

1 OCTOBER 1964

AD657336

**FINAL REPORT ON ARPA ORDER 414,
PROGRAM CODE 3860,
THIN-FILM HALL-EFFECT MAGNETOMETER**

JANUARY 1963 - JULY 1964

**DIELECTRICS AND SEMICONDUCTORS BRANCH
ELECTRICITY AND MAGNETISM DIVISION
RESEARCH DEPARTMENT**

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ABSTRACT

The experimental and theoretical investigations were concerned with (1) the fabrication of semiconductor films for the detection of small magnetic fields by means of the Hall effect, (2) the investigation of magnetic flux concentrators to be used in conjunction with such Hall elements, and (3) the development of a hand-carried battery-operated magnetometer based on this effect. Of the four complete magnetometers that were constructed and tested in the laboratory, two were delivered to ARPA. These magnetometers may be used to detect and measure magnetic fields as small as 10^{-5} oe in spite of large magnetic field gradients and in spite of the large bias provided by the earth's magnetic field. The properties of flux concentrators used in conjunction with such films were investigated, and optimum design criteria were established. Various deposition and crystallization techniques were investigated, but only with reference to one semiconductor—indium antimonide. Attempts to compensate the earth's magnetic field by means of an auxiliary electronic system were not successful. In the laboratory, such compensation is feasible, but two precision analog computers are required for this purpose. Magnetometers based upon the Hall effect are shown to be useful for fixed-station operation and for detecting the motion of ferromagnetic objects radiating a magnetic field vector equal to or greater than 10^{-5} oe.

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FOREWORD

This is the final report on the development of a thin-film Hall-effect magnetometer for the Advanced Research Projects Agency in accordance with Order 414, Program Code 3860. The work was conducted at the Naval Ordnance Laboratory, Corona, California, under contract from 1 January 1963 to 1 January 1964 and was extended to July 1964. The purpose of the work was to investigate the feasibility of using the Hall effect for measuring magnetic fields below 1 oe and for constructing a prototype magnetometer capable of measuring magnetic anomalies induced by small ferromagnetic objects in the earth's magnetic field.

Personnel participating in this program were H. H. Wieder, GS-14, principal investigator, 1/4 man year; Arthur Clawson, GS-12, Physicist, 1 man year; and David Collins, GS-11, Engineering Aide, 1/2 man year. One paper, "Detection and Measurement of Small Magnetic Fields," by A. R. Clawson and H. H. Wieder, was presented at the Symposium on Rotating and Static Precision Components, sponsored in March 1964 by the Department of the Navy, Bureau of Naval Weapons, and published in the Symposium Proceedings. One patent application, Navy Case 37709, entitled "Semiconductor Film Hall Generators Processed on Oxide-Metal Substrates" by H. H. Wieder and A. R. Clawson, was authorized for submission to the Patent Office by the Office of Naval Research on June 15, 1964.

In the interests of simplification and economy, and to expedite the design and construction of the subject magnetometer, commercially available components and materials were employed where practicable. It is to be emphasized, however, that neither the use of any commercial product nor the mention in this document of the supplier's name constitutes an endorsement of the product of one manufacturer over that of another.

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INTRODUCTION

Magnetometers for the detection and measurement of static or time-variable magnetic fields are based on a variety of physical principles and employ many different instrumentation techniques. For field strengths of the order of 10^{-5} oe, portable instruments based on the free nuclear precession principle have found wide application; other devices based on quantum-mechanical properties of radiation-pumped rubidium vapor or metastable helium have sensitivities of the order of 10^{-7} oe. Such instruments measure the total field and do not readily yield the vector magnitude of a small magnetic radiator. While they are highly accurate, their sensitivity is a function of the local geomagnetic field gradient; the precession magnetometer, for example, is useless in gradients of 2×10^{-3} oe/ft to 4×10^{-3} oe/ft. Flux gate magnetometers or other saturable magnetic core devices are capable of high sensitivity and rapid response, but are limited by inherent Barkhausen noise in the core and by the complexity of the associated drive and sensing circuitry. For the detection of magnetic fields in the range of $1 \text{ oe} \geq H \geq 10^{-5} \text{ oe}$, magnetometers based upon the Hall effect offer some distinct advantages.

The direct proportionality between the magnetic induction and the generated Hall voltage leads to an obvious application of the Hall effect for detection and measurement of small magnetic fields. Commercial magnetometer sensors using this effect are available and cover the range from 1 to 10^4 oe.

Since the Hall effect depends upon the vector magnitude of the magnetic field, it is immune to extraneous magnetic fields and will respond only to a magnetic induction normal to the direction of the flow of current through the sensor. This directional sensitivity of the Hall effect may be enhanced by one order of magnitude and the sensitivity to small magnetic fields may be increased two or three orders of magnitude by placing the Hall sensor in a gap between appropriately shaped high permeability flux concentrators such as Mumetal, permalloy, or ferrite rods.

The vector-sensing character of a Hall-effect magnetometer presents some limitations to its operation. The most severe problem is having to work in the presence of the earth's magnetic field. Although the desired application of this magnetometer is to detect the induced field of ferromagnetic objects in the earth's field, the directional sensitivity of the field sensor becomes a problem.

The magnetic field contribution due to the earth's field can be balanced out so that any anomaly in the field will be detected as a positive or negative deflection from a null.

DESIGN CONSIDERATIONS

HALL GENERATOR

The criteria for optimum performance of a Hall-effect magnetometer may be grouped into four distinct but interrelated categories: the properties and the application of Hall generator elements, the material properties, the geometry of the flux concentrators, and the design of the Hall-voltage amplifier-indicator system.

The parameters of Hall generator elements are a function of the galvanomagnetic properties of the material from which the Hall plate is fabricated, and they are also dependent upon the geometry of the Hall plate.

The transverse Hall voltage v_h generated across the plate by the Lorentz forces acting upon the charge carriers comprising the current is

$$v_h = (R_h/d) B i_h \times 10^{-8} \text{ volt} \quad (1)$$

where R_h , the Hall coefficient, is a material parameter expressed in cm^2/coul , d is the thickness in centimeters of the plate traversed by the current i_h in amperes, and B is the magnetic induction in gauss. The Hall mobility μ_h in $\text{cm}^2 (\text{volt-sec})^{-1}$ and the conductivity σ in $(\text{ohm-cm})^{-1}$ are related to the Hall coefficient by $\mu_h = R_h \sigma$. In accordance with Eq. (1), the maximum sensitivity of a Hall generator is obtained by choosing a material with a high electron mobility and low conductivity such as found in semiconductors.

Indium antimonide (InSb) has an exceptionally high mobility $\mu_h = 7.8 \times 10^4 \text{ cm}^2 (\text{volt-sec})^{-1}$ and a low conductivity $\sigma = 3 \times 10^2 (\text{ohm-cm})^{-1}$ at room temperature. It is readily grown in the form of micron-thick films on a variety of insulating substrates; and, although the mobility of such films is much lower than that of the bulk material, nevertheless a considerable advantage may be realized over bulk devices, because of the increased open-circuit v_h in accordance with Eq. (1).

The impurities incorporated into the film during deposition determine the type, concentration, and effective mobility of the charge carriers.

In general, all films of InSb evaporated by means of the three-temperature control process (Ref. 1, 2, 3) are n-type, if acceptors are not deliberately introduced into the heated crucibles or the vacuum chamber. For n-type InSb, $R_h = (1/ne)_i$, deliberate doping of a film with donor impurities reduces the temperature dependence of R_h . For a predetermined, permissible change in R_h over a given temperature range, the minimum donor concentration, N_{\min} , is

$$N_{\min} = \frac{an_i}{(1 - a)^{1/2}} \quad (2)$$

where a = permissible fractional change in R_h and n_i is the intrinsic electron density.

If v_h is to change by 2 percent or less between -50 and $+50^\circ\text{C}$ (i. e., $a = 0.98$ and $N_{\min} = 6.95 n_i$), at 323°K the intrinsic carrier concentration is

$$n_i = 6 \times 10^{14} \times 323^{3/2} \exp \left(-\frac{1510}{323} \right) \quad (3)$$

Consequently, it will be found that $n_i = 3.28 \times 10^{16}$ electrons/cm³ and $N_{\min} = 2.28 \times 10^{17}$ donor impurities per cm³. The Hall coefficient in the extrinsic region should not exceed a value $R_h = 27.6 \text{ cm}^3/\text{coul}$ if $(\partial v_h / \partial T)_{B, i}$ is not to vary by more than 2 percent over the temperature range specified above. Films less than 10^{-4} cm in thickness generally contain a large number of pinholes, and sequentially evaporated films (deposited under apparently identical evaporation procedures) vary in thickness by more than 100 percent. Thicker films are pinhole free, appear to be better crystallized than the thin films, and have X-ray diffraction patterns that suggest complete stoichiometry of the compound. Films in the thickness range of 10^{-4} to 2×10^{-4} cm appear to have more reproducible electrical characteristics, and the subsequently described experiments apply primarily to such films.

For zero magnetic flux, a potential will generally appear across the output electrodes of a Hall plate when a drive current is applied to it. This potential has its origin in the misalignment of the Hall electrodes with respect to an equipotential plane across the Hall plate.

Methods of compensating for the misalignment voltage on a Hall plate generally depend on the use of external resistances. One method balances the bridge equivalent of the Hall plate at zero field by simply

paralleling one leg of the bridge with an external resistance. Another method to compensate for the misalignment voltage is to arrange a current path parallel to the Hall plate. By adjusting the resultant potentiometer circuit, the voltage across the Hall contacts at zero field can be brought down to a value less than $5 \mu\text{v}$.

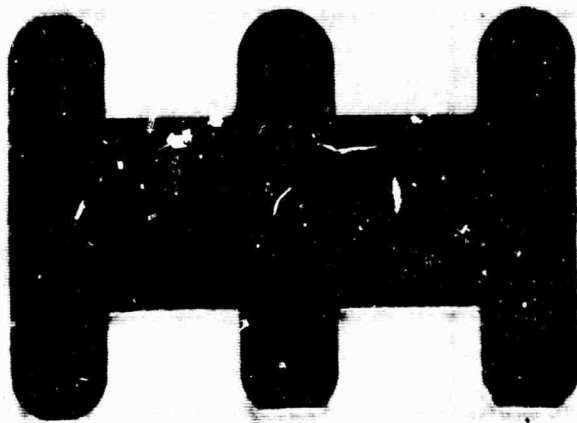
Each of these methods has the advantage that very little output power will be lost in the compensating network. There are some apparent disadvantages, however. By means of an equivalent bridge circuit, it may be shown that (for the bridge configuration) the change in the misalignment potential with temperature is proportional to the temperature dependence of the resistivity of a Hall generator driven by a constant-current source. The equivalent bridge can be balanced only at one temperature by an external resistance, unless the temperature dependence of all the bridge elements is the same. This difficulty is not encountered in a potentiometer compensator. The problem of compensating the thermal variation of the misalignment potential is a serious one, especially when small Hall potentials must be processed by a magnetometer operating below 1 oe. The balancing system will be discussed later.

