Everyman's Magnetometer

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Introduction

The proton magnetometer is an instrument of great value to prehistoric archaeologists particularly in its ability to locate buried nonmetallic cultural features such as hearths, burned floors, trash pits, burials, etc. Moreover, it is highly sensitive to the presence of iron making it quite useful in detecting features at historic sites as well. While the magnetometer is by no means foolproof, it can greatly assist the archaeologist in locating those areas within a site which are most likely to produce useful data. Hence, it serves to help maximize the amount of relevant information recovered per unit of dirt moved. The advantages of such increased efficiency should be self-evident particularly at a time when archaeologists are commonly faced with the dilemma of having to accomplish specific research objectives within the constraints of very limited budgets and restricted field schedules.

In view of its wide capabilities, it is clear that the magnetometer has not been employed nearly as often as its utility would warrant particularly in areas such as the eastern United States. The reasons for this shortcoming have been manifold. For one thing, the prices of commercially available magnetometers have been prohibitive, generally in the range of $2000-$3000 and up. These commercial instruments offer a very high sensitivity coupled with a digital readout that allows the user to make a "magnetic map" of the site being investigated. The electronic complexity required to produce such an accurate quantitative output is considerable, hence the high price of the instruments. Much recent literature has dwelt on the use of these digital devices and on the formulation of highly sophisticated techniques (usually involving computer analysis) by which magnetic survey data can be more accurately interpreted (e.g., Linington 1970 and Scollar 1970). Such developments have certainly provided us with some powerful research tools, but these are tools which few archaeologists can afford, not only in terms of equipment cost, but also in technical expertise.

It is unfortunate that the recent literature's preoccupation with expensive hardware has tended to obscure the fact that a much simpler device--the differential proton magnetometer (or proton gradiometer, as it is sometimes called)--is adequate in most applications. The unit's simplicity and very low cost are achieved by making the output non-quantitative--it detects archaeological features by means of a qualitative change in the tone of an audio signal which is monitored by the operator on a set of headphones. The device is light in weight, fully portable, and can easily be operated by a single individual. It is a bit less sensitive than its highly sophisticated cousins and cannot be used to accurately map the configuration of buried features. It can, however, locate such features just as effectively as its more expensive counterparts and can cover a given area of ground much more rapidly.

Differential proton magnetometers like the one described above are not available commercially, yet it is not difficult to build one at a materials cost of less than $70. The rest of this paper will be devoted to a description of how to construct and operate such a device, which has been tested in a field situation and shown to be reliable and highly effective. In making available these plans, it is our hope that more of our colleagues will now find it within their means to acquire this useful instrument and apply it in their research.

Basic Principles

Before we embark upon the presentation of our instrument's design, it is appropriate that the reader become acquainted with the basic principles by which the differential proton magnetometer operates. The discussion here will be deliberately brief and non-technical. A more comprehensive treatment of the subject can be found elsewhere (Aitken 1961: 7-59).

Magnetic anomalies. Essentially, the differential magnetometer is a device that reacts to minute changes in the earth's magnetic field. Its effectiveness as a detector stems from the fact that certain types of buried remains can, in their immediate vicinity, slightly affect the intensity of the earth's field. These small, localized variations in intensity are called magnetic anomalies. Anomalies strong enough to be picked up by the differential magnetometer are usually caused by one or more of the following kinds of cultural remains:

I) Iron or other ferrous metals.

II) Burned features such as hearths, houses, kilns, etc.; also concentrations of ash, daub, or other baked clay objects.

III) Features which are characterized by midden soil intruding into a matrix of lesser organic content, or vice versa. Specifically, these can take the form of midden-filled pits or wall trenches, or in the opposite situation, accumulations of sterile earth or stone imbedded in a deposit of midden (e.g., walls or foundations).

Of all these categories, the magnetometer is by far the most sensitive to iron. A barbed wire fence, for example, can easily be picked up from as much as five feet away. At the same time, it is important to realize that the instrument is very selective in this respect: the magnetometer does not react to non-ferrous metals.

