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INSTRUMENTATION FOR INDUCTION STUDIES ON LAND*

P.H. SERSON

Division of Geomagnetism, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Ont. (Canada)

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Instruments for recording the natural variations of the geomagnetic and geoelectric fields on land are reviewed, with emphasis on portable equipment suitable for the investigation of anomalies of electromagnetic induction within the earth. Examples of recently designed apparatus are shown, and the fundamental limitations of various types of sensors are discussed.

1. Introduction

This paper is a review of instruments used on land to record magnetic and earth-electric fields for studies of electromagnetic induction in the earth. Induction studies, in the broadest sense of the term, can involve a great range of frequencies, from secular change to the kilohertz frequencies used in electromagnetic prospecting for minerals. The present discussion will be limited to equipment for observing fields of natural origin with primary sources external to the earth.

Fig. 1A illustrates the amplitudes of natural variations in the magnetic horizontal component useful for induction studies. The diagram is intended to represent typical amplitudes of the signals likely to be analysed, rather than a spectrum for a particular station. Different phenomena vary with latitude in different ways; the figure attempts to show a world-wide mean. Some of the variations are always present, while others, such as bays and pulsations, are available only during selected intervals.

Amplitudes rise with increasing frequency from 5 nT** for the annual and semiannual variations, through the 27-day period and its harmonics, to tens of nT for the diurnal variation and its harmonics. At periods of about one hour, bays and the fluctuations associated with moderate magnetic storms give 100 nT more or less. Between one hour and one second, amplitudes decrease roughly in proportion to the period, to 0.1 nT for micropulsations *Pc1*. In the E.L.F.-range, there is some evidence of an increase of amplitude with frequency, but the literature is not unanimous on this point, or on the general level of these signals. The E.L.F. levels shown in Fig. 1 may be an order of magnitude too large.

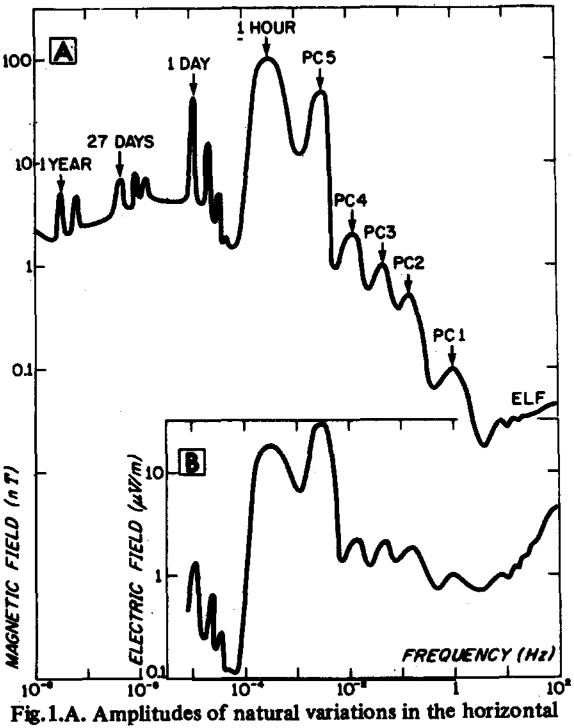

Fig. 1.A. Amplitudes of natural variations in the horizontal geomagnetic field useful in induction research. B. Corresponding amplitudes in the earth-electric field, computed for a model earth of uniform resistivity 20 Ω-m.

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** 1 nanotesla = 1 gamma = 10^{-5} gauss.

Fig. 1A refers to variations in the north component. In general, a similar level of activity is found in the east component, but amplitudes in the vertical component are several times smaller – perhaps ten times smaller at the higher frequencies.

At standard magnetic observatories, the limit of resolution has been 1 nT since the time of Gauss and Weber. Quantitative interpretation of induction effects in records from standard variometers at periods less than 100 s will generally be impossible, not because of limitations of frequency response, but rather because short-period phenomena with sufficient amplitude are too rare to be useful.

