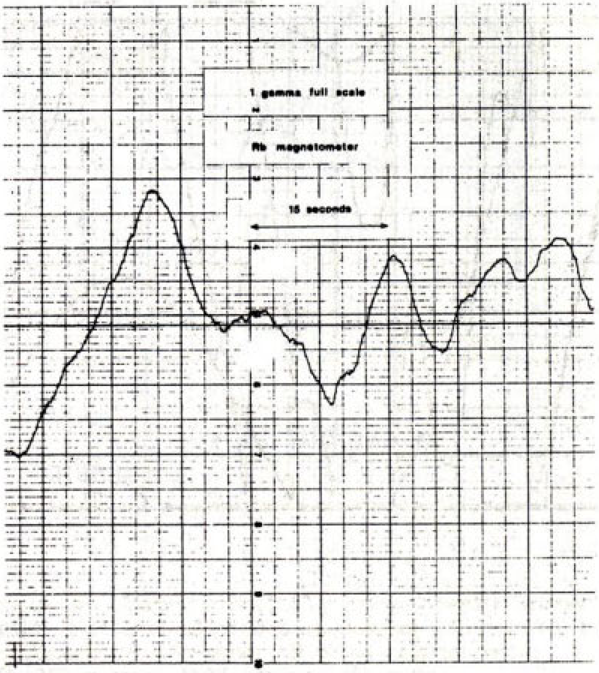

Figure 2: Recording of optically pumped rubidium magnetometer operating as a base station diurnal reference. Courtesy, Varian Associates.

III. DIFFERENTIAL MAGNETOMETER CONFIGURATION

Many of these conventional magnetometers are used differentially in configurations commonly known as differential magnetometers or gradiometers. To be precise, a differential magnetometer is simply two magnetometers of the same characteristics whose difference in signals is measured. A magnetic gradiometer, on the other hand, can be considered to be a differential magnetometer where the distance between sensors is fixed and small with respect to the distance to sources whose fields are measured. Differential magnetometer applications are of particular interest even in this discussion of conventional magnetometers because it is the purpose of this paper to establish a base line, as it were, of what is used and exists today and compare this state of the art with applications of SQUID magnetometers. Since many of the applications of SQUID magnetometers are in differential or gradient configurations, it would be useful to examine the same configurations in conventional magnetometers.

Differential magnetometers are often used to remove coherent noise by common mode rejection, noise which may be of instrument origin or noise arising from sources within the measured environment. The measurement obtained from a differential magnetometer is still assumed to be in units of nT since the field from one is simply subtracted from the other. When used as a gradiometer, the measurement is the ratio of the difference in field intensity to the distance between sensors, expressed in nT/m or some similar gradient unit.