The anomalies caused by nonmetallic features are usually substantially weaker than those caused by iron. Burned areas are readily detectable due to the property of thermo-remanent magnetism. Detection of features in the third category, however, and of concentrations of daub and ash is a considerably more uncertain proposition. Such anomalies are caused by the juxtaposition of soils with highly contrasting magnetic properties. The degree to which such features are detectable depends not only on their size and their depth, but also on their physical structure, and (most importantly) on the magnetic properties of the soils involved. In general, the strength of such an anomaly is directly related to the degree of contrast between the organic content of the feature itself and that of the surrounding matrix. Thus, for example, a large, midden-filled pit lying in a matrix of subsoil would amost certainly be detected, while a midden-filled pit in a matrix of midden would probably be missed. Ash and burned clay (apart from its thermo-remanent magnetism) also have magnetic properties that contrast markedly from those of sterile subsoil.

Detection. The basic element of all proton magnetometers is the detector coil which consists of a coil of wire wrapped around a plastic bottle or some other suitable container. The bottle is filled with distilled water or some other fluid rich in hydrogen nuclei--i.e., protons.

In order to understand how the detector coil operates, we must first briefly discuss the physical principle of proton free precession. This principle refers to the fact that protons under the influence of the earth's magnetic field precess around an axis parallel to that field. This precession is exactly analogous to the slow gyration of a spinning top. In the case of protons, the frequency of gyration (i.e., the number of gyrations per second) is directly related to the intensity of the earth's magnetic field. The stronger the field, the higher the frequency of precession.

Each proton can in essence be visualized as a small bar magnet. As each one precesses, its tiny magnetic field is capable of generating an infinitesimally small voltage in the surrounding coil. Under normal circumstances, all the protons in the bottle precess at the same rate, yet because their gyrations are out of phase with respect to each other, their individual effects interfere in such a way as to produce no net voltage in the coil. In order for the effects of this precession to be measurable, the protons must be made to act in phase so that the miniscule voltages induced by the individual protons add together rather than cancel out.

It is for this reason that the protons must be subjected to a strong polarizing field before each measurement. An electric current (approximately one ampere) is passed through the coil setting up a strong magnetic field within the bottle. Because this field is much more intense than that of the earth, the protons become aligned along its lines of force. When the current in the coil is abruptly cut off, the protons cease to be constrained by the polarizing field and once again begin to precess around the earth's magnetic field. Having initially been polarized, the protons gyrate in phase, and a small, yet appreciable signal is induced in the detector coil having an amplitude on the order of a millionth of a volt. The frequency of this signal is equal to the frequency of proton precession and hence is proportional to the local intensity of the earth's magnetic field.

Once the influence of the polarizing current has disappeared, however, the protons do not remain in phase for long. Various internal effects cause the phase coherence of the protons to gradually die out and disappear. As a consequence, the induced signal also "decays" and slowly decreases to zero. The time it takes for the signal to disappear entirely is comparable to a value termed the <u>relaxation time</u>. Relaxation time varies from one fluid to the next, being about three seconds for distilled water. When the protons get out of phase, they must once again be polarized before another measurement can be made.

The differential proton magnetometer to be described in this paper basically consists of nothing more than two detector coils, a switching circuit, a high-gain amplifier, and a set of headphones. The two coils are mounted at either end of a six foot long horizontal staff, and the circuitry is mounted in between (Figure 1). The switching circuit controls the timing in a cycle whereby a three second <u>polarization period</u> continually alternates with a three second <u>precession period</u>. A polarizing field is applied to both bottles simultaneously and then is cut off, allowing the protons to precess and causing a precession signal to be induced in each of the coils. These signals are added together and then amplified so that they can be heard through the headphones.

If an area being tested has a constant magnetic field, then the precession frequency induced in each of the coils is the same. When the two identical signals are added together, the operator hears a steady tone which gradually decreases in amplitude as the protons get out of phase and disappears within three seconds.

In the presence of an anomaly, however, a totally different kind of tone is heard. Because the magnetic field at each coil is not the same, the protons in each precess at different rates, and signals of different frequency are produced. As these signals are added together, they interfere with each other: the operator hears a wavering tone, increasing and decreasing in amplitude until it finally dies out. The peaks in amplitude are called <u>beats</u>, and the rate at which they occur is called the <u>beat frequency</u>. The beat frequency is equal to the difference between the two signal frequencies. Clearly, then, the beat frequency is directly related to the degree of difference between the magnetic field intensities at each of the two coils. Restating this somewhat, the more beats that are heard per unit time, the stronger is the magnetic anomaly causing them.