It is more difficult to speak of typical earth-current signals; the electric field measured in the earth at the time of a given magnetic variation may range over many orders of magnitude, depending on the local underground conductivity and structure. However, Fig. 1B shows the electric-field amplitudes corresponding to the magnetic signals of Fig. 1A which would be measured, according to the elementary theory of Cagniard (1953), at the surface of an earth of uniform resistivity 20Ω-m. Even this crude model exhibits some of the characteristics of real earth-current records – large amplitudes at periods between one hour and 5 minutes, and a much slower decrease in amplitude between periods of 2 minutes and one second than in the magnetic case. Assuming electrode separations of 100–1000 m, and bearing in mind the great range of ground conductivities which may be encountered, one sees that earth-current equipment for field use should be designed to record signals ranging from microvolts to a volt or more.

2. Systems for recording earth currents

To measure earth currents, or more precisely the potential gradient in a given direction, all that is necessary is a pair of electrodes in contact with the ground, insulated connecting wires, and a suitable recording voltmeter. In spite of the apparent simplicity of the equipment, considerable care is necessary to obtain reliable results. Contact potentials between the electrodes and the ground are large in comparison with the signals to be recorded, and they can change rapidly with temperature and the concentration of the solutions surrounding the electrodes.

For permanent installations, the most common electrode is a large lead plate, or a grid of lead wires, buried at a depth of 2 m, where one hopes the temperature and moisture content will be fairly constant. Contact resistances are of the order of 100 Ω in clay soil and 1000 Ω in rock. Rooney (1939) has pointed out that even with these low electrode resistances, it is necessary to maintain good insulation of the connecting wires (many MΩ), particularly where they pass through the surface of the earth, because it is there that large and rapidly varying potentials may occur.

For temporary installations, non-polarizing electrodes consisting of a copper rod in a porous container filled with a copper sulphate solution, or cadmium in a cadmium chloride solution, are often used. Their contact potential is more predictable, but in time the solution contaminates the soil, and they cannot be properly maintained if they are deeply buried. Good results have been obtained in survey work with steel-cored copper or cadmium-plated rods (of the type used by electricians) driven into the soil.

Early recordings of earth currents were of course made with galvanometers in circuits of rather low impedance compared with the electrode contact resistances. The electrode resistances had to be measured frequently, and corrections applied to the recordings. Nowadays, a great variety of potentiometric recorders and low-noise amplifiers with effectively infinite input impedance are available, and changes in electrode resistance are rarely a problem.

Rapid changes in electrode contact potential still cause trouble. The record drifts off-scale, unless an operator monitors the equipment and adjusts the biassing circuit, or an automatic device is provided to do the same. One solution to this difficulty is to admit that the lowest frequencies cannot be used anyway because of this contamination, and to remove them before recording by means of a high-pass filter (Beblo, 1972).

Trigg (1972) has described a telluric amplifier incorporating active resistance-capacitance filters to remove contact potentials of low frequency and man-made noise of high frequency. The pass band is 10,000 sec to 10 sec, with accurately controlled amplitude and phase characteristics. With modern components and techniques of construction, very large resistance values (over 200 MΩ) can be used to achieve long time-constants without sacrificing reliability under field conditions. A switch is provided to reduce the time-constants by a factor of 100, so that the circuit can be put into operation in about 5 minutes. Another feature of the design is lightning protection. Local thunderstorms can induce voltage spikes of the order of 10 kV in the earth-current lines. Current-limiting resistors at the amplifier input and a special spark-gap device prevent damage to the circuit.

3. Magnetometers

3.1. Suspended magnet systems

Many investigations of electromagnetic induction have been based on the records from permanent magnetic observatories. Several detailed reviews have been published recently describing the classical photographic variometers in use at most permanent observatories (Wiese, 1960; Alldredge, 1967; Laursen and Olsen, 1971). We will not attempt to duplicate these reviews here, but will concentrate on instruments designed for temporary recording stations.

Temporary observatories were used in the early detailed studies of induction anomalies in Germany and Japan, but the equipment consisted of standard observatory variometers, or simplified versions of them, set up in a darkened room. The idea of mounting three variometers in a light-tight box, which could be carried from station to station and quickly set into operation, is an old one. There are two principal difficulties. The first is eliminating the effects of the large variations of temperature to which the apparatus is subjected in the field. The second problem, which is less obvious but of great importance in induction work, is the interaction between the variometer magnets. In a photographic system, the magnets must rotate to produce a record, and the rotation produces a false variation at the other variometers, roughly in proportion to the inverse cube of the distance between the instruments.