Of the thin-film Hall generators that we have made, those with the highest electrical efficiency are two-phase InSb-In films that have been recrystallized (Ref. 4). Some typical specimens are shown in Figure 1. The best of these films have an equivalent mobility approaching $40,000 \text{ cm}^2/\text{volt-sec}$. This mobility is determined from the ratio of Hall voltage to resistivity. Because of the two-phase nature of the film, this mobility does not represent the carrier drift velocity per unit field; however, it does describe the film efficiency as a Hall generator. The galvanomagnetic characteristics of the recrystallized films are superior to the InSb evaporated films made by the three-temperature method. The recrystallized films are also less critical to produce.

The first step in making the recrystallized InSb-In film is to deposit an InSb film, masked to the desired shape. The quality of this film is not very critical as we have had good success from depositing layers of In and Sb, InSb layers from vaporized InSb, and InSb layers made by the three-temperature method. Purity, of course, is maintained as high as possible. An excess of In is introduced by deposition of a thin In layer on top of the InSb. The composite film is then heated in vacuum or an inert gas atmosphere so that an indium-rich InSb molten layer is formed. The liquid InSb is cooled and pure InSb crystallized out of the melt, normally forming dendrites in the plane of the substrate. There is apparently impurity segregation from the crystalline InSb to the melt, so these dendrites are quite pure InSb. The melt becomes increasingly indium-rich as the film cools. Upon exhaustion of the Sb, the In solidifies and forms inclusions throughout the InSb film.



(a)



(b)

FIGURE 1. Two-Phase InSb-In Film Hall Generators on Glass Substrates. (a) Deposited through a mask; (b) deposited on a shaped substrate.

These films are characterized by a Hall coefficient that is roughly a factor of 10 lower than normal InSb. The resistivity is correspondingly reduced. This reduction in resistivity causes no problem, since the film thickness is only about one micron. The film Hall generator resistance is typically about 200 ohms, a value still much higher than for commercially available InSb or InAs Hall generators made from the bulk material.

A limited investigation of the temperature dependence of the recrystallized films shows qualitatively similar behavior to bulk InSb. The impurity concentration can be estimated from this qualitative similarity, although by present techniques it can not be calculated directly because of the modified Hall coefficient and resistivity of the two-phase films.

Those of our InSb films that have a sensitivity suitable for use as small-field sensors are all on glass substrates. The primary disadvantage of the glass substrate is the thickness necessary to maintain mechanical rigidity. The thinnest suitable glass substrate is about 0.007 in. Further decrease in the thickness makes the substrate too fragile for handling and allows the deformation of the substrate under heat treatment of the film.

Several other substrate materials were investigated. The desired features were very small thickness and good thermal conductivity to minimize heating of the film. Anodized foils of aluminum and tantalum, cleaved sheets of mica, and wafers of ceramic were used as substrates. The thermal conductivity of each of these materials is superior to glass; however, the thickness limitation of the ceramic is similar to that of glass.

The electrical properties of the InSb films were best on the glass substrate, although very good films were produced on ceramic. Because of the success and availability of glass, the concentration of investigation was on glass substrates. However, fairly good films were made on anodized foils of aluminum and tantalum. These materials have the advantage of a thickness of about 0.001 in. Indium-rich films of InSb were deposited on these substrates and recrystallized. There is apparently no interaction between the film and substrate during the heating cycle. Considerable difficulty was encountered with electrical conduction through the oxide layer between the film and the metal. This was evidently due to tunneling or some similar mechanism and was not linear with voltage. Initiation of the conduction frequently required application of some minimum forming voltage, and it seemed to be dependent on both time and temperature. The practical difficulty of this conduction is the excess noise it introduces in the Hall voltage. The production of films with mobilities of approximately 9000 cm²/volt-sec from just these initial attempts is quite promising. Further investigation

of the problems encountered will have to be made to determine the usefulness of the anodized metal substrates.

A further step in decreasing the gap width of the flux concentrators would be to eliminate the supporting substrate and fabricate the film directly on the end of one of the concentrator rods. An insulating layer of evaporated silicon monoxide (SiO) or perhaps anodized aluminum (Al_2O_3) would be necessary to electrically isolate the semiconductor film from metal flux concentrators. No investigation was made of this technique.

The choice of geometry for the thin-film Hall generator was somewhat arbitrary. It was only necessary that the Hall generator fit within the cross-sectional area of the flux concentrators so that it would lie in a fairly uniform field. The Hall generator chosen (Figure 1a) is in the configuration of a symmetrical cross with arms 0.050 in. wide by 0.250 in. long. The electrical leads were attached with silver paste to the ends of the Hall generator so that its effective length was only approximately 0.200 in. This provided a large enough ratio of length to width so that the magnitude of the Hall voltage was unaffected by shorting effects of the electrodes. This allowed us to use the same sample configuration for evaluation of the galvanomagnetic properties and as a Hall generator. In terms of efficiency, a better Hall generator geometry would use a smaller ratio of length to width. This would somewhat reduce the Hall voltage for a given current, but the reduction in resistance would be much greater. The choice of an optimum Hall generator geometry for the magnetometer is dependent on more than efficiency, however. Because of the high sensitivity demanded of the magnetometer, the ratio of signal to noise must be as large as possible. No investigation has been made of the effect of noise on the geometry of the Hall generator.

The operation of the thin-film Hall generator is limited in sensitivity by noise. There seem to be two causes of noise: one is a long-term thermal drift and the other is a short-term electronic noise. The thermal drift is dependent on the variation of the ambient temperature and upon the heat sink available to the Hall generator. Thin-film Hall generators mounted in free air showed no signs of stabilizing over a period of 70 min. When mounted in intimate contact with metal flux concentrators, the rate of drift decreases as the temperature of the Hall generator stabilizes. The thermal drift has two sources. First is the temperature dependence of the Hall coefficient, and second is the temperature dependence of the zero-field null voltage. Since the magnetometer operates about a null (i. e., the earth's field balanced out) any drift in the Hall coefficient will cause a shift in the null. Similarly, even in a field-free environment, the unbalance voltage due to misalignment of the Hall electrodes drifts with temperature.

The short-term instability of the thin-film Hall generator appears as random noise and is independent of the stabilization of long-term drift. The magnitude of the random noise does not change with the use of flux concentrators and thus must be in the film itself. This noise varies in different films; however, the film qualities on which it depends have not been determined. The noise is roughly proportional to current in the Hall generator for low current values. For higher currents, the noise increases more rapidly. A typical thin-film Hall generator operating at full sensitivity of the magnetometer shows noise of about 5 percent full scale. The sensitivity of a good thin-film Hall generator (mobility $27,000 \text{ cm}^2/\text{volt-sec}$, resistance 220 ohms) is about 10^{-4} volt/gauss.

Experimental measurements were also made on commercially available bulk crystalline Hall elements. An F. C. Bell BH-200 Hall generator made of InAs was used in one of the sensor assemblies. The semiconductor area is 0.080×0.180 in. and fits properly into the $1/4$ -inch-diameter area of the flux-concentrator rods. The temperature coefficients of both the Hall coefficient and resistivity are less than for InSb; therefore, the thermal stability at $B = 0$ and for a balanced detector is very good.

The noise problem in bulk semiconductor Hall elements is less acute than in thin films. Hall generators with particularly low noise are the Siemens FC-32 and the F. C. Bell BH-200. For the BH-200 Hall generator driven by a source of 4 ohms and for a current of 150 ma, the sensitivity is 16.5×10^{-6} volt/gauss. By matching the Hall generator to the amplifier input, the sensitivity becomes 260×10^{-6} volt/gauss. Because of the superior signal-to-noise ratio, the performance of the bulk semiconductor is better than that of thin films. However, because of the greater thickness, amplification of the magnetic field by use of flux concentrators must be less, and the operating power is about 100 times greater.

FLUX CONCENTRATORS

The simplest construction, Figure 2, of a flux concentrator system uses two identical cylinders (of a high-permeability material such as Carpenter Hy-mu 80) that have zero residual magnetization, total length l , and circular cross sections of diameter δ . The cylinders are aligned along their major axes with a gap of length λ between them in which the Hall element is placed. In determining the effective field in the gap as a function of the variables (l/δ) , λ , and permeability μ , an analytical solution is extremely difficult. A simple experimental method and an empirical relation will be presented, which show the effectiveness of the applied field as a function of l/δ and λ . When the effective field

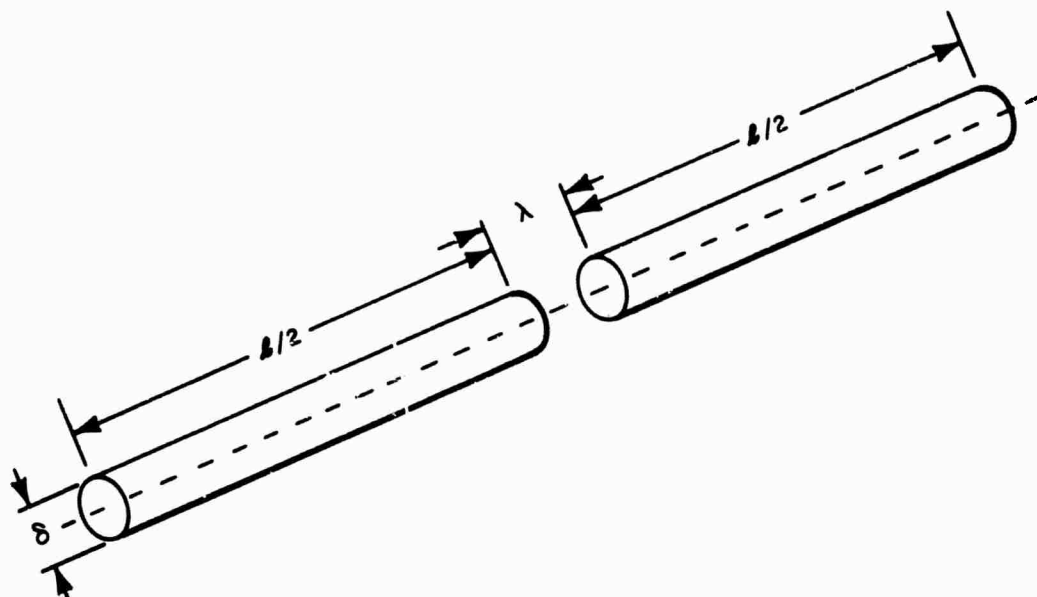


FIGURE 2. Flux Concentrator Rods of Materials Having High Permeability and Zero Residual Magnetic Induction. Geometrical structure shown is used to increase the effective magnetic field acting upon Hall generator placed within the gap λ .