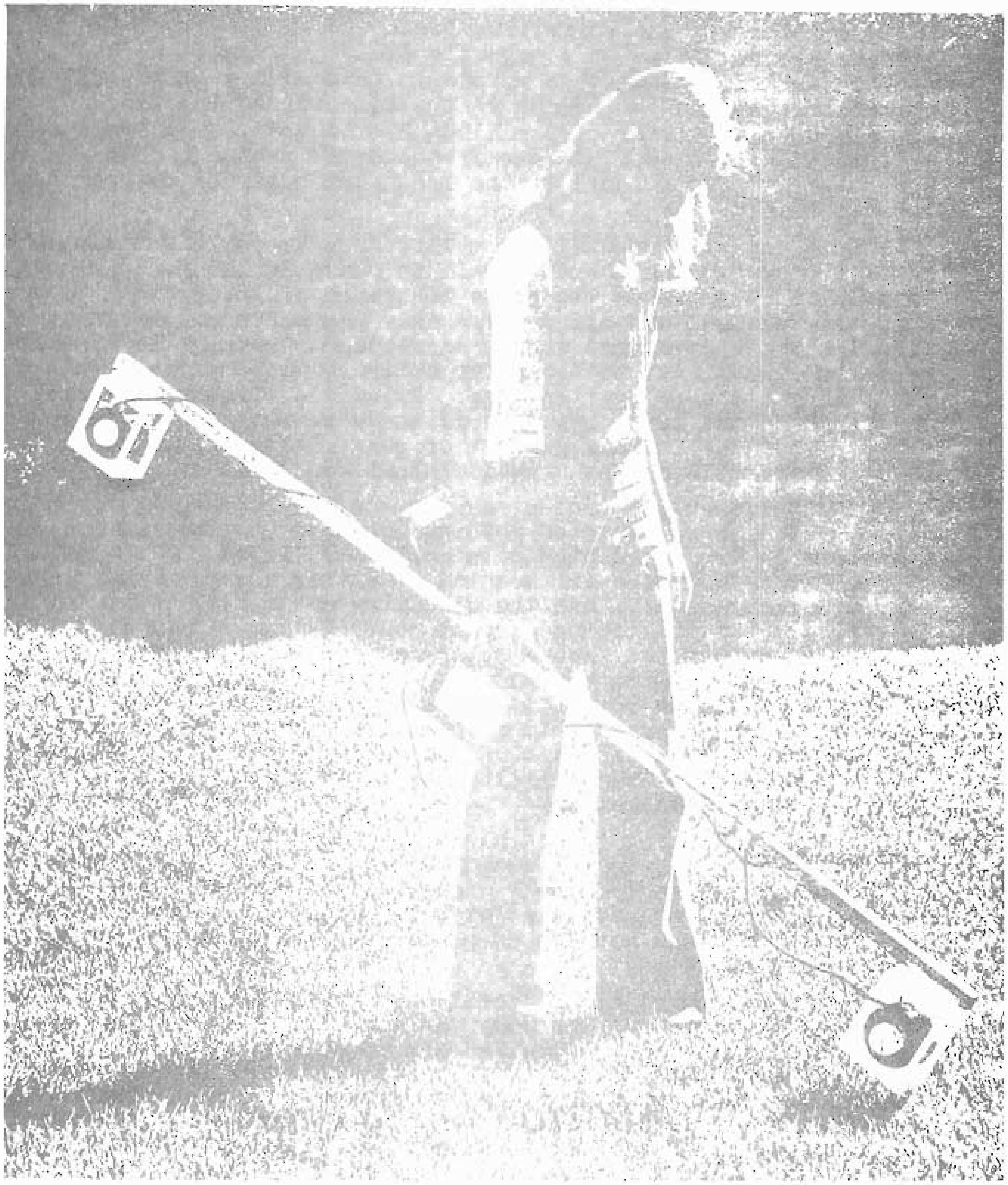

Figure 1. The Portable Magnetometer

Construction

The design presented here is new. Its development was undertaken for the simple reason that other designs we found in the literature were inadequate for our purposes. Some designs were not described in enough detail; others specified components which were either outdated or not available in this country. The instrument described below is comparable in effectiveness to those previously published. It incorporates various aspects of these other designs, but is put together of components more readily available. Particularly valuable as sources of basic design ideas were articles by Aitken (1961: 52-58) and Harknett (1969).