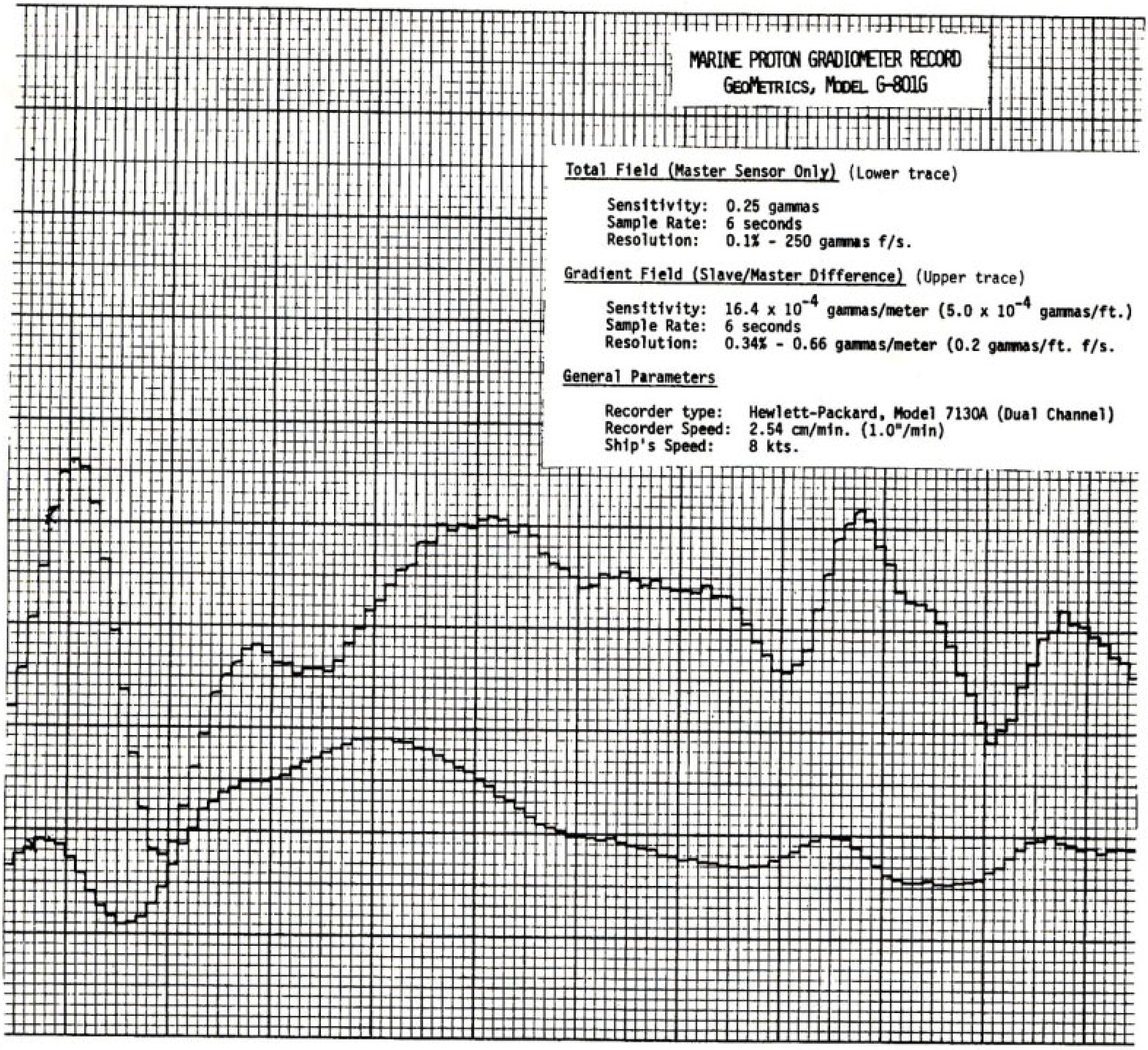

Figure 3: Marine magnetometer and magnetic gradiometer record (Two proton magnetometers towed in line, 500 feet apart). Courtesy, EG&G Geometrics.

The magnetic gradiometer is used to remove noise coherent in time, such as time variations of distant origin. Gradiometers are also used to remove noise sources more or less coherent in space, i.e., a long distance from the gradiometers, such as distant or deeper lying geological sources or regional gradient. The latter application can be considered a distance filter and the former a time variation filter. The distance filter can also be viewed as one that enhances local sources at the expense of distant sources. Specifically, anomalies vary inversely with distance at a rate one order higher for a gradiometer than for a magnetometer. See, for example, the application described by Hood, in this publication.

A third application of gradiometers is one that permits accurate mapping of a useful vector, the gradient of the scalar field intensity, from a moving platform with greater accuracy relative to many applications than would be possible measuring the vector component directly. The gradient of the scalar field intensity is itself a vector with much the same useful interpretation characteristics as the vector components of the field itself. However, an angular change in one vector sensor (e.g., fluxgate) is equivalent to a relative change in a geophysical anomaly several orders of magnitude higher than the same orientation change would be on a gradient of the scalar utilizing optically pumped or proton precession instruments.

Consider, for example, a 100 nT total field anomaly (7×10^{-2} nT/m vertical gradient anomaly) from 3,000 m depth in a field of 50,000 nT. A one-degree change in orientation of a vector sensor would cause a 900 nT error in the measured intensity, 9 times larger than the anomaly itself. The same one degree change in orientation of a gradiometer measuring the vertical gradient of this total field intensity anomaly would produce an error of 10^{-3} nT/m, a 1 percent error in the gradient anomaly.