enhancement in the air gap between the cylinders is defined as $\mu' = B/H_a$, where B is the effective field intensity in the gap, then μ' multiplies the applied field H_a . Figure 3 shows the effective field enhancement as a function of gap spacing for two different sets of Hy-mu 80 rod flux concentrators. The field in the gap was determined from the Hall voltage with the concentrators oriented parallel to the horizontal component of the earth's magnetic field. The curves shown appear to be hyperbolas; this was substantiated in subsequent measurements and also confirmed the earlier measurements of Hieronymus and Weiss (Ref. 5). If a hyperbolic relation is assumed between μ' and λ , a plot of $1/\mu'$ as a function of λ should be linear. That this is indeed the case is shown in Figure 4 for $1/\mu'$ as a function of λ , with l/δ as a constant parameter. (Note that l is the total length; i. e., twice the length of each cylinder.) It would not be expected that $1/\mu'$ would extrapolate to zero at $\lambda = 0$, because μ'_0 in the center of a Mumetal cylinder is finite and a function of l/δ , as tabulated by Bozorth and Chapin (Ref. 6). By using Figure 4, an empirical relationship may be written as

$$\frac{1}{\mu'} = k\lambda + \frac{1}{\mu'_0} \quad (4)$$

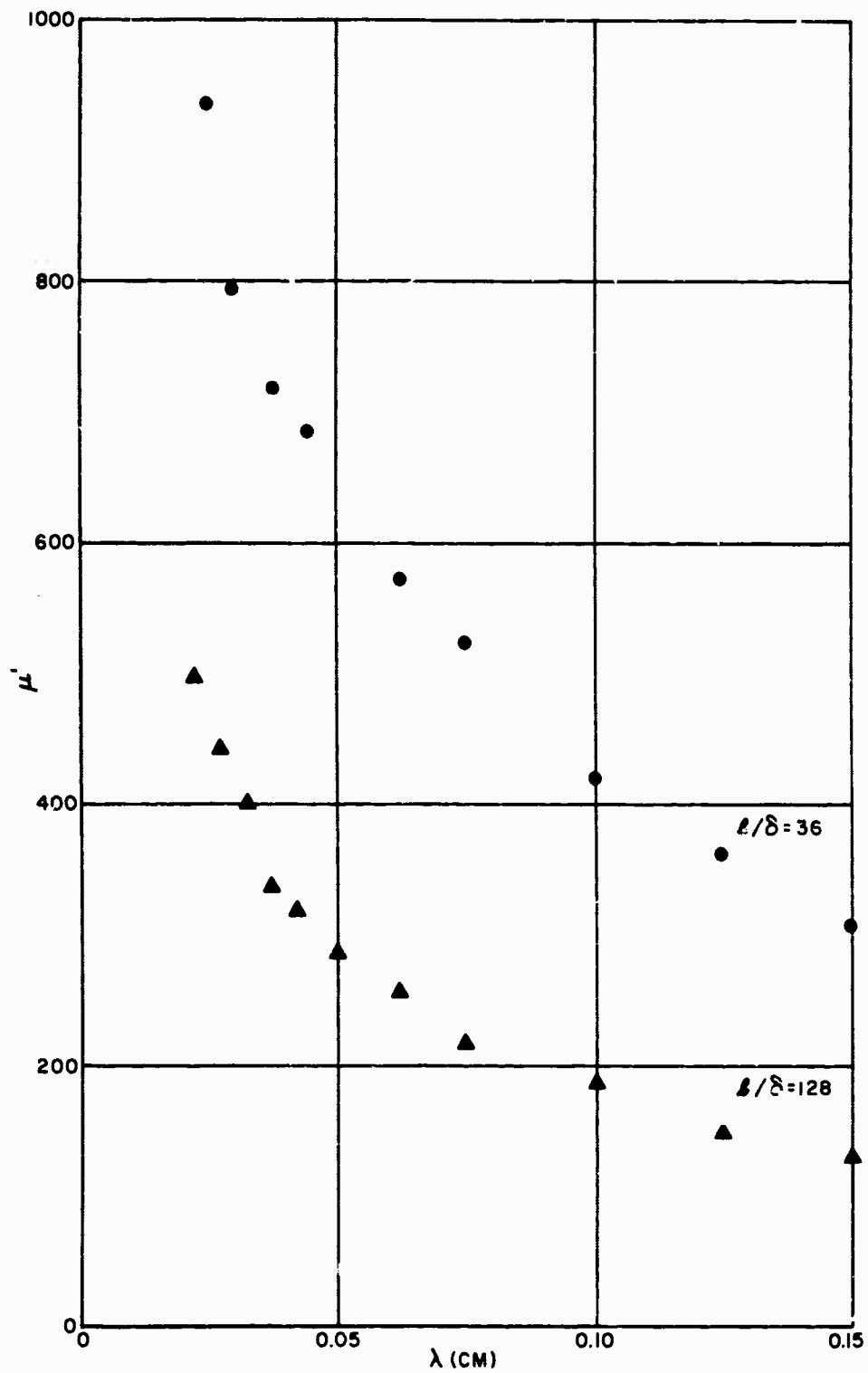


FIGURE 3. Measured Effective Field Enhancement μ' of a Hy-Mu 80 Cylindrical Rod Fluor Concentrator System as a Function of λ With the l/δ as a parameter

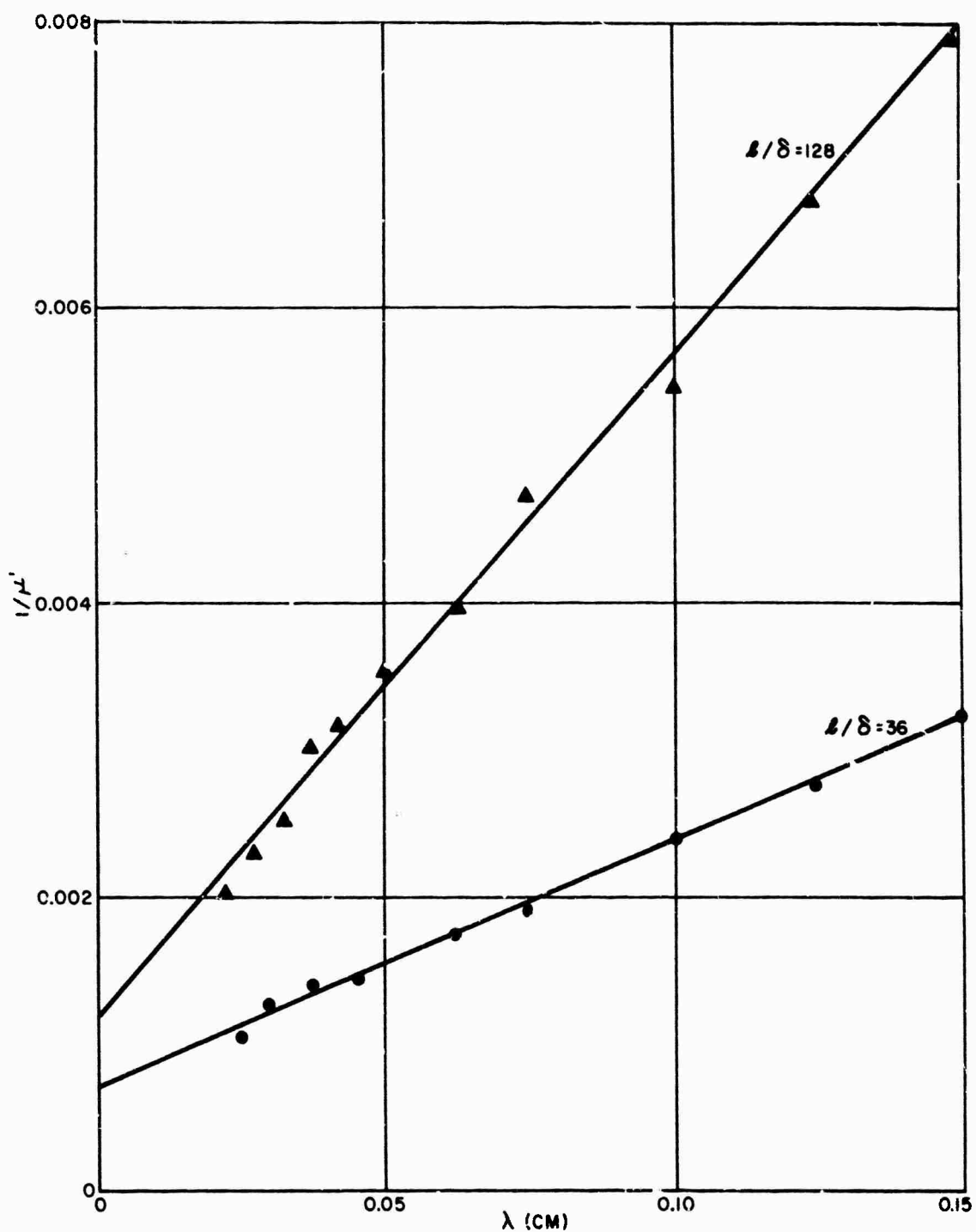


FIGURE 4. Reciprocal of Effective Field Enhancement $1/\mu'$ of a Hy-Mu 80 Cylindrical Rod Flux Concentrator System as a Function of λ With l/δ as a Parameter

where k is the slope of the lines shown in Figure 4 and both k and μ'_0 are a function of l/δ . The dependence of μ'_0 upon l/δ may be determined from the data supplied by Bozorth and Chapin (Ref. 5), who show that if the true permeability of the cylinders is such that $\mu \rightarrow \infty$, then $(1/\mu'_0) = (N/4\pi)$. Plotting reveals that $\log (N/4\pi) = 0.0121 l/\delta$, and it follows that

$$\frac{1}{\mu'} = k\lambda + \exp(-1.21 \times 10^{-2} \frac{l}{\delta}) \quad (5)$$

The data for the slope k of Figure 4 as a function of l/δ is at present sufficient for only a gross approximation. It is noted that, if l/δ is homogeneous along the length of the flux concentrators, the slope k is proportional to the ratio l/δ ; e. g., for $l/\delta = 127$, the slope k is larger than that for $l/\delta = 36$. A tentative empirical relation for homogeneous isotropic and uniform cylindrical concentrators is

$$k = 4.6 \times 10^{-4} \frac{l}{\delta} \quad (6)$$

The multiplication factor μ' of the applied field, upon substituting Eq. (6) into Eq. (4), is

$$\mu' = \frac{\delta \mu'_0}{4.6 \times 10^{-4} l \lambda \mu'_0 + \delta} \quad (7)$$

For $\mu \rightarrow \infty$, Eq. (5) and (6) introduced in Eq. (7) yield

$$\mu' = \frac{\delta \exp(1.21 \times 10^{-2} \frac{l}{\delta})}{4.6 \times 10^{-4} l \lambda \exp(1.21 \times 10^{-2} \frac{l}{\delta}) + \delta} \quad (8)$$

The slope k in Eq. (6) is also dependent on μ ; hence Eq. (8) is applicable only for Hy-mu 80 rods. For rods of lower permeability, k is larger. The value k for 52-48 Fe-Ni (Allegheny-Ludlum AL 4750) is $k = 2.8 \times 10^{-3} l/\delta$ and for ferrite rods (Ferroxcube 4B) $k = 5.2 \times 10^3 l/\delta$.