It is possible to minimize the three interactions when space is limited by the choice of special geometries (Wiese, 1960). The well-known Askania Variograph, introduced in 1951, however relies on the use of magnets of small magnetic moment with large optical magnification, so that the movements of the magnets are restricted to small angles (± 1.5°).

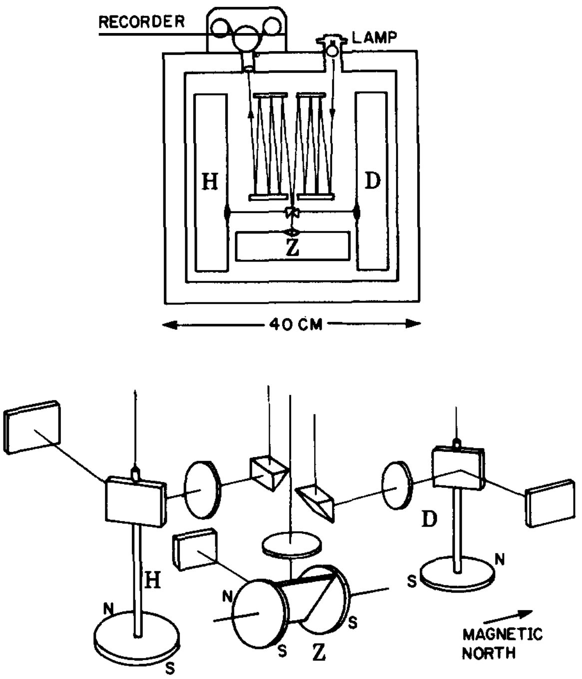

Fig. 2. Askania Variograph.

Fig. 2 shows the design of the Askania Variograph. The case is insulated and electrically thermostatted. A light path of 1.7 m is obtained by multiple reflection between large mirrors. The light beam is reflected twice by the moving mirror, so that its deflection angle is four times that of the magnet. The moving mirrors actually have three surfaces to give reserve traces, and a total range of 1000 nT in H and Z, and 3° in D. Temperature compensation of the H and Z variometers is achieved through the use of suspension fibres of different temperature coefficients (apparently bronze and tungsten in most instruments). The magnets are in the form of discs, 1 cm in diameter. The field produced by the Z system at the D magnet is about 500 nT, and it is compensated by a fixed magnet. Since the cosine of the maximum deflection angle equals 0.9997, interactions between the magnets should be negligible if the magnet axes are properly aligned. Accuracy in alignment is based on a manufacturing technique whereby the angle between the magnet's axis and its mirror is made exactly 45°. Tests carried out at Wingst magnetic observatory indicate that the resulting alignment errors are consistently less than 1° (Meyer, 1954).

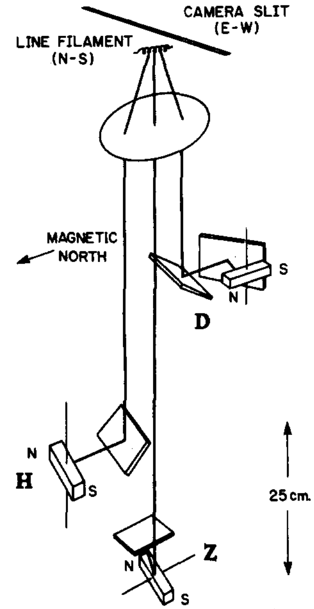

Fig. 3. Three-component magnetometer of Gough and Reitzel.

The main disadvantage of the Askania Variograph is its high cost, and the high cost of repairs. Gough and Reitzel (1967) have designed a three-component photographic variometer which can be built in a university workshop at a much lower cost, with the result that large numbers of instruments can be operated simultaneously in a dense array of stations. The three variometers are arranged in a vertical aluminium tube, which is set into a hole in the ground. This reduces the diurnal variation of temperature to less than 0.1°C at a depth of 1 m, eliminating the need for electrical temperature control. The three moving magnets are supported by taut-wire suspensions, as shown in Fig. 3. Polished and aluminized surfaces on the magnets act as mirrors. Double reflection is used in the *Z* variometer. The recording lamp is switched on briefly every 10 seconds, and the traces appear as a series of dots on the 35 mm photographic film. Not shown in Fig.3 are small auxiliary magnets which are used to vary the sensitivities and to provide a first-order temperature compensation, accurate to 3 or 4 nT/°C.