An additional application of gradiometers is one that exploits the mathematical relationship of the gradient and total field anomalies to determine such parameters as depth-to-source, direction of source, and characteristics of the source such as magnetic moment, susceptibility, etc., when such is desired.

Magnetic gradiometers are in frequent use in geophysics, particularly the vertical gradiometer using optically pumped magnetometers in the airborne configuration for the above application; the longitudinal gradiometer using proton magnetometers for the marine application to remove time variations of the field and still have total field intensity (Figure 3); and the transverse gradiometer using proton magnetometers in each wing tip in the airborne configuration for better mapping of the field on a two dimensional plane. Three such transverse gradiometers have been installed in aircraft, one in 1970 and more recently by the geological surveys of Canada, Finland, and the U.S., the latter having a third sensor in a tail stinger for the combined advantages of all the gradiometers mentioned above. (See Figure 4.) Induction coil, fluxgate, proton, and optically pumped gradiometers and differential magnetometers have all been used for magnetotelluric surveys, paleomagnetic, and other geophysical applications.

IV. RELATIVE CHARACTERISTICS OF MAGNETOMETERS

A. Sensitivity

Over a wide range of frequencies of geophysical interest, say, 0-10 Hz, the optically pumped magnetometer has a sensitivity of 5×10^{-4} nT, or one or two orders of magnitude better than the other conventional magnetometers. At a frequency of 100-1000 Hz, a large, or ferrite-cored, induction coil might exhibit sensitivity comparable to an optically pumped magnetometer when measuring time rate of change of field. (NOTE: It is important when comparing sensitivities of magnetometers to consider also the frequency band of interest as some instruments are decidedly better at specific frequencies either due to enhanced signal or reduction in noise, e.g., induction coil at 1000 Hz or proton magnetometer at dc.)

In order to evaluate the effective sensitivity of a magnetometer in a specific application, one must also take into consideration the realistic effects of non-instrument noise and environmental errors (see the following section). The relative sensitivities of each of these instruments is shown in three frequency bands in Figure 5.

B. Frequency Response

The desired frequency response of a magnetometer should, of course, bracket the highest and lowest (sometimes including zero or dc) frequency in which an anomaly can be resolved satisfactorily. Signals within this frequency band can always be obtained or enhanced by real time or subsequent filtering. Of the conventional magnetometers, the optically pumped magnetometer probably possesses the widest frequency response, zero to several MHz, followed by the fluxgate magnetometer which may exhibit near zero (limited by temperature dependence) to several hundred Hz or higher (see Figure 6). Relative to these two instruments, the induction coil has good high frequency response at several thousand Hz, but poor at 10^{-3} Hz. The proton magnetometer has the best extremely low, i.e., dc, frequency response being an absolute magnetometer. If operated within each reading cycle, the proton magnetometer can respond to several hundred kHz, but as a continuous magnetometer, it is generally limited to resolving signals less than 5 or 10 Hz. The mechanical magnetometers are similar in response to the proton magnetometer, but because they are not generally absolute and have some temperature dependence, they do not exhibit as good a dc response.

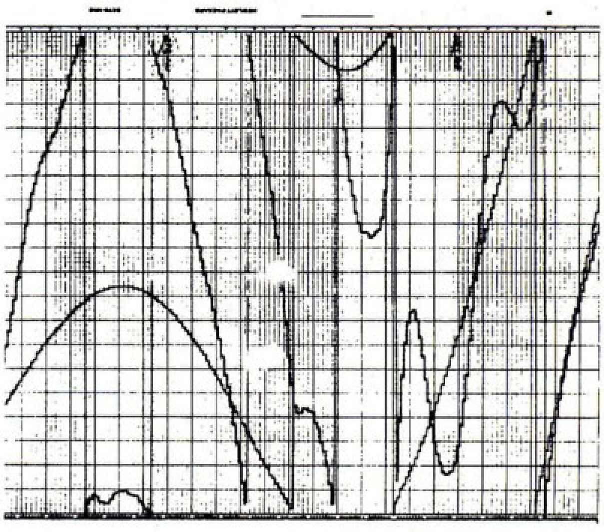

Figure 4: Airborne optically pumped cesium magnetometer and vertical gradiometer record in towed bird configuration. Smoother trace - - magnetometer, 100 nT (100 gammas) full scale; other trace, 3×10^2 nT/m (10^{-2} gammas/ft) full scale. Courtesy, Aero Service Corp.