Flux concentrators were made from materials that were readily available. These included Carpenter Hy-mu 80 (4% Mo - 79% Ni-Fe), Allegheny-Ludlum AL 4950 (48% Ni-52% Fe) and Ferroxcube 4B ferrite. The flux concentrator rods of the metals were hydrogen-annealed at about 1100°C and cooled to room temperature in 4 to 6 hr. The following experimental evaluation of the materials and the rod geometries was performed.

Cylindrical Concentrator Rods of Hy-mu 80

Two rods having a diameter of 1/2 in. and a length of 9 in. were adjusted for a gap of 0.010 in. between them. Hall generator 7b was placed in the gap and a direct current of 10 ma was applied to it. The earth's field (horizontal component) at NOLC in the laboratory surroundings was previously determined to have a mean value of 0.25 gauss. After alignment of the flux concentrators in the earth's field the Hall voltage detected by the Hall generator was $v_h = 9.25$ mv. Accordingly, field sensitivity was

$$\frac{v_h}{B} = \frac{9.25}{0.25} = 37 \text{ mv/gauss}$$

An independent measurement of film sample 7b in a 5×10^3 gauss field maintained by an electromagnet yielded the value $v_h = 210$ mv. Hence

$$\frac{v_h}{B} = 0.042 \text{ mv/gauss}$$

Consequently, the amplification due to the flux concentrators is $\mu' = 37/0.042$ or $\mu' = 880$.

We measured, thereafter, the dependence of μ' upon the gap width between the rods. The results are illustrated in Figure 3 for the concentrators with length-to-diameter ratio $l/\delta = 36$.

Similar measurements were made with two other cylindrical flux concentrators having a diameter of 1/8 in. and a length of 8 in. A different Hall generator, No. 109 (on pyrex substrate), was used. The above described procedure for alignment in the earth's field yielded a flux amplification $\mu' = 470$ for a gap of 0.010 in. Note that, in spite of a higher value of l/δ , the amplification factor is smaller—probably because the permeability of the rods is less than the other Hy-mu 80 rods, perhaps due to improper annealing. In the limit for zero gap, the flux should be much greater for the larger l/δ ; however, in Figure 4, the reciprocal of the field amplification is extrapolated to zero gap, and the result indicates a lower permeability. The dependence of μ' on gap width is also shown in Figure 4 for the concentrators with $l/\delta = 128$.

Cylindrical Concentrator Rods of AL 4950

Two rods having a diameter of 1/4 in. and a length of 5 in. were positioned as flux concentrators for Hall generator 43B. The rods were arranged as a symmetrical cross of InSb with legs 0.050 in. wide and 0.250 in. long on a glass substrate 0.004 in. thick. The dependence of

μ' on gap was measured using the technique described above, and the results are shown in Figure 5 for the $l/\delta = 40$. The scatter of the data is due to the coercivity of the material. Upon rotating the assembly 180 deg in the earth's field to obtain Hall measurements of both polarities, there was a small remanent magnetization of the rods from their initial orientation. Although this could cause problems for a Hall-effect compass or similar application, no difficulty was encountered with the flux concentrators when they were held in one position in the earth's field.

Two rods having a diameter of 1/4 in. and a length of 8 in. were also tried. Measurements were made with a gap of 0.019 in. only. The resulting field amplification was $\mu' = 236$.

Cylindrical Rods of Ferroxcube 4B Ferrite

Two rods having a diameter of 1/4 in. and a length of 3-1/2 in. were also used with Hall generator 43B. The dependence of μ' on gap is shown in Figure 5 for the concentrators of $l/\delta = 28$. The low permeability of the ferrite limits the field amplification in the gap; however, for alternating magnetic fields, the ferrite would not suffer from eddy current losses.

Noncylindrical Geometry Flux Concentrators

Several other flux concentrators of different shapes were tried with varying success. Various shapes of Mumetal sheet were tried; however, the material was not annealed, and the area cross section of the gap was much less than that of the Hall generator. Accordingly, a very nonuniform field resulted.

A pair of wing-shaped concentrators made by Motorola, Inc. (for use in a Hall-effect compass) were also evaluated. The shape is illustrated in Figure 6. The gap cross section has an area 1/16 by 5/32 in. The wings are Hy-mu 80, although the performance of AL Mumetal is said to be identical. The amplification of the concentrators according to Motorola is about 220 for a Siemens MB-23 ferrite-encased Hall generator. By evaluating their performance with an F. C. Bell BH 200 Hall generator and a gap of 0.019 in., an amplification of 140 was obtained. This is nearly identical with the performance of the low-permeability AL-4750 cylindrical concentrators of 1/4-in. diameter and 10-in. total length, which had an amplification of 137 when measured under the same conditions.

An attempt was also made to circumvent the vector sensitivity of the Hall generator by means of a multidirectional flux concentrator such

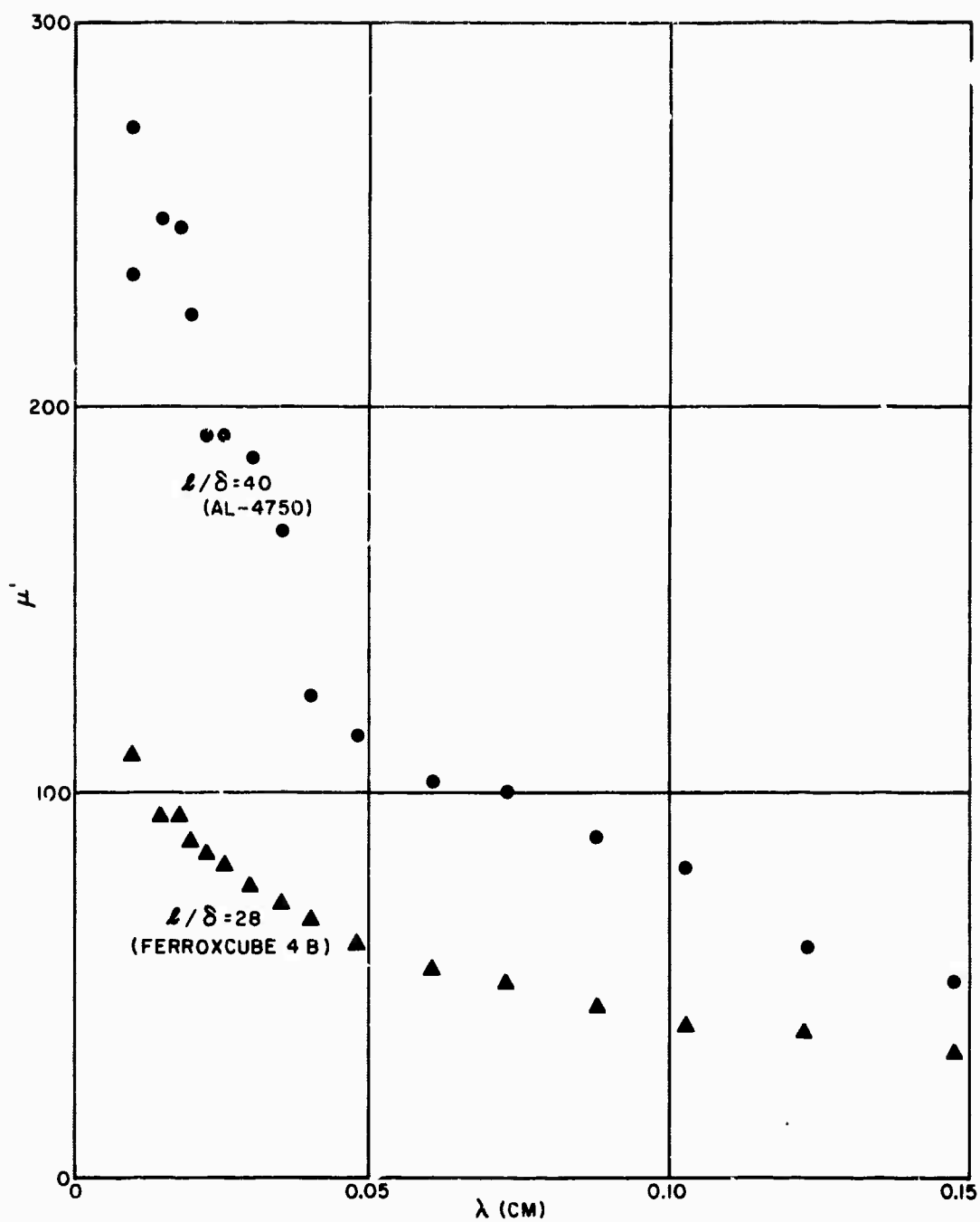


FIGURE 5. Measured Effective Field Enhancement μ' of Cylindrical Rod Flux Concentrators of AL 4950 ($l/\delta = 40$) and Ferroxcube 4B ($l/\delta = 28$) as a Function of λ