Circuitry. The circuitry in this unit is not especially complicated and can easily be assembled by any competent electronics technician or even by a reasonably proficient hobbyist. The schematic diagram and technical description is presented in the Appendix.

The construction of this circuit is reasonably straightforward, but a few constraints are recommended. Ceramic capacitors should not be used, as they tend to be highly microphonic. Components made of ferrous metal should also be avoided if at all possible. The latter is not to be taken as an absolute restriction, however, because the circuitry is mounted in a position equidistant from the two detector coils where very small amounts of iron will not significantly affect the instrument's performance. Aluminum sockets should be used for the cables leading to the coils.

The headphone used with this unit is a standard crystal headset. In order to prevent oscillation in the output, the wires leading to the headset should either be encased in a grounded shielding braid or be replaced with a coaxial cable.

The completed circuit can be accomodated in an aluminum minibox. Mounted externally on the minibox should be: 2 aluminum coaxial cable sockets (one of which must be floated, i.e., insulated from the minibox itself), a plug for the headset jack, a volume control (R15), a plug for the cable that leads to the batteries, and (if desired) a variable tuning capacitor (C1). The circuit diagram does not incorporate an on-off switch necessitating that the battery be mechanically disconnected when the unit is not in use. There is, of course, nothing that precludes the builder from installing such a switch if it is found to be more convenient.

Detector coils. As long as the electronic properties of the detector coils fall within reasonable bounds, the actual details of construction are for the most part quite flexible. There are two critical conditions, however, that must be taken into account. One is that the coils be waterproof. Even small amounts of moisture in the windings of a coil can serve to destroy its sensitivity. Second, there must be no ferrous metal anywhere in the immediate vicinity of the detectors. If bolts are to be used in construction or mounting, both aluminum and plastics are suitable. Brass should be avoided as it may sometimes contain ferrous impurities.

The coils used in our prototype model were constructed in the following manner: The core consisted of a six ounce polythene bottle 1.85 inches in diameter (available from any chemists' supplier). Two plexiglass endplates (4"x6"x3/8") were machined with holes of the same diameter as the bottle. These endplates were then slid onto the bottle and cemented in place, 2" apart. The coil itself was pile wound (layer winding is not necessary) with 3 pounds (945 feet, approximately 1300-1400 turns) of #20 AWG enamelled copper wire. The leads of the coil were soldered to a coaxial cable which passed in snugly through a hole drilled in one of the endplates. The coil was then entirely boxed in with plexiglass, the pieces being attached with cement (Figure 2). All seams and cracks were sealed to make the coil fully waterproof. Finally, an additional piece of 3/8" plexiglass was cemented to the top of the coil assembly. Into this piece were drilled two holes which were then tapped to receive the aluminum bolts which secured the coil assembly to the frame.

Both coils should be made identically--that is, they should be wound in the same direction and their ends should be attached to the coaxial cable in the same order. This is important because the wiring of the coaxial cable sockets, as shown in the schematic diagram, is such that the coils, when plugged into the circuit, are connected electrically in opposition to each other. The advantage of this arrangement is that it serves to minimize external interference by causing most of the ambient electromagnetic pickup to cancel out.

One other consideration deals with the coaxial cables which connect the coils to the circuit box. Normal cable suffers from electrostatic microphony so that even a blade of grass rubbing up against it can cause an undesirable crackle in the earphones. This problem can be remedied either by enclosing the cables in the frame to protect them from mechanical disturbance or by using a special low-noise graphited cable that largely overcomes the unwanted effect.

<u>Final assembly</u>. The final assembly involves mounting the circuit box and both coils to the frame. There are, of course, innumerable ways in which this can be done. The distance between the coils is not critical and can vary anywhere from five to ten feet. Similarly, the batteries can be carried separately, or they can be attached to the frame. The frame itself can be constructed of aluminum, wood, or plastic, but it should not be made of ferrous metal. Moreover, the coils must be oriented so that their axes are perpendicular to that of the frame.