C. Absolute Accuracy

The proton precession magnetometer has an absolute accuracy of perhaps 0.1 nT and at present is considered the accepted reference for earth's field measurements. With a magnetically clean sensor and a stable reference oscillator, the accuracy can be related to an atomic constant, the gyromagnetic ratio of the proton that is presently known to 0.2 ppm accuracy. The optically pumped magnetometers generally have an absolute accuracy of approximately 1 nT, particularly if operated on single resonance lines and with proper calibration of electronics, light intensity and temperature. Some mechanical magnetometers, used for years as

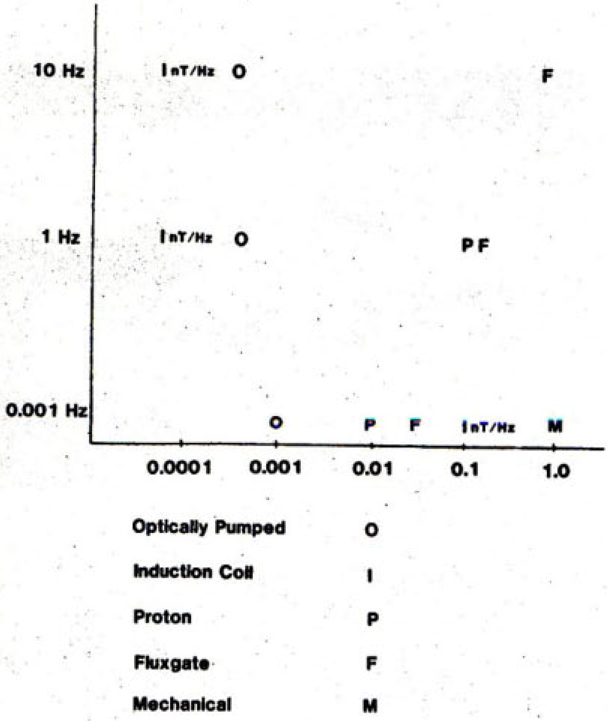

Figure 5. Relative sensitivities of conventional magnetometers as a function of frequency.

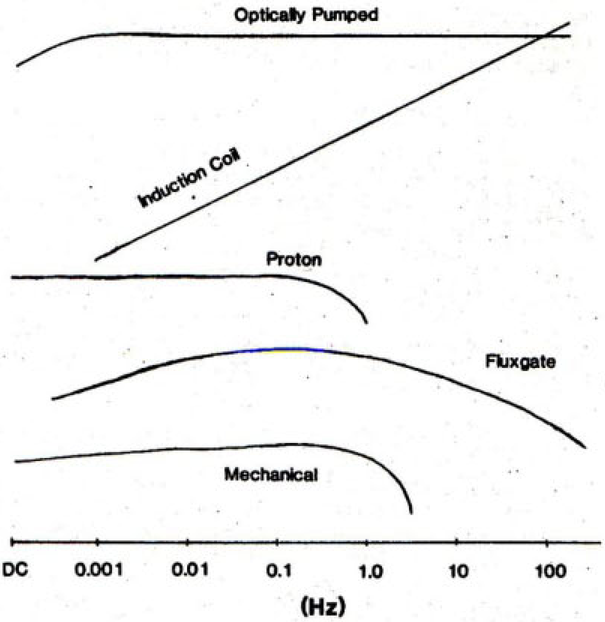

Figure 6. Relative frequency response of various conventional magnetometers.

observatory references, also exhibit high absolute accuracy of approximately several gammas. With the characteristics of a variometer, the fluxgate and induction coil type magnetometers do not have a specification for absolute accuracy.

D. Vector vs. Scalar Instruments

With the exception of the spin precession types, all magnetometers including those described here such as the fluxgate, induction coil and mechanical magnetometers, are inherently vector component instruments. The spin precession types, namely, the proton and optically pumped magnetometers can, as well, be made to operate as vector instruments as previously described.