As originally designed, the vertical spacing between pairs of variometers was 50 cm. At this separation, the steady field at one moving magnet due to another was about 60 nT, and interactions due to deflections of the magnets were negligibly small. Later, some of the instruments were shortened to make them less awkward to handle in the field. With a separation between magnets of 25 cm, interactions became apparent. The most serious was between *H* and *Z*; a real change of 100 nT in *H* produced a false change of 4 nT in *Z*, and corrections must be applied in processing the data.

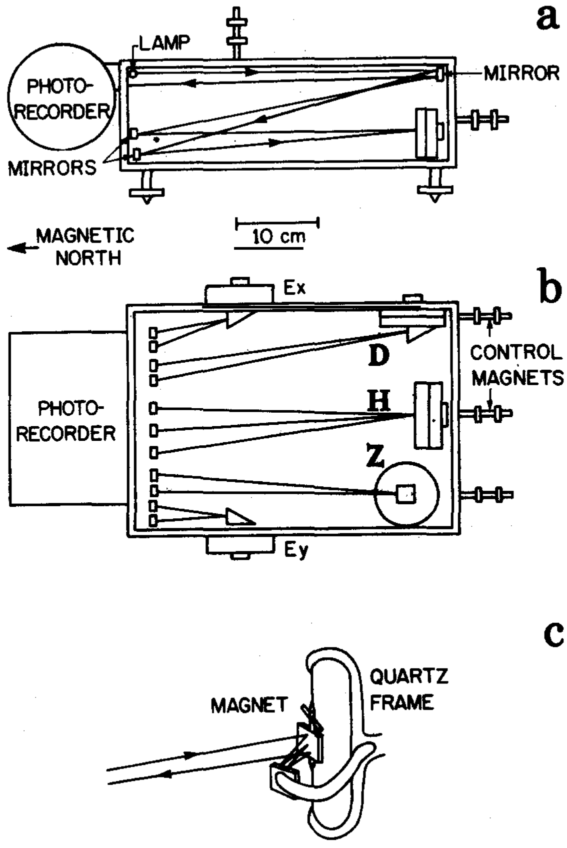

Fig. 4. Bobrov's five-component variation station: (a) side view; (b) top view; (c) detail of quartz magnetometer.

Sensitivities are usually adjusted to give about 10 nT/mm on the 35 mm film. With suitable optical magnification, changes of less than 1 nT can be resolved.

Fig. 4 shows the five-component electromagnetic variation station of Bobrov (1971). It includes two astatic galvanometers for earth currents, recording on the same drum as the *D*, *H* and *Z* variometers. An optical lever of 1 m is obtained by mirrors. The light beam is reflected from the moving mirror 5 times, with the aid of a small mirror fixed close to it, so that the angular deflections are multiplied by a factor 10. All of the parts shown in Fig.4c, with the exception of the magnet, are made of quartz. The magnets are of vicalloy, which has a temperature coefficient less than 10^{-5}/°C. The magnetic moments are so small that even though the spacing of the variometers is only 10 cm, the steady field of one magnet at the next is less than 300 nT. In view of the large optical magnification, interactions should be negligible.

Control magnets are provided outside the case, for reducing the temperature coefficient to zero, and for adjusting baselines and sensitivities. Apparently scale values of 0.2–0.3 nT/mm are often used, which would give 50 nT across the 200-mm drum. Reserve traces are provided by the extra mirrors below the exit slit.

The astatic galvanometers are similar in construction to the variometers. Since they are highly sensitive (10^{-10} A/mm), they can be used in a circuit of high resistance to record earth currents, without need of electronic amplification.

Before proceeding to other types of magnetic sensor, it is interesting to inquire into the limits of resolution attainable with suspended magnets. Is it possible to see a milligamma (10^{-3} nT) at a period of one second? Blackett (1952) has shown that high sensitivity with a short response time can be achieved through the use of very small magnets; a theoretical limitation of resolution is then imposed by thermal agitation of the suspended magnet. From the tables given by Roy (1963), it is easy to design a magnet system, including a mirror of ample area, which at a period of 1 second would have a thermal noise level corresponding to a magnetic signal of $0.2 \cdot 10^{-3}$ nT. However, even with the optical magnification employed by Bobrov, such a system would give a scale value of 10 nT/mm, and small signals could not be resolved on the record. In fact, Bobrov's design appears to be close to the optimum compromise between low thermal noise and high sensitivity with a response time of the order of 1 second.