Given these constraints, our prototype (see Figure 1) was constructed in the following manner. The frame consisted of a six foot long hollow aluminum rod, one inch square in cross section. The coils were positioned at either end of this rod with the capped end of each bottle pointing in the same direction perpendicular to the rod. Each coil was mounted with two

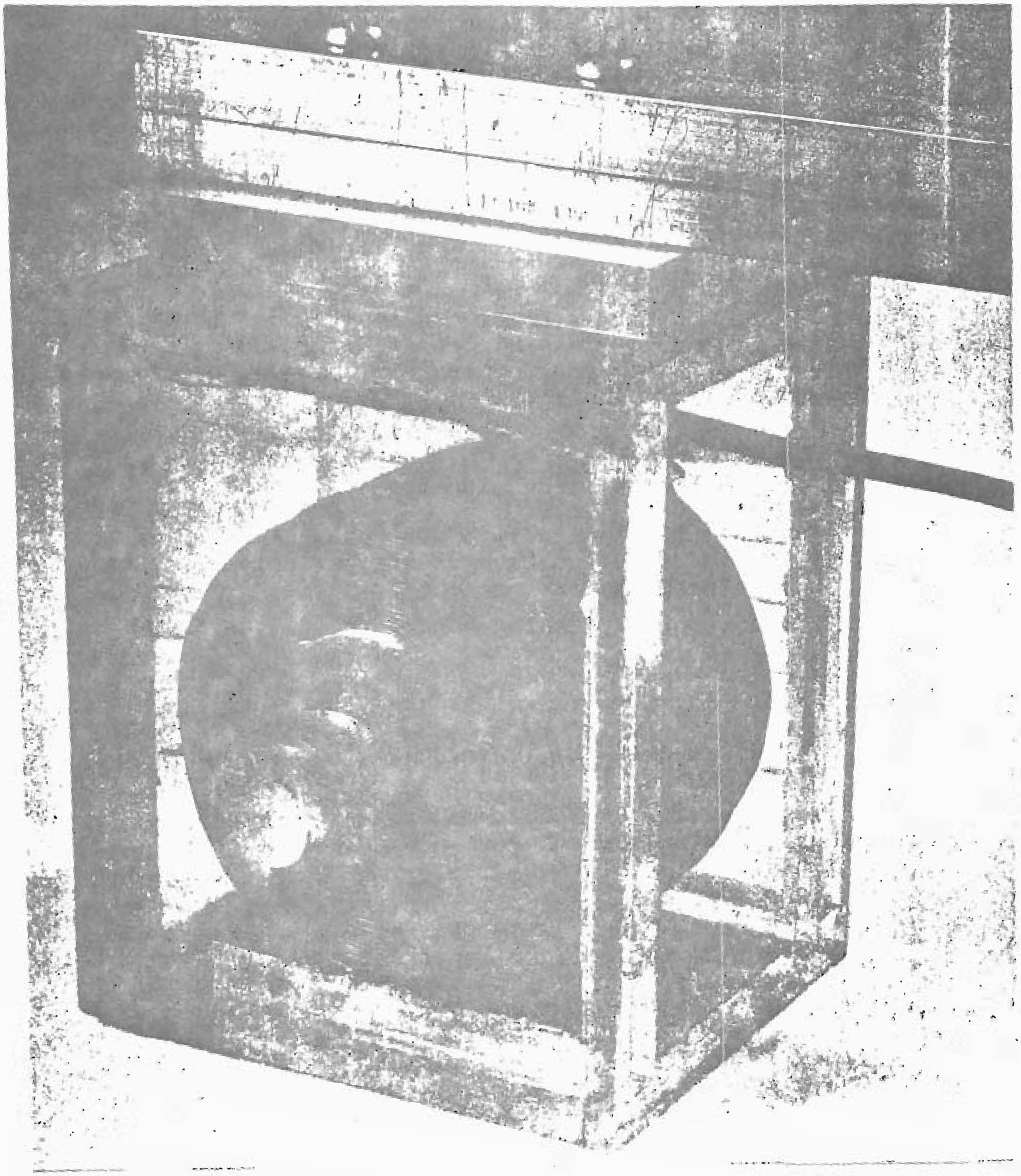

Fig. 2. Close-up of boxed detector coil. (Photo by Hillel Burger)

aluminum bolts which passed down through the rod and into the tapped holes in the top of the plexiglass coil assembly. The circuit box was attached with aluminum brackets directly below the center of the frame leaving enough space between the rod and the top of the box to allow one to use the center of the rod as a hand-grip. The batteries were secured to a belt around the operator's waist. Two conventional six-volt lantern batteries were used, connected in series. In order to prevent false readings, we found it absolutely necessary to remove the batteries metal casings. This task was easily accomplished with a can opener and a pair of pliers.