The proton and optically pumped magnetometers are inherently scalar (magnitude of the total field intensity vector) instruments and the oriented fluxgate is scalar by virtue of its modified operating characteristics. It is interesting to note that in essentially all geophysical applications, these magnetometers, though scalar instruments, actually operate as earth's-field-determined vector component magnetometers. This can be seen by constructing a vector diagram of the magnitude of the total field as measured in the presence of a typical anomalous perturbation, small in relation to the earth's field.

Attempts have been made to make a scalar instrument from an array of three mutually orthogonal fluxgate sensors in order to exploit the advantages of the simplicity and size of the fluxgate instrument for use on a moving platform. Such a sensor would be operated in various orientations in the earth's field from which the square root of the sum of the squares of each of the three intensities would be used to compute the magnitude of the total field intensity. However, to do so requires that the three individual sensors be precisely, mutually orthogonal and that all possess identical and very precise linearity through the entire range of near zero field to 10^5 nT. To date, only limited success has been obtained with such efforts.

E. Size

The minimum size of the basic sensing element in each of these magnetometers varies substantially. The fluxgate sensor, for example, can be made smaller than a cubic centimeter in volume. An induction coil, albeit low sensitivity, may be made which is less than several cubic centimeters but is more likely to be several thousand cubic centimeters in volume; the proton, optically pumped and mechanical magnetometers can be less than 100 cubic centimeters.

The housing for any of these, including the sensor, necessary electronic and mechanical support environment, however, may add considerable size to some of these instruments. When comparing claims for small size of magnetometers, it is important to consider the complete systems and configuration as deployed.

F. Power Requirements

The power requirements for continuous operation of fluxgate, induction coil and mechanical magnetometers are generally less than milliwatts.

The optically pumped magnetometer may be tens or hundreds of milliwatts and the proton magnetometer greater than several watts average power.

G. Cost/Complexity

Including the support environment for the magnetometer sensor, conventional magnetometers if rank ordered in increasing cost and complexity would be as follows: induction coil, mechanical, fluxgate, proton, and optically pumped magnetometers. To be sure, the complexity of proposed state-of-the-art systems is rather subjective but is meant to take into consideration such items as the sensor configuration, use of multiple optical and electronic components, requirement for exotic materials, etc.

V. ENVIRONMENTAL AND APPLICATION LIMITATIONS

Consideration of the environment in which each of these instruments is used and the various monitoring and survey applications is important when evaluating the usefulness of such characteristics as sensitivity, accuracy, and frequency response. Moreover, evaluation of magnetometers with even better characteristics such as the SQUID, should entail an examination of whether these environmental limitations can be overcome with clever use of, say, a SQUID, or whether they are inherent and made even more apparent with such improved instrumentation.

Mechanical magnetometers present severe limitations in their use in almost all applications when compared to the other more modern conventional magnetometers. Chief among the limitations is lack of sensitivity, poor information display, requirement for environmental correction and immobility. Fluxgate magnetometers, are primarily used in ground portable, 3-axis ground recording modes and some airborne surveys. Temperature drift, sensitivity, and calibration for the latter two applications are the principal limitation.

The induction coil is primarily limited in high sensitivity applications to frequencies between 0.001 and 100 Hz due to inadequate signal-to-noise and the attendant size, motion sensitivity and limited band of response. (See paper in this publication by G. V. Keller.) These represent limitations in its use in magnetotellurics and, in this 1 Hz to 100 Hz, prevent its use completely in deeper penetration airborne electromagnetic systems for exploration of conductive ore bodies.

Proton precession magnetometers are affected by roll, pitch, and yaw motion in survey applications when used in a rapidly moving platform such as a towed marine (fish) or airborne (bird) sensor. This noise is generated by rotation of the receiving coil (which is otherwise assumed to be stationary) about the precessing protons and is sometimes referred to as Doppler-precession error. The error is proportional to the component of the rate of rotation of the sensor in the direction of the earth's magnetic field and has a maximum value of 1 nT per 0.04 Hz of rotation. The effects are such that for towed deployment of the sensor and depending upon its stability, this noise may be a few tenths nT.