It is possible to detect small angular deflections photoelectrically, in which case it is advantageous to apply feedback to the suspended magnet by means of a coil. Adam and Major (1967) describe a magnetic variometer based on this principle, which has been used in magnetotelluric surveys in Hungary. The magnet system is immersed in a liquid, which provides protection from mechanical shock and additional damping. The noise level with a bandwidth of 0.4 Hz is less than 0.02 nT.

A photoelectric declinometer employing modulated light sources, designed by Mosnier (1970), has been extensively tested in France. Comparisons of pairs of instruments under field conditions indicate a long-term stability (over several weeks) of 0.1–0.2 nT, and a short-term noise level (over 10 minutes) of 0.01 nT for a bandwidth of 0.2 Hz.

The above performances would seem to represent the practical limit of resolution with suspended magnet sensors under field conditions. Attempts to extend the response to higher frequencies have been disappointing, because of the sensitivity of the apparatus to mechanical vibrations of the ground, due to traffic or wind. We must turn to other types of magnetic sensor for the higher frequencies of interest in induction studies.

3.2. Induction coils

The simplest way of measuring rapid geomagnetic variations is to measure the electrical signal induced in a coil of wire. Since the induced e.m.f. is basically proportional to the rate of change of the magnetic field, coil systems effectively compensate for the decrease in amplitude with increasing frequency of geomagnetic signals, and thus have a distinct advantage in the micropulsation range over sensors which respond directly to the magnetic field. Still, the design of coil systems with adequate resolution is not easy, especially for use in the field.

In the design of portable coil systems, size and weight are critical. It is easily shown that the mass of wire in a circular air-cored coil is proportional to $S^2 a^{-2} R^{-1}$, where S is the sensitivity (in volts per nT per second), a is the radius of the winding and R its resistance. A fundamental limit of resolution is imposed by thermal noise, which equals $1.27 \cdot 10^{-10} (R\Delta f)^{\frac{1}{2}}$ volts r.m.s., where Δf is the bandwidth of the system. To resolve 10^{-3} nT at 1 Hz with a bandwidth of 10 Hz, a coil 1 m in diameter must weigh at least 40 kg in copper, or 20 kg in aluminum.

Such a coil would not be unreasonable for field work, but when one takes into account amplifier noise, even with the remarkable low-noise amplifiers now available, the weight of wire must be increased by a factor of 5 or more. A further design difficulty is that inductance and inter-winding capacitance become important when many turns of fine wire are necessary to match the amplifier characteristics, as is often the case. In spite of these problems, air-cored coils have the advantage that their performance can be predicted accurately, and they can be constructed relatively inexpensively by commercial electrical shops. Typically, the cost is one third wire, one third other materials, and one third labour. Detailed designs of air-cored coil systems have been published by Thellier (1957), Duffus and Shand (1958), Whitham (1960), Lokken (1964), Foster (1965), and Campbell (1969).

Problems of size and weight can be reduced greatly by the use of cores of high permeability. Cores 1–2 m long, with effective permeabilities of the order of 1000, are often used. Here the inductive reactance is usually much larger than the coil resistance at the frequencies of interest, which makes proper matching to the amplifier difficult. Permeable-cored coils must be calibrated carefully and frequently, which is not an easy task with long cores. Ferromagnetic materials are inherently nonlinear, so that the sensitivity can be affected by the ambient geomagnetic field, harmonic distortion of signals may occur, and large magnetic variations of low frequency may modulate the smaller variations of higher frequency. It is difficult to estimate these effects, but they can be determined empirically, together with frequency and phase response. The widespread popularity of cored induction coils suggests that the problems can be overcome (Kato, 1949; Selzer, 1957; Hill and Bostick, 1962).

3.3. Fluxgate magnetometers

The fluxgate sensor makes use of the nonlinear properties of ferromagnetic cores to modulate the magnetic induction, so that a signal is induced in a pickup coil at a frequency of the order of a kilohertz. In geomagnetic measurements the device is almost always employed as a null detector; that is, the magnetic field at the fluxgate is reduced to a small fraction of 1 nT by strong feedback, and the current fed back constitutes the output of the instrument.