Operation

Tuning. Before the magnetometer can be operated effectively, it must be tuned to the expected frequency of proton precession which varies with geographical location. This frequency can be derived from the formula:

$$F_p = (4257.6)(M)$$

where: F_p is the proton precession frequency, and

M is the total intensity of the earth's magnetic field in c.g.s. units at the geographical region being investigated (see Appendix).

The appropriate value for the tuning capacitor (C1) is then derived as follows:

$$C = \frac{1}{(39.5)(L)(F_p)^2}$$

where: C is the value of the tuning capacitor (C1) in farads, and

L is the combined inductance of the detector coils (twice the value of a single coil) in henrys.

Each of the detector coils in our prototype magnetometer has an induction of .075 henrys when filled with water. It is highly recommended that the builder empirically measure the value of L for his coils, for variations can be expected to occur due to differences in construction.

Because of the low Q of the coil circuit, precise tuning is not critical. Thus, the instrument can be used over a fairly large geographical area with a fixed value for C1. If, however, it is anticipated that the instrument will be employed in several widely separated areas, then it may be preferable to install a variable capacitor instead.

Field operation. Once the magnetometer has been tuned, it is ready to be used in the field. This instrument can be expected to perform well in a wide variety of circumstances except that it will not work effectively in urban areas or in the immediate vicinity of power lines.

When the magnetometer is operating normally, a three second polarization period continually alternates with a three second precession period. During the former, the operator hears nothing in the headphones. During the latter, a sound is heard which can be divided into two components. The first of these is a crackling and whooshing static that remains at a constant level throughout the period. This static is merely electrical "noise" and should be entirely disregarded. The second component consists of a much purer tone which starts out at a fairly high amplitude but gradually diminishes (in about 2.5 seconds) to a point where it can no longer be heard above the noise. This tone is the proton precession signal. With a bit of practice, the operator's ear becomes attuned to the proton signal and easily sorts it out from the background noise.

A steady decline in the proton signal's amplitude indicates a constant magnetic field, while a wavering decline or a series of "beats" indicates the presence of an anomaly. The strength of the anomaly is proportional to the number of beats heard: the more beats, the stronger the anomaly. One exception is that in the presence of an extremely strong anomaly (almost invariably one caused by iron) the proton signal disappears almost immediately, being referred to as a "killed signal."(Aitken 1961: 46; 1970: 687).

Unlike some other comparable instruments, the one described here is designed to be held horizontally rather than vertically (see Figure 1). Maintaining it in this position is much less fatiguing to the operator. It must be kept in mind, however, that an anomaly can be picked up by either of the two detector coils. In practice, it is more often than not readily apparent which coil is actually doing the detecting, but it is nonetheless important that one be very careful in making certain, for attributing an anomaly to the wrong coil can lead to an error in location of six feet (or more, if the separation between the coils is larger). Whenever any doubt arises as to the actual location, the confusion can almost always be resolved by approaching the locus in question from a different direction. In searching for weak anomalies, or in trying to pinpoint the center of a large one, it is often helpful to keep the forward coil tilted closer to the ground causing it to pick up the anomaly readings more strongly.

If the procedures outlined above are followed and special attention paid to the strictures of construction and operation that we have stressed, then a sensitive operator and experience should produce outstanding results with this modest instrument. We wish you luck!

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Appendix. Circuit Description

The schematic diagram presented here dupicates exactly the circuitry in our prototype unit. We are well aware that it can be improved in a number of ways; yet, because we have not had the chance to test these improvements ourselves and show them to be effective, we have decided not to include them in the present paper. Our design as it appears here may seem inelegant to some, but at least we can be certain that it works.

Switching circuit. Q9 and Q10 form a stable multivibrator controlling the "on" or "off" state of Q8. The duration of each half-cycle is determined by the time constants R32*C20 and R33*C21 respectively; both in this case are approximately 3 seconds. Q7 (turned "on" and "off" by Q8) drives the power transistor Q6. Q6 supplies the polarizing current to the detector coils L1 and L2. R25 absorbs the energy of the inductive surge which occurs when the polarizing current is turned off.

Amplification. C1 forms a parallel tuned circuit with the detector coils L1 and L2, adjusted to resonate in the vicinity of the proton precession frequency. Q1 and Q2 form a low-noise high-gain preamplifier, capacitatively coupled to the op-amp Z1. R15 acts as a volume control by varying the amplitude of the signal passing from Z1 to the high-gain output amplifier Q3.