Figure 7: Three-sensor magnetometer installation, one proton magnetometer in each wing tip and one in a tail-mounted stinger. Wing tip sensors constitute a transverse gradiometer. Courtesy, U. S. Geological Survey.

Optically pumped magnetometers are limited in some applications by the orientation-dependence of the sensor that limits its absolute accuracy as well as creating certain position-dependent errors and non-operating orientations when used as a ground portable instrument and in towed airborne and marine survey applications. For a single or dual-cell optically pumped magnetometer, there is a heading error about any 360^0 turn of 0.2 to 1 nT, which for typical maneuvers of the towed sensor has an orientation noise of approximately 0.1 nT. As in the proton magnetometer, the optically pumped magnetometer similarly possesses a rate-dependent Doppler-precession error, but it is two to three orders of magnitude smaller.

In any sensor installed in a towed airfoil (bird), the airfoil constantly swings, and because it is aerodynamic in shape also rotates at its natural pendulum period. It also moves from one position to another in the earth's magnetic field gradient of up to ten or more times the undisturbed vertical and horizontal north-south gradient of 0.02 nT/m and 0.004 nT/m, respectively.

For airborne survey requirements, the motion-, orientation-, and position-dependent errors inherent in the proton and optically pumped magnetometers can be reduced by installation of the sensor on a rigid stinger or wing tip of the aircraft. However, the maximum practical required magnetic compensation (for permanent and induced magnetism, and eddy currents) of the aircraft is limited to approximately 0.5 nT to 1 nT for a 360^0 turn, so that typical yaw - heading changes cause heading errors of 0.1 nT or more. The net result of all of these effects is that for airborne survey applications using present techniques of magnetic compensation, the maximum obtainable sensitivity for a magnetometer, whatever the type, is generally not consistently better than 0.1 nT throughout the course of the survey. (See Figure 7.)

For marine survey applications, sensor motion is similarly a problem for the same reasons as those that pertain in airborne surveys. In addition, however, sea swells produce a magnetic field perturbation due to the EMF generated by the conducting sea water moving through the earth's magnetic field. The noise thus generated is equal to a few tenths nT up to several nT in high sea states and is almost always noticeable when operating a magnetometer at sensitivities of 0.1 nT.

Uncertainties of position of the platform and sensor represent an additional limitation, particularly at higher desired sensitivities. The position uncertainty times the gradient in each of the three directions can readily be estimated and shown to produce a larger error in magnetic field values than is usually assumed or implied in the maps or profiles. For the latter, however, position is not nearly as important.

The effects of micropulsations, diurnal variations and other time variations when they are not considered to be the signal, but rather noise, also represent a limitation on survey information depending upon the ability to cancel such effects. The coherence of such time variations depends upon distance from the points of measurement, the uniformity of conductivity of the subsurface, and the relative state of the magnetic activity and current systems in the magnetosphere such as the auroral effects, equatorial electrojet current system and other time varying magnetic field sources of noise.

This paper does not allow adequate treatment of the various noise sources and environmental effects. To be sure, in many of the applications of conventional magnetometers, it is not the instrumentation that is the principal limitation in the successful use of the measurements, but rather conditions external to the instrumentation.

VI. CONCLUSIONS

Throughout this paper, the term conventional magnetometers was utilized to distinguish the majority of magnetometers employed in geophysical applications from the SQUID magnetometer. The term "conventional" though should not attribute to these instruments any suggestion that they may be obsolete or that further development is not warranted for their use in geophysics. Many of the shortcomings of these instruments were intentionally emphasized in order to lay the ground work for the other papers in this publication and future work involving SQUID magnetometers. Efforts at solving the many problems that remain in the geophysical applications of the magnetometers such as the ambiguities in interpretation, greater use of vectors in both survey as well as monitoring applications and in the correction of systematic and non-systematic noise sources should be encouraged and in some cases made possible by the use of SQUID magnetometers supported by computer processing of the data.

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Edited by

HAROLD WEINSTOCK

Office of Naval Research and
Illinois Institute of Technology
Chicago, Illinois

WILLIAM C. OVERTON, Jr.

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

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