Early fluxgate magnetometers had a poor reputation because of noise, drift, and sensitivity to temperature, but many of their shortcomings should be blamed on the associated electronics rather than on the sensor. With solid-state techniques it is now possible to ensure low circuit noise, pure waveform of the excitation current, and stable currents for biasing the sensors. In a well-designed instrument, the limits of resolution are determined by noise generated in the ferromagnetic cores. It is convenient to divide this noise into short-term noise, long-term noise, and reversible temperature effects.

The short-term noise is in practice much larger than would be predicted from considerations of thermal agitation or Barkhausen noise. A recent investigation by Scouten (1972) indicates that the source of the problem lies in the fact that it is impossible for the excitation field to saturate the core material completely. Small volumes of the core behave differently in successive cycles of excitation, producing uncertainties in the flux when the cores are nominally saturated.

Trigg et al. (1971) describe a three-component fluxgate magnetometer employing sensors of conventional design (two parallel rods excited in opposition), which has seen wide use in induction studies. The short-term noise of this mass-produced instrument is of the order of 0.05 nT in a period bandwidth of 5 sec to 500 sec. It is more difficult to describe the long-term noise, which is in the form of abrupt changes in the output, of the order of 1 nT, which may occur at intervals of hours or even days. The origin of these shifts is not well understood, but they tend to occur when the temperature of the sensor changes. Over a month, an offset as large as 10 nT may accumulate. Reversible temperature effects with these sensors are consistently below 1 nT/°C.

In recent years, fluxgates using a core in the shape of a closed ring with a toroidal winding have been developed for space research (Gordon and Brown, 1972). With a short-term noise level of 0.05 nT in a bandwidth of 1 Hz, the ring-core sensor has a small advantage over the conventional type. However, the long-term noise is greatly reduced (± 0.05 nT in 24 h), as is the temperature sensitivity (0.1 nT over a total range of –40°C to +70°C).

There are two additional temperature effects in a complete magnetometer which are important under field conditions. The first is the change with temperature of the dimensions of the coil or solenoid used to cancel a constant part of the geomagnetic field. In the design of Trigg et al. (1971), the source of bias current is controlled by a platinum resistance thermometer in the magnetometer head to compensate for this effect, which otherwise would amount to 3 nT/°C in the largest component. Temperature changes can also produce changes in the orientation of the sensor axes, for example, when the fluxgate head is heated asymmetrically by exposure to sunlight. A tilt of 1′ can produce a false signal of 10–20 nT. Recent practice is to mount the fluxgate head underground, whenever possible, in a plastic garbage can which is then covered over with earth. Burial in snow is also effective. Under conditions of extreme cold, the electronics, recorder, and dry batteries are operated together in a well-insulated aluminum case. The heat generated by the batteries and electronics is enough to maintain the recording meter (and batteries) above the freezing point.

3.4. *Resonance magnetometers*

Proton precession magnetometers and optically-pumped magnetometers employing rubidium, caesium, or helium are basically total-intensity measuring devices. As such they are not very useful in induction work, except perhaps near the equator where they measure the horizontal component, or near the poles where they measure the vertical. Even then, knowledge of the other components of the variation field is generally necessary for quantitative interpretation. However these instruments have the advantages of high sensitivity, the absence of drift and temperature effects, and an output in the form of a frequency which is naturally suited to digital recording. They have therefore been adapted to the measurement of the components of the geomagnetic field, but they do not adapt easily.

Two basic methods have been used to measure components with a total-intensity magnetometer. The first method is to apply a constant artificial field in a known direction, so that the vector resultant at the sensor is the desired component (Nelson, 1958; Hurwitz and Nelson, 1960).

A question of some importance in induction work is what happens when the component being cancelled departs from its normal value. Suppose that the vertical component Z is opposed by a constant field Z_0 in order to record the horizontal component H. The resultant R measured by the total-field sensor is given by:

$$R^2 = H^2 + (Z - Z_0)^2 = (H + \Delta H)^2$$

where ΔH is the error in the computed value of H.

$$\Delta H \approx (Z - Z_0)^2/2H$$

The error is thus proportional to the square of the variation in Z, and is analogous to the cosine-type error of interacting magnets discussed in section 3.1. It is is always of the same sign, and can become quite large when one attempts to record a small component of the geomagnetic field. To record the east component, for instance, it is necessary to add an additional bias field in the east direction. When three components are recorded simultaneously, it is possible to make the appropriate corrections by computer.