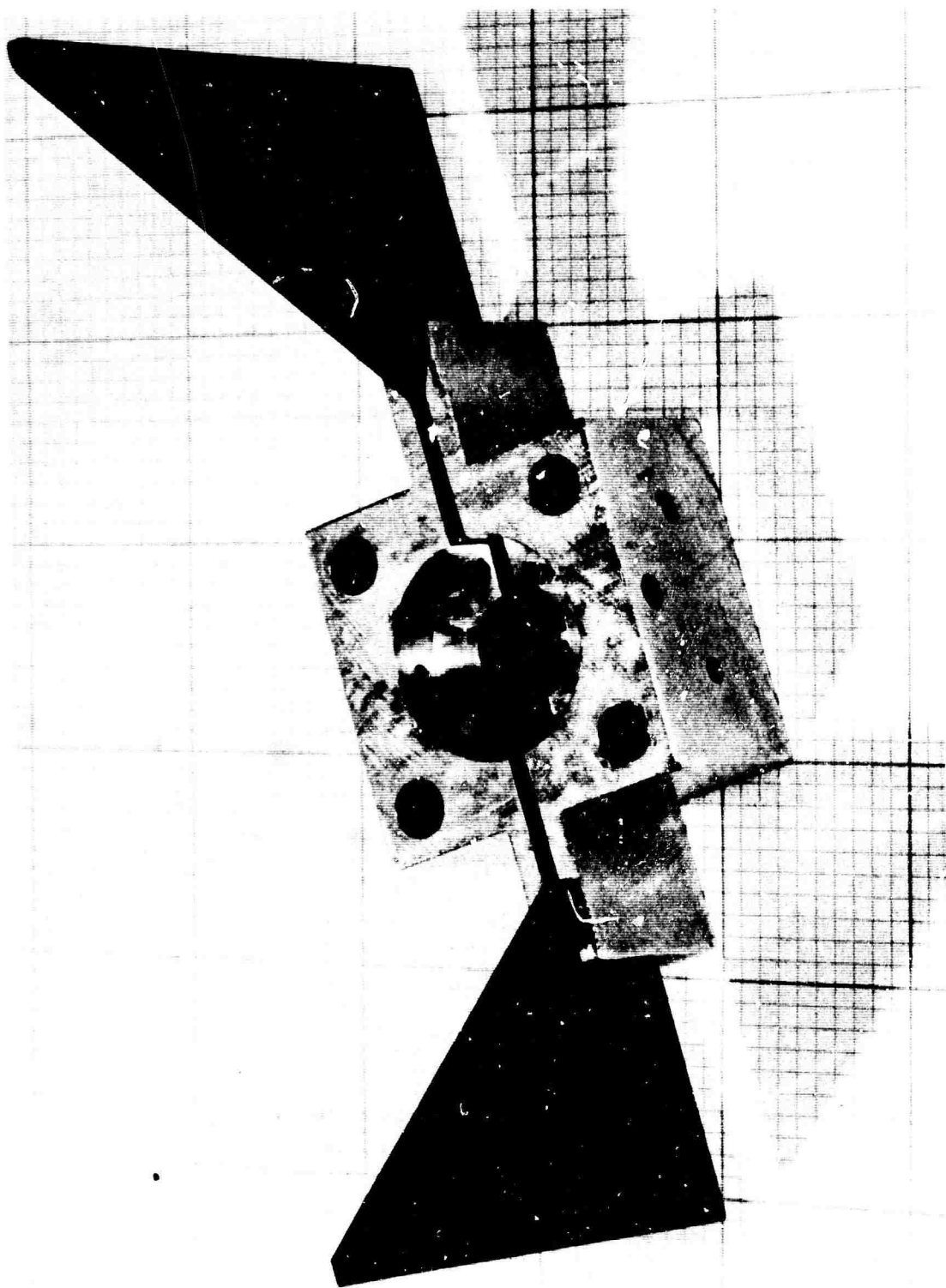


FIGURE 6. Wing-Shaped Flux Concentrators of Mumetal (Motorola, Inc.)

as that shown in Figure 7. The field amplification of this arrangement was found to be $\mu' = 23$, and the directional sensitivity was that of an equivalent single concentrator rod along the geometrical center of the multiple rods.

Since there is apparently no advantage in complicated geometrical shapes for flux concentrators in reducing the directional sensitivity of a Hall magnetometer, the main design criterion is maximum gain. The basic problem is the demagnetizing factor associated with these geometries. Although there is no direct discussion available about the demagnetizing factors of the complicated shapes, the general behavior can be inferred from the behavior of simple geometries such as cylindrical rods and ellipsoids for which the theory has been worked out. Needle-shaped concentrators provide the maximum flux concentration. Geometries that have a large cross section compared to their length have large demagnetizing factors and offer much less flux concentration.

The effect of the gap width on the flux across the gap is to decrease the flux with increase in gap. The relationship is exponential, however, so that for small gaps very small changes in width have a large effect on the flux. The relationship is not just a function of gap width, but is dependent also on the rod diameter. The same gap width has far less effect on large-diameter rods than on small rods whose l/δ is the same. If such a relationship does exist, then there must be some optimum diameter for rods of given permeability, length, and gap that compromises the gain due to increased length-to-diameter ratio and the loss due to decrease of the diameter-to-gap ratio. When a particular permeability material, a maximum physical length, and a minimum gap are specified, these could possibly be used as the criteria for choosing the size of Hall generator to be used, rather than just choosing some size arbitrarily.

The flux concentrator used in the operational magnetometer consists of two AL 4750 high-permeability rods having a length of 5 in. and a diameter of 1/4 in., with the Hall generator positioned in the gap between the rod ends. The geometry of these rods is a compromise of several considerations, the first being a limited physical size. Second, a large length-to-diameter ratio of the rods provides a small demagnetization factor, so the effective permeability of the concentrators will be high. Third, the rod diameter must have some minimum limit to provide an area of homogeneous flux across the active area of the Hall generator. The AL 4750 material was chosen strictly because of its availability in 1/4-in. diameter rod. A better choice would be Hy-mu 80 or AL Mumetal.

The rods and the Hall generator are positioned securely in an aluminum housing. All the mounting hardware is nonmagnetic.

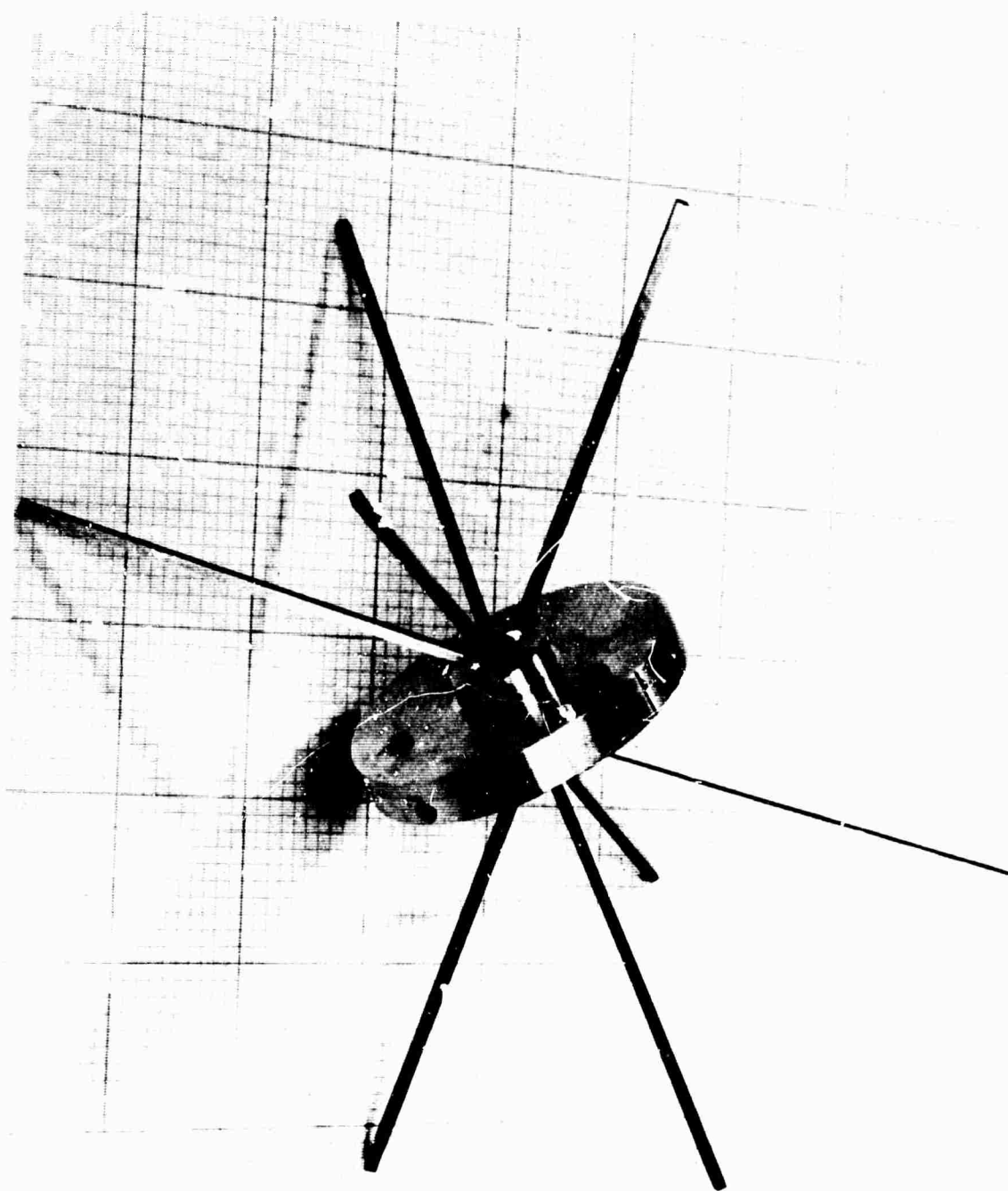


FIGURE 7. Multi-Direction Flux Concentrator of Hy-Mu 80

The advantage to be realized from the use of films (Ref. 7) depends to a large extent on their substrate. It is imperative that the substrate be as thin as possible in order to obtain the advantages due to a low-reluctance magnetic circuit by keeping the gap between the flux concentrators at a minimum. A thin film in good thermal contact with a heat sink allows a higher Hall current to be applied to the film and hence increases the effective sensitivity $(\partial v_h / \partial B)_{i_h} = \text{constant}$ of a Hall generator sensor. It is desirable to improve the thermal transfer of heat from the film and its substrate to the flux concentrators. In magnetometer applications that do not have provisions for cooling, the flux concentrators represent the effective heat sink.

SYSTEM ELECTRONICS

The electronic system of the Hall effect magnetometer consists of a current source and a high-gain detector. Because of the high-gain and stability requirements, ac circuits were employed. The Hall plate drive current is supplied by a 1-kc transistor oscillator and power amplifier; the Hall voltage (1 kc) is amplified by a high-gain transistor amplifier, rectified by a detector, and displayed on a meter. A significant feature is the synchronous demodulator that provides a narrow bandwidth and a high signal-to-noise ratio. In order to cancel the signal generated by the earth's field, a potential that is 180 deg out of phase with the Hall voltage is introduced at the amplifier input. This potential is also used for canceling the electrode misalignment voltage in the Hall probe.

The detailed features of the system are shown in Figure 8. The upper portion of the diagram contains the current source and balancing network. Starting at the left, the first circuit is an LC-tuned fixed-frequency 1-kc oscillator. The oscillator drives an amplifier that provides the current for the Hall generator and also switches the transistors of the synchronous demodulator. The driver stage steps up the signal to allow practical use of a Class B common-collector output stage. The output from the amplifier is chosen to provide the desired current for a particular Hall generator. Further reduction of current must be accomplished by use of a resistor in series with the Hall generator. Matching to an extremely high- or low-resistance Hall generator may require a different transformer ratio.

The amplifier stage for driving the Hall generator was designed to provide adequate power for any Hall generator. Since it was necessary to allow complete flexibility of the electronics in order to try all types of Hall generators, the drive amplifier is larger than necessary for the thin films. The measured output voltage from the 4-ohm tap of the



FIGURE 8. Circuitry for Hall-Effect Magnetometer Using a Thin-Film Field Sensor

prototype drive amplifier is plotted as a function of load resistance in Figure 9.