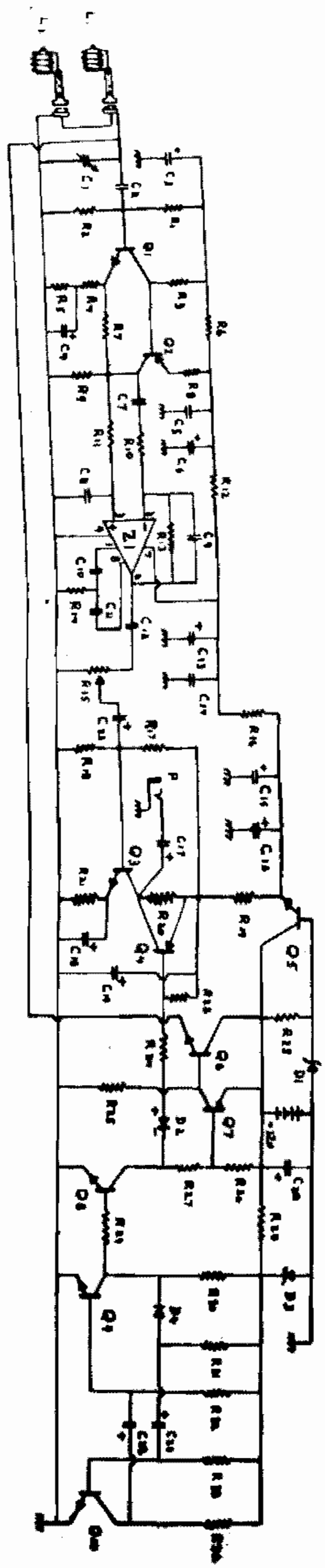
Q5, D1, and R23 form a voltage regulator which maintains a steady 6 volt supply to the amplifier.

Q4 acts to switch off the earphones during the polarization period. When Q8 is on, D2 is forward biased, and Q4 is switched on, shorting out R20 and preventing a signal from being passed to the earphones. During the precession period, Q8 is off, D2 is reverse biased, and Q4 is off and effectively out of the circuit.[1]

Part list:

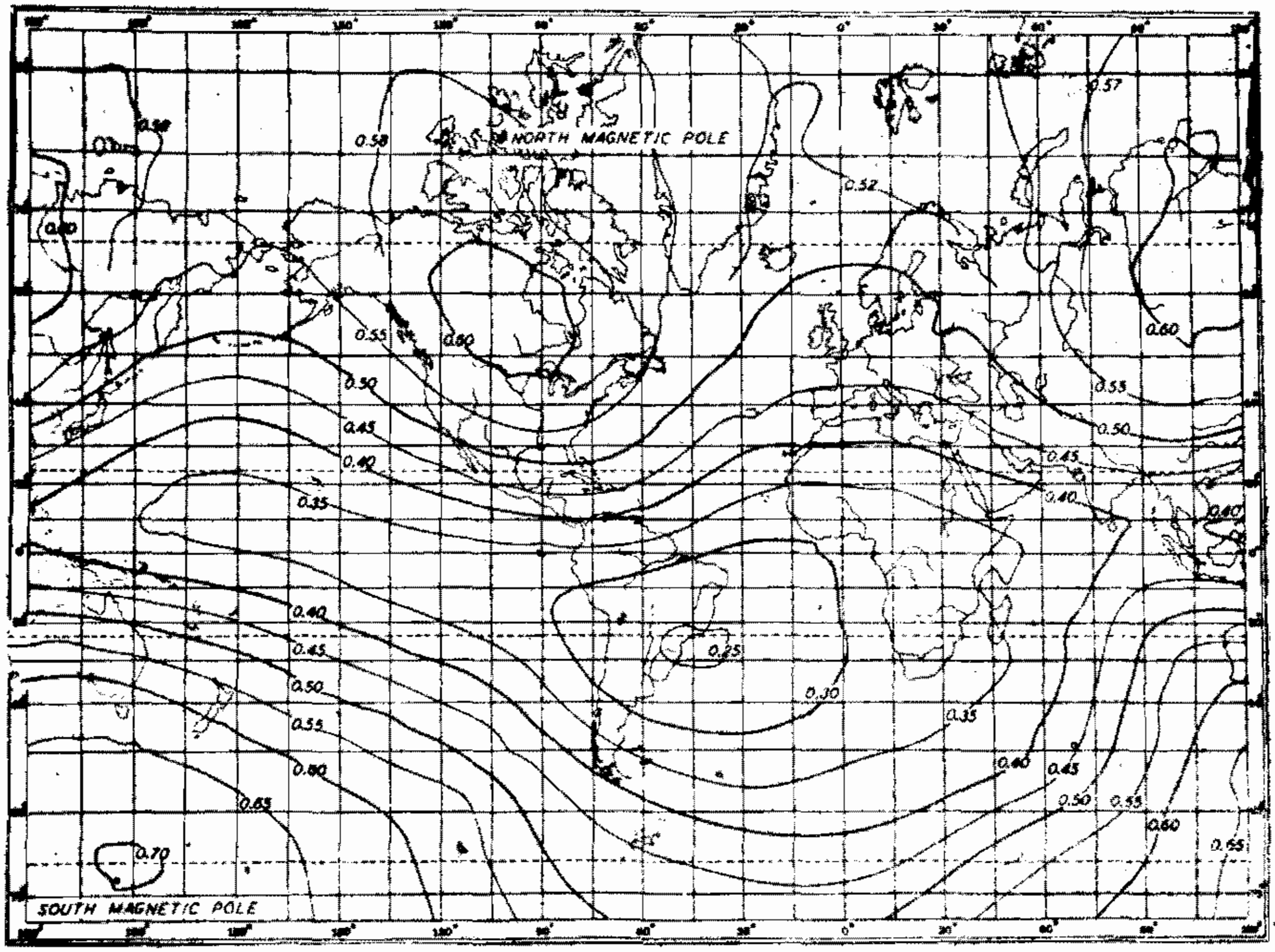
C1	Tuning capacitor	R1	110kΩ
C2	.0022mf	R2	150kΩ
C3	22mf/15v	R3	30kΩ
C4	.47mf/15v	R4	120Ω
C5	1mf	R5	100kΩ
C6	22mf/15v	R6	1kΩ
C7	.047mf	R7	13kΩ
C8	.068mf	R8	15Ω
C9	27pf	R9	5.6kΩ
C10	27pf	R10	2kΩ
C11	27pf	R11	2kΩ
C12	.022mf	R12	360Ω
C13	22mf/15v	R13	2.2mΩ
C14	1mf	R14	10kΩ
C15	100mf/25v	R15	5kΩpot.
C16	15mf/20v	R16	200Ω
C17	4.7mf/35v	R17	39kΩ
C18	6.8mf/35v	R18	20kΩ
C19	100mf/25v	R19	100Ω
C20	30mf/15v	R20	5kΩ
C21	30mf/15v	R21	3.3kΩ
C22	30mf/15v	R22	33kΩ
C23	4.7mf/10v	R23	1kΩ
D1	1N5235/6.8v	R24	10kΩ
D2	FD777	R25	1kΩ
D3	1N754A/6.8v	R26	4.7kΩ
D4	1N914	R27	3.9kΩ
		R28	620Ω
L1	.075 (detector coil)	R29	100kΩ
L2	.075 (detector coil)	R30	15kΩ
P	phone jack socket	R31	10kΩ
		R32	100kΩ
Q1	SE4021	R33	100kΩ
Q2	2N4355	R34	5.6kΩ
Q3	2N5133	Z1	301A
Q4	2N3906		
Q5	2N5133		
Q6	2N5190 (w/ heat sink)		
Q7	2N2907A		
Q8	2N5133		
Q9	2N5133		
Q10	2N5133		

[1]We are greatly indebted to Cecil Hayes (Rutgers University), Sam Maslak (MIT), and Jeff Millman (MIT) for generously giving their time and talents in designing the circuitry presented in this article.



Schematic Diagram

Everyman's Magnetometer.



The geomagnetic total intensity in c.g.s. units for 1945 (Vestine 1961).

BULLETIN NO. 18

SOUTHEASTERN ARCHAEOLOGICAL CONFERENCE

PROCEEDINGS OF THE

THIRTY-FIRST

SOUTHEASTERN ARCHAEOLOGICAL CONFERENCE

ATLANTA, GEORGIA

OCTOBER 25 AND 26, 1974

EDITED BY

DREXEL A. PETERSON, JR.

MEMPHIS, TENNESSEE

1975