The requirement for three separate sensors, and a large separation between coil systems to avoid errors from stray fields, makes the system awkward for field work. However, the low noise level of modern resonance sensors – for example, 0.001 nT in a bandwidth of 0.2 Hz (Usher and Stuart, 1970) – and the possibility of covering a great range of frequency with one type of instrument make this approach to geomagnetic recording attractive (Stuart et al., 1972).

The other approach to measuring magnetic components with a scalar sensor is to apply a succession of bias fields to a single total intensity magnetometer. To measure the component P in an arbitrary direction, where P, Q, R are orthogonal components of the geomagnetic field, one first measures the total intensity F. Then an artificial field A is applied in the direction of the component P, by applying a direct current to a coil system, and the new resultant field F_1 is measured. Then the current in the coil is reversed, giving an artificial field $-A$, and the resultant F_2 is measured. From the three readings, one can calculate both the magnitude of A and the component P, as shown below. The procedure is repeated with a different bias coil to obtain a second component Q, and the third component R can of course be calculated.

$$F^2 = P^2 + Q^2 + R^2$$

$$F_1^2 = (P + A)^2 + Q^2 + R^2$$

$$F_2^2 = (P - A)^2 + Q^2 + R^2$$

$$A^2 = \tfrac{1}{2}(F_1^2 + F_2^2) - F^2$$

$$P = (F_1^2 - F_2^2)/4A$$

Thus far, we have assumed that the geomagnetic field remains steady while the measurements are being made. What does the calculation give if P changes to P_1 and then P_2 during the measurement?

$$F^2 = P^2 + Q^2 + R^2$$

$$F_1^2 = (P_1 + A)^2 + Q_1^2 + R_1^2$$

$$F_2^2 = (P_2 - A)^2 + Q_2^2 + R_2^2$$

$$(F_1^2 - F_2^2)/4A \approx \tfrac{1}{2}(P_1 + P_2) + \frac{P}{2A}(P_1 - P_2) + \frac{Q}{2A}(Q_1 - Q_2) + \frac{R}{2A}(R_1 - R_2)$$

The standard calculation gives the mean of P_1 and P_2 plus three error terms proportional to the changes occurring in the various components. In practice, the coefficient of at least one of the error terms will be larger than unity. If the sequence of measurements requires several seconds, and the geomagnetic field is changing at the rate of 1 nT per second, errors of many nT may result. Errors of this sort cannot be corrected in the computer, because the method gives insufficient information concerning the short-period behaviour of the field. The result is that even though the cycle of measurements can be repeated at intervals of say 10 seconds, the computed data will contain high-frequency noise, which limits the useful resolution to periods of perhaps 1 minute.

Nevertheless, this method of measuring magnetic components has been most succesful in induction research. The Cambridge University instruments, described by Everett and Hyndman (1967), use a proton magnetometer as the sensor, and spherical coils to produce artificial fields of high homogeneity.

4. Recording techniques and integrated systems

With the exception of the photographic variometers, all the above instruments produce an output in the form of an electrical signal, a voltage, a current, or a frequency, which must be recorded in either analog or digital form. For induction work, analog methods have many advantages. The equipment is simpler, and it is easier to monitor the recording in the field, and to select interesting events for analysis. The main problem in anolog recording is the great dynamic range of geomagnetic variations; it is difficult to maintain adequate resolution of small signals without risk of losing the record because of saturation during intervals of high activity. With digital recording techniques, the provision of sufficient dynamic range is easy, and the labour-saving advantages of being able to enter field data directly into the computer are obvious. Factors which have delayed the adoption of digital recording in induction research are high cost, large power requirements, and the general unsuitability of available equipment for use in the field. The situation is changing rapidly. Reliable compact digital systems suitable for battery operation have been introduced recently, and the prices, although still high, are decreasing. An important consideration in any decision to adopt purely digital recording is the cost of computer time. Even with careful planning, computing costs for just the preliminary processing of the data can exceed the costs of field operations and instrumentation.