The purpose of the balancing network is the introduction of an error signal that compensates for undesired components in the Hall voltage output. In the operation of the magnetometer, the error voltages are treated as one source and are balanced out by adjusting a control for the resistive signal components and a control for the reactive signal components. Ideally, the error voltages due to misalignment of the electrodes on the Hall plate and to the Hall voltage from a constant background field are in phase with the drive current and can be balanced out by introduction of a compensating voltage 180 deg out of phase. The error voltages due to capacitance and inductance in the Hall generator and the connecting cables, can be balanced by a compensating voltage 90 or 270 deg out of phase with the drive current, as the case requires. This reactive-error component should be constant, since change of the magnetic field should affect only the resistive component. With the method of balancing used in the magnetometer, the adjustment of the resistive and reactive controls are not independent of each other. If the resistive component is changed more than just slightly, the reactive component must also be readjusted. A much more satisfactory balancing system would use a technique in which the phase shift is independent of the signal amplitude.

The initial method used to provide a compensating voltage to balance the error voltage was to use a voltage divider across the Hall generator current electrodes. Representing the Hall generator as a resistance bridge, this method is shown in Figure 10. The voltage necessary for compensation is normally only a small fraction of the total drop across the Hall generator. The potentiometer across the Hall generator does not have sufficient resolution to allow complete compensation without the use of an additional vernier control. The reactive component is provided by a similar voltage divider coupled by a capacitor to provide a ± 90 -deg phase shift. This method is used in the magnetometer using a thin-film Hall generator.

An alternative method of compensation is shown in Figure 11. A separate transformer winding provides the compensation voltage. The winding turns ratio is adjusted to provide only the voltage necessary for compensation. For our case, the compensation voltage is mostly for the misalignment component. There was no attempt made to minimize the misalignment voltage on the Hall generators; consequently, it was as high as 4 percent of the voltage drop across the current electrodes. A 10-turn center-tap coil (AWG 30 wire) provides ± 5 percent compensation for the 4-ohm output tap. The resistance of the 1-k potentiometers is much higher than that of the Hall generator and thus contributes only minor loading. A vernier control is still necessary with the resistive balance.

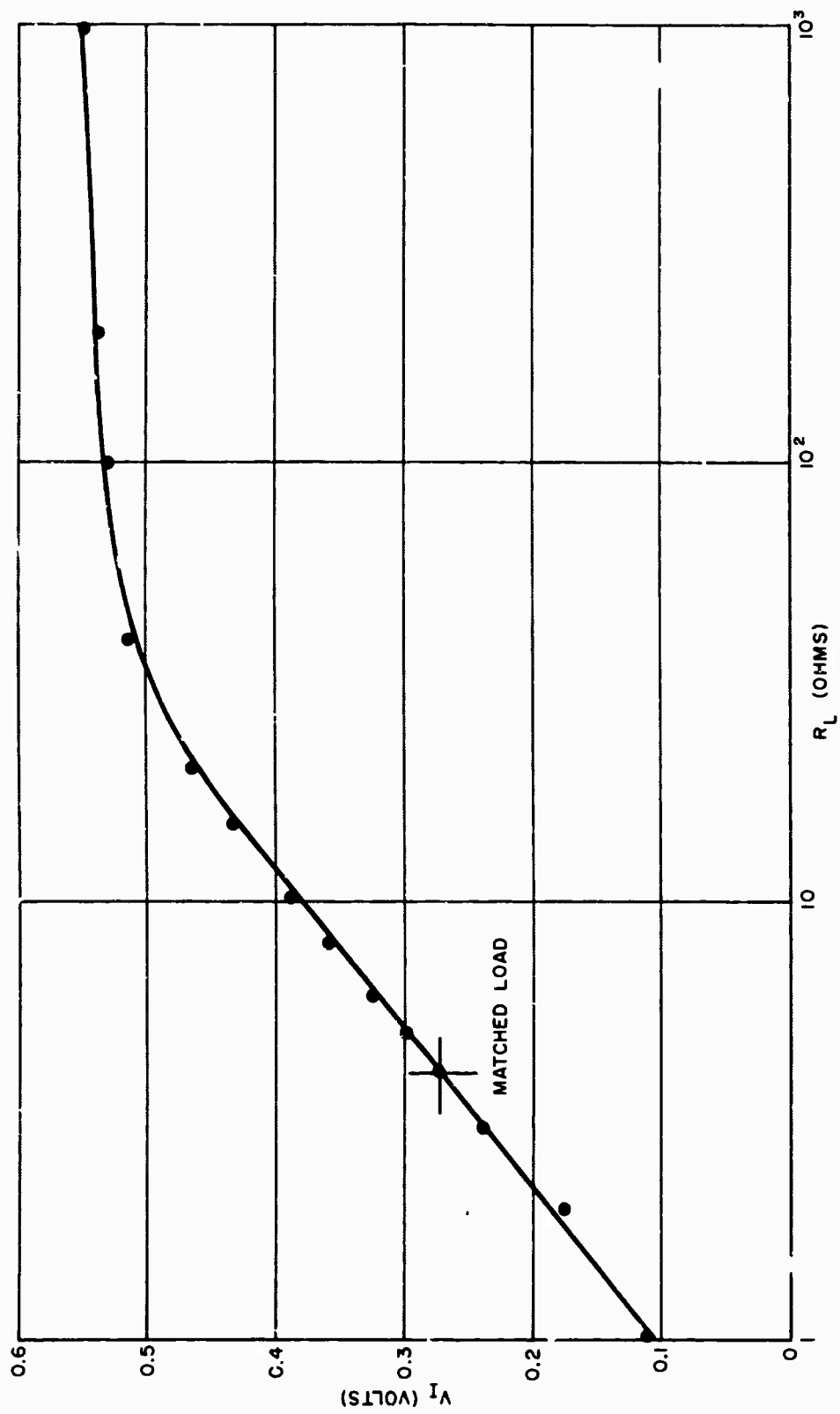


FIGURE 9. Output Voltage V_I of the Drive Amplifier as a Function of Load Resistance Across the 4-Ohm Tap

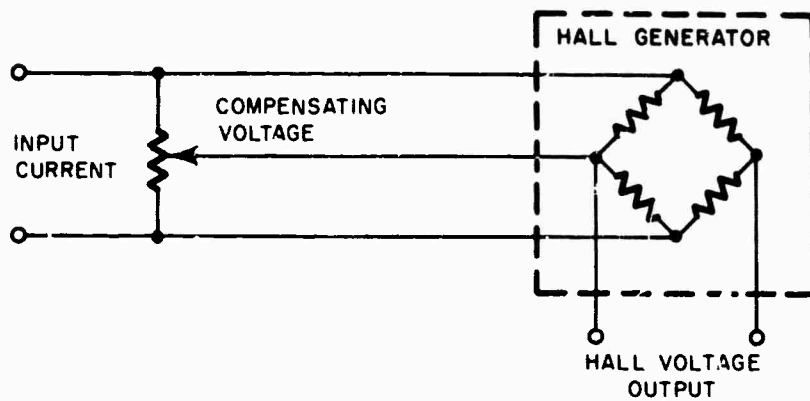


FIGURE 10. Null Balancing Network Using a Potentiometer Across the Hall Generator Input

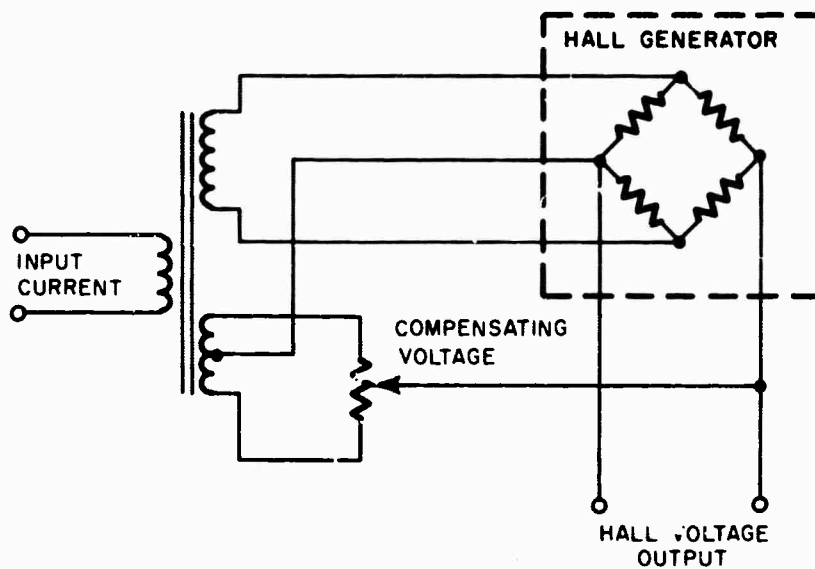


FIGURE 11. Null-Balancing Network Using a Separate Transformer Winding as a Voltage Source

This method of balancing was adapted for use with low-resistance commercial bulk crystalline Hall generators. The electronic system of a magnetometer using such a Hall generator is shown in Figure 12. The compensating voltage is introduced at the secondary of the transformer matching the Hall generator to the amplifier input.

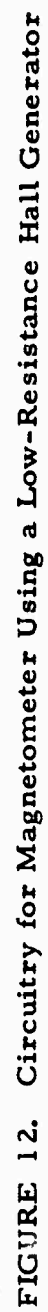
In evaluating the balancing network, consideration must be given to its potential as a possible noise source. Stability of the balance voltage is very critical, since the magnetometer requires only 2.5×10^{-6} volt at the input to give full-scale deflection. The voltage drop across the balancing potentiometer is about 0.5 volt, thus the necessary instability to cause full-scale deflection is only five parts in one million. The same stability, of course, is demanded of the Hall generator.

The stability of the balancing network cannot be evaluated independently; however, an equivalent resistance bridge was substituted for the Hall plate. Initially, a 220-ohm symmetrical bridge of 1/2-watt carbon resistors was used. This bridge was relatively unstable, allowing a long-term variation in the output over the range from -40 to +90 (where full scale = ± 100) over a 25-min period. A 350-ohm symmetrical bridge of precision wire-wound resistors was substituted. The long-term drift was limited to a range of 0 to -30 during a 40-min period. The maximum rate of drift was less than 2 per min. Short-term drift was less than 1.

The Hall generator output drives the input of the high-gain amplifier in the lower portion of Figure 8. No impedance matching has been employed, since the thin-film Hall generators used are normally of the order of 100 to 200 ohms. This is comparable to the amplifier input impedance. For very low- or very high-resistance Hall generators, a matching transformer would be necessary. For the low-resistance Hall generator in Figure 12, a 1-to-15.8-turn-ratio step-up transformer is used. This very nearly matches the ~ 1 -ohm Hall generator output to the amplifier input impedance of ~ 250 ohms.

The amplifier input impedance was measured with a high-impedance 1-kc generator across the input. A variable resistor was placed across the input and adjusted to provide an output half that available without the resistor. The amplifier input impedance was considered equivalent to this resistance R_I . Measurements using the synchronous demodulator were achieved by adjusting the oscillator to beat slowly with the switching signal. The output is read as the maximum deflection of the meter at the beat frequency. The results for the initial prototype magnetometer are as follows:

1. With the bridge detector
 - a. Full gain, maximum meter sensitivity. . . $R_I \approx 550$ ohms



- b. Full gain, minimum meter sensitivity . . . $R_I = 300$ ohms
- c. Gain 1/10 maximum, minimum meter sensitivity $R_I = 300$ ohms
- 2. With the synchronous detector
 - a. Full gain, maximum meter sensitivity . . . $R_I = 200$ ohms
 - b. Full gain, minimum meter sensitivity . . . $R_I = 210$ ohms
 - c. Gain 1/10 maximum, minimum meter sensitivity $R_I = 220$ ohms

The amplifier has four RC coupled common-emitter stages with a compound connected common-collector output stage. A 1-kc band-pass filter is used in addition to the synchronous demodulator. The major purpose of the filter is to prevent saturation of the amplifier by induced 60- and 120-cps signals and the second harmonic Hall signal due to any induced 1-kc magnetic field. Also, the synchronous demodulator passes fractional amounts of odd harmonic signals, and these are eliminated by the filter. A conventional 500-ohm line-to-grid band-pass filter connected backwards is used in conjunction with a 200-ohm resistor and capacitor in series across the filter output to load the filter for proper attenuation one octave above the pass band. The output from the amplifier is transformer-coupled through the synchronous demodulator directly to the output meter.

The synchronous demodulator provides that only 1-kc signal components are rectified. The narrow bandwidth and the polarity sensitivity of this detector are extremely useful. There are some circumstances, however, that can cause erroneous readings in the output. The reactive 1-kc signal component is 90 deg out of phase with the switching of the demodulator; thus, ideally, it should allow zero output. Due to nonlinearities in the amplifier, phase shift, and departure from ideal switching, a small reactive signal does appear at the output. A much more serious problem of the reactive signal component arises from overloading the amplifier. The pass band of the amplifier itself is 1 kc with a 150-cycle bandwidth and is indiscriminate to the signal phase. Consequently, large 1-kc signals can be passed by the amplifier, but never detected by the phase-sensitive demodulator. The dynamic range of the amplifier is fairly limited; too large a signal will overload the amplifier. It is, therefore, important to cancel completely the reactive signal component. An alternative bridge rectifier demodulates the signal and provides an rms reading of all frequency components in the amplified signal. Thus, a true null of the reactive components is observed.

For the initial operation of the magnetometer in the presence of large magnetic perturbations, a signal is obtained that swamps the detector output. The detector sensitivity must be decreased and the balance adjusted as closely as possible while the gain is increased. The amplifier gain control decreases the gain by a factor of 10^3 ; however, further decrease in sensitivity is often necessary. This is accomplished by increasing the resistance in series with the output meter. This initial balancing of the detector is best done with the bridge rectifier switched into the circuit.

THE MAGNETOMETER

The assembled magnetometer sensor uses flux concentrators with a diameter of $1/4$ in., a total length of 10 in., and a gap just wide enough to allow for the Hall generator. (See Figure 13.) For the thin-film Hall generator, a gap of 0.007 in. provides space for the film, the glass substrate, and a thin sheet of mylar that electrically insulates the film surface from the end of the concentrator rod. The Hall generator is a symmetrical cross with arms 0.050 in. wide and 0.250 in. long. The electrical leads are attached with silver paste to the ends of the Hall generator so its effective length is only ~ 0.200 in. The substrate is a glass disk having a $3/8$ -in. diameter and a 0.007-in. thickness. The sensitivity of the Hall generator (mobility $27,000/\text{cm}^2/\text{volt-sec}$, resistance 220 ohms) operating from the 16-ohm tap of the drive amplifier (~ 5 -ma drive current) is about 10^{-4} volt/gauss. With concentrators of $1/4$ -in. diameter, 10-in. length, and 0.007-in. gap, the amplification is ~ 270 . The total sensitivity is then about 2.7×10^{-2} volt/gauss. The magnetometer amplifier gives full-scale deflection for 2.5×10^{-6} volt, so the sensitivity of the unit is about 10^{-4} gauss full scale.

For the field sensor fitted with an F. C. Bell BH-200 indium arsenide (InAs) Hall generator, the gap width was 0.019 in., thus reducing the gain of the $1/4$ - by 10-in. concentrators to ~ 130 . With the Hall generator driven from the 4-ohm tap of the drive amplifier, the current is about 150 ma, which provides a sensitivity of 16.5×10^{-6} volt/gauss. By matching the Hall generator output to the amplifier input, 2 to 500 ohms (a step-up ratio of 1 to 15.8), the sensitivity is 260×10^{-6} volt/gauss. With the flux concentrators, the sensitivity is 3.4×10^{-2} volt/gauss. This is nearly identical with the sensitivity of the thin-film Hall generator, providing an output sensitivity of $\sim 10^{-4}$ gauss full scale; however, the noise is considerably lower. The power to drive the bulk semiconductor Hall generator is roughly 200 mw compared to 2 mw for the thin film. No provision for temperature compensation was incorporated into this laboratory model, although standard feedback techniques may be applied for thermal stabilization of the device. The stability of the instrument in a laboratory environment was

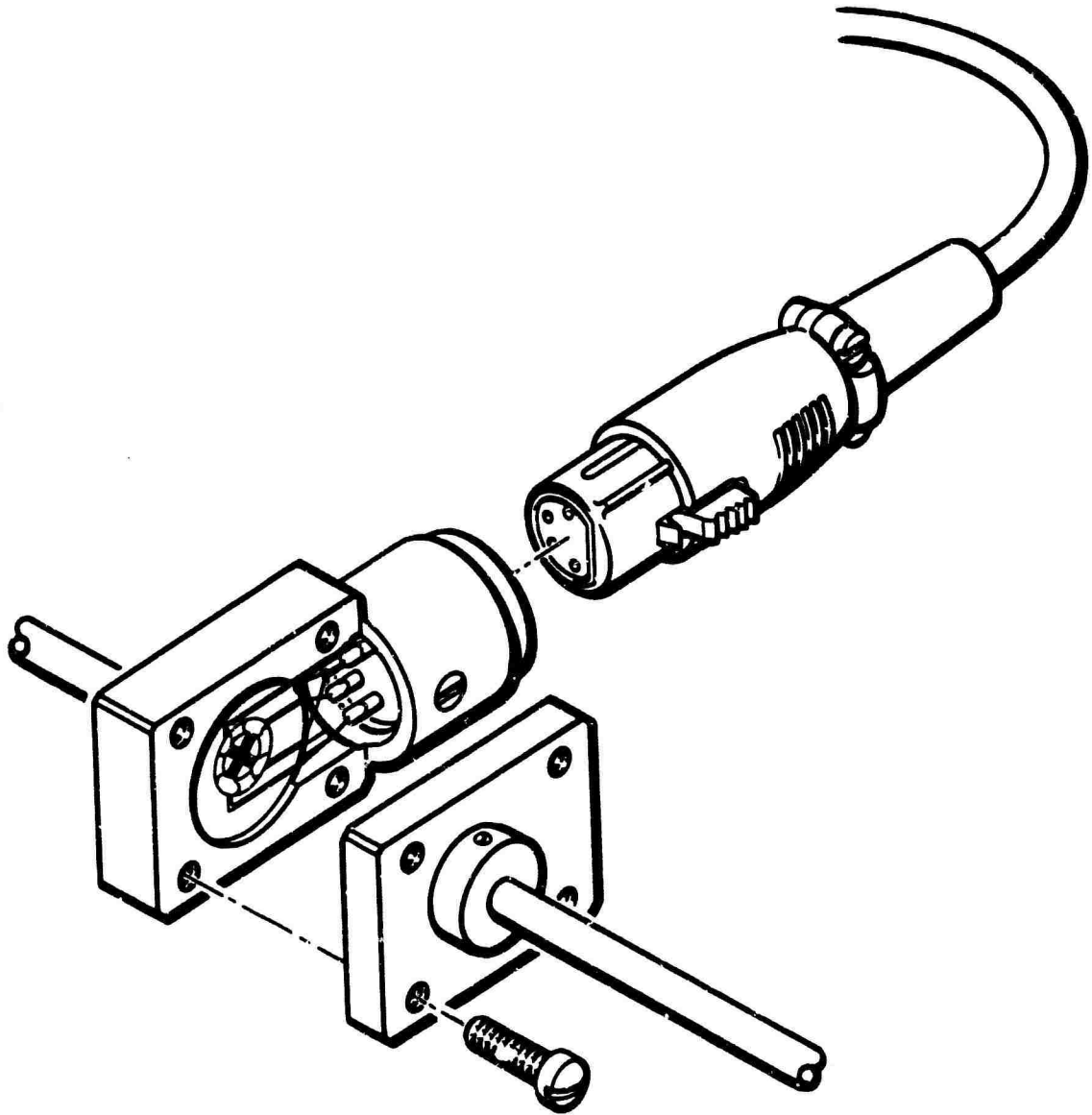


FIGURE 13. Field Sensor Assembly Showing the Hall Generator and its Electrical Leads Mounted Between High-Permeability Flux Concentrator Rods in an Aluminum Housing

found to be excellent. The self-contained portable battery-operated detector is shown in Figure 14.

The magnetometer using the thin-film Hall generator and the magnetometer with a bulk semiconductor Hall sensor both have the same sensitivity of approximately 10 gamma full-scale; however, the bulk semiconductor provides a somewhat better signal-to-noise ratio. Amplifier noise with the input shorted is about 1 percent full-scale output. Noise limitation of the Hall generator makes the amplifier gain adequate for this detector. If an accurate indication of field strength is required, the flux concentrators are necessary for $H < 0.1$ oe. Mapping of the field of small static magnetic radiators, such as permanent magnets, may be accomplished with ease. Typical dipole radiation patterns have been obtained from either permanent magnets or Helmholtz coils.

These magnetometers are particularly useful for the detection of a magnetic anomaly having a sharp gradient and a magnitude smaller than that of the local terrestrial field.

Portable operation of the magnetometer requires that the earth's field, along each of the coordinate axes, be continuously nulled at the detector in order to sense the relatively weak magnetic field of a ferromagnetic object having a remanent magnetization two to three orders of magnitude smaller than the earth's field. This requires that the Hall sensor operate as a continuously balanced system with a response time at least as fast as any motion of the sensor induced by the moving operator or by minute perturbations in the earth's field.

Laboratory experiments were started with a view towards compensating for the earth's magnetic field in the horizontal plane and then measuring the sensitivity of the magnetometer to a magnetic anomaly. Any technique to accomplish this requires the use of at least one additional sensor. In using such a gradiometric system, one sensor serves as a reference (for the earth's field) and the other detects any variations with respect to the reference signal. If the distance from the object to the position of each sensor is not identical, then the difference in the effective fields will be large, since the magnetic field of a dipole decreases as $1/\text{distance}^3$. Such a differential technique seems quite attractive; however, there are some severe practical limitations. The balance between the field sensors for an error less than 10^{-5} gauss must be better than 0.002 percent to operate in the earth's field (~ 0.5 gauss maximum). This puts rather severe demands on both the electrical balance and the positional stability of the sensors relative to each other. If the magnetometer is balanced in the horizontal component of the earth's field (~ 0.25 gauss at NOLC), a variation of one minute of arc from the horizontal will cause an apparent change in field of 10^{-4} gauss.

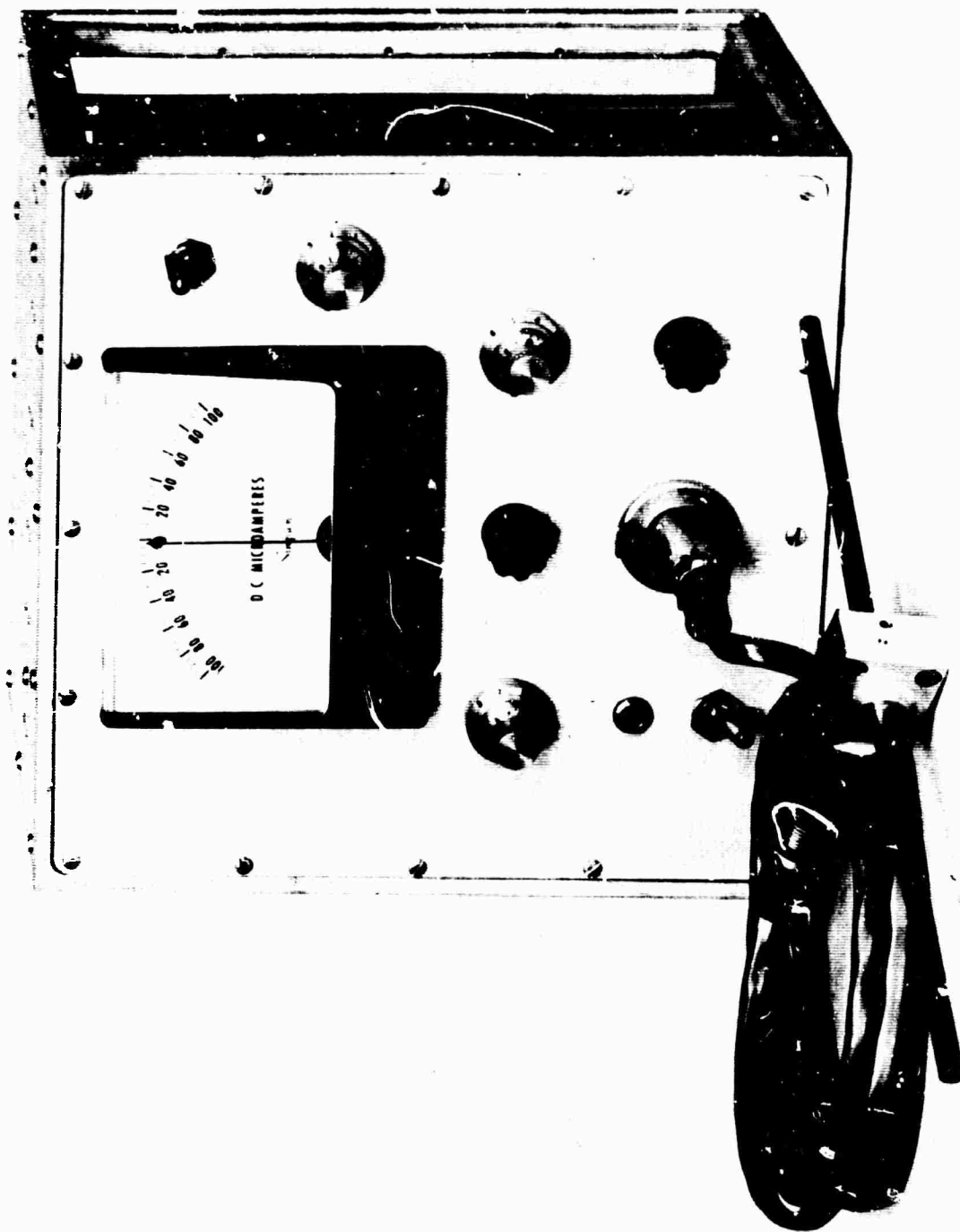


FIGURE 14. Self-Contained Portable Battery-Operated Magnetic Field Detector

The following gradiometric methods were investigated:

1. A differential method was employed, using two Hall generators spaced at variable distances from one another and feeding a differential amplifier. The complete apparatus was tested for sensitivity and stability. The magnetometers and auxiliary circuits are shown in Figure 15. Measurements were taken at arbitrary angles with respect to the horizontal component of the earth's field. Adequate sensitivity from a magnetic radiator was obtained only when the Hall signal generated by the earth's field was compensated by mechanical orientation of the entire assembly. Figure 16 shows response of such differentially connected sensors.

2. Two magnetometers at right angles to each other were used, and their outputs were summed using various analog summing procedures. It was hoped that a reduction in the directional sensitivity of the complete assembly would not impair the overall sensitivity of the detected signal. Figure 17 shows the type of compensation for the earth's field that may be obtained by such a system. Neither the mechanical nor the electrical stability were sufficient for the detection of fields less than 0.1 gauss.

3. An electro-optic feedback element was used between the amplified output of a Hall generator magnetometer and the input current control. By moving the magnetometer in a circular horizontal plane with respect to the earth's field, a compensation of the order of 5 to 1 was obtained as shown in Figure 18, which compares the magnetometer readings before and after feedback was applied to the magnetometer.

A continuous analog compensation for the earth's field in three dimensions is an absolute necessity for allowing the portable operation of the magnetometer, and either a mechanical or an electrical feedback system is required to provide a dynamic balance to at least 0.01 percent. Therefore, further work on these techniques was discontinued, although in principle the system is entirely feasible, provided that no limitations are imposed on the requirements of the electronic data processing system or power supply limitation.

RECOMMENDATION FOR FUTURE WORK

It is recommended that work be continued on the Hall effect in thin films of the intermetallic compounds similar to InSb for the following purposes:

1. The detection of magnetic fields of 10^{-6} oe by means of flux-concentrator-equipped magnetometers. This appears feasible in view



FIGURE 15. Differentially Connected Magnetometers and Associated Circuits

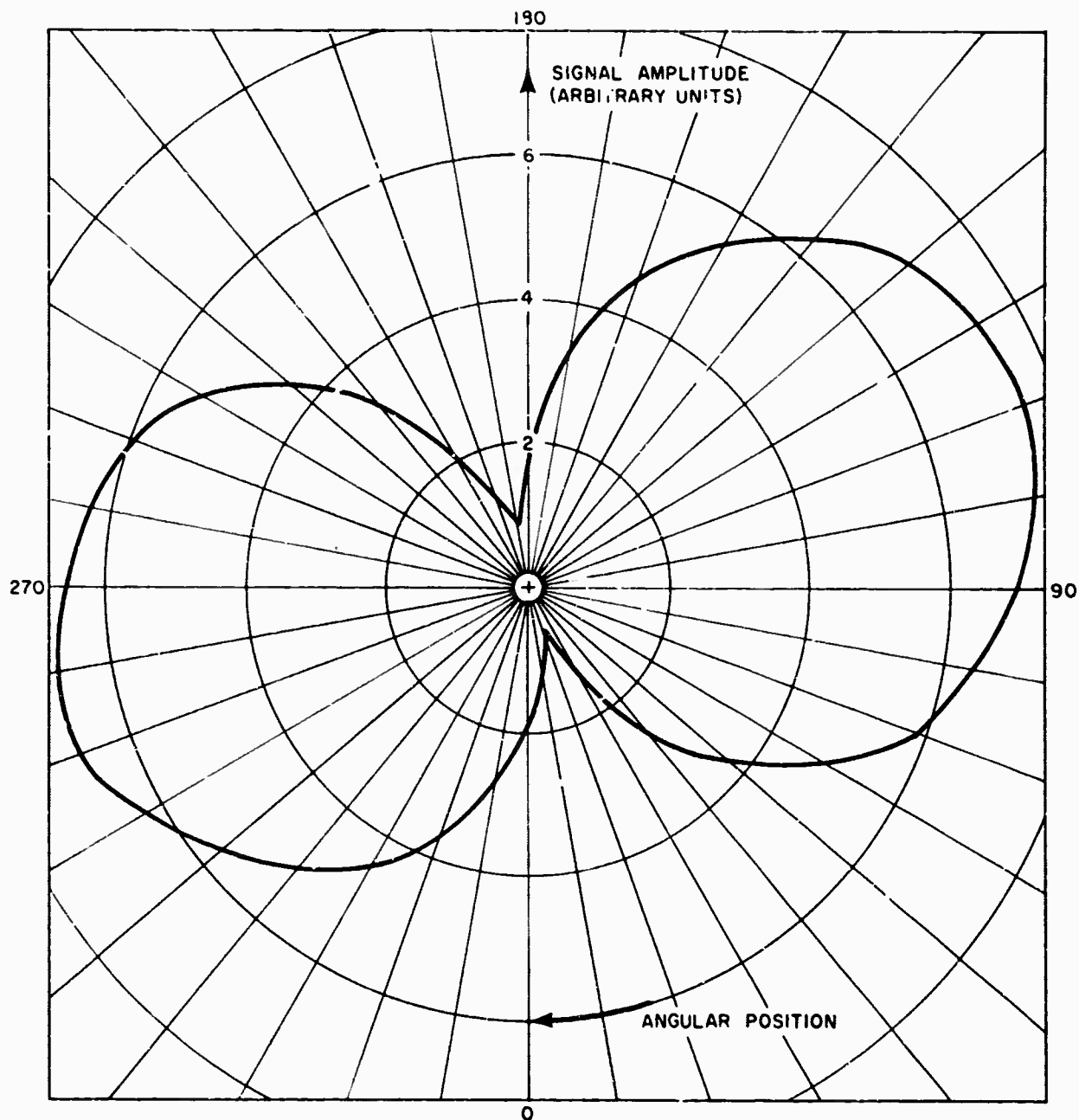


FIGURE 16. Output of Two Parallel Differentially Connected Hall-Effect Field Sensors as a Function of Position in the Earth's Field. The signal is an error voltage due