An important technique often used in induction work, to overcome the dynamic range problem in analog recording or to reduce computing costs in the case of digital recording, is to separate the spectrum to be covered into two or more overlapping bands, by means of filters, and to record the bands separately. This approach, with analog recording, was used by Caner and Auld (1968), in a broad-band magnetotelluric study at Victoria magnetic observatory. Both magnetic and telluric signals were recorded in three overlapping bands: 1–50 sec, 20–500 sec, and 400 sec–d.c. The same telluric electrodes were used over the entire frequency range, but three distinct magnetic sensors were used in the three bands: air-cored induction coils, fluxgate magnetometers, and the standard observatory photographic variometers.

Vozoff (1972) describes a digitally recording magnetotelluric system, employing permalloy-cored induction coils, which records in three bands: 0.13–10 sec, 2–100 sec and 40–500 sec. The sampling intervals in the three bands are respectively 0.03, 0.5 and 10 sec. It should be noted that it is not necessary to record in the three bands simultaneously. After sufficient data have been obtained in one band, the filters and sampling interval can be switched to the next band.

This review will be concluded with a short description of the portable wide-band equipment of Caner and Dragert (1972). This was designed to provide magnetic and telluric data for quantitative interpretation over the period range $10-10^5$ seconds, with special attention to the problem of obtaining useful signals in the vertical compont at short periods. Over a large region of western North America, variations in Z are attenuated to about one tenth of the 'normal' amplitude at periods of 1000 sec, but periods longer than an hour or two suffer no attenuation. Thus an especially wide dynamic range is required.

The system is designed to be used either with a seven-track slow-speed frequency-modulated tape recorder of the type employed in seismic research, or with a seven-track scratch recorder – a recording galvanometer which scratches a record on opaque 35 mm film. When only magnetic signals are required, the entire range of periods can be recorded at once. The output of a three-component fluxgate magnetometer (Trigg et al., 1971) is recorded, in two frequency bands. Band A (d.c.–200 sec) is recorded at a full-scale range of 200 nT, but the effective range is increased to 1600 nT by including scale expanders (Trigg, 1970) in the circuit. These devices automatically add or substract an increment of 100 nT when ever the input to the tape recorder exceeds preset limits. Band B (500–5 sec) can be recorded at a higher sensitivity (e.g., 10 nT full-scale), because band-pass filters remove the large-amplitude fluctuations of low frequency.

In magnetotelluric work, the requirement for five data channels limits recording, at any one time, to either the long-period band or the short-period band. The earth-current circuits employ the same type of scale expanders and band-pass filters as the magnetometers.

The electronic equipment, including a time-signal receiver and quartz clock, is mounted in a waterproof transit case giving good thermal and mechanical protection. When the magnetic tape recorder is used, the system will operate unattended from automobile-type batteries for five days. The scratch recorder has significant advantages in reliability and recording capacity, with equivalent dynamic range and resolution to the tape recorder, but its large power consumption (30 watts) prohibits operation from batteries.

Caner and Dragert (1972) show examples of recordings made with this system indicating that it permits the resolution of short-period magnetic signals as small as 0.2 nT peak to peak, while at the same time providing a useful record of long-period variations of several hundred nT.

5. The future

Limitations of space have restricted this survey to types of instruments which have already been used in induction studies. In conclusion, several new kinds of magnetometer which promise to be useful in this field will be mentioned briefly.

Thin-film magnetometers (Irons and Schwee, 1972) differ from the fluxgates of section 3.3 in that their operation depends on the magnetic anisotropy of a thin ferromagnetic layer deposited in the presence of a magnetic field. They offer the advantages of small size, low power consumption, and very wide bandwidth (100 MHz). At present, they would appear to have no advantage over fluxgates in resolution at frequencies below 1 Hz, but long-term stability is being improved.

A vector rubidium magnetometer (Fairweather and Usher, 1972) permits the recording of three components without the use of bias fields. The direction of the geomagnetic vector is determined from the relative phases of modulation of two perpendicular light beams passing through a single rubidium vapour cell. The total intensity is provided by the frequency of self-oscillation. The resolution, for a bandwidth of 1 Hz, is 0.1 nT in the field direction and 0.01 nT in the magnitude.

Finally, superconducting quantum magnetometers with a resolution of 10^{-5} nT (Webb, 1972) should make possible the recording of time variations in the horizontal and vertical gradients of the magnetic field. Sufficiently sensitive measurements of such gradients may prove useful in the interpretation of anomalies of electromagnetic induction (Schmucker, 1973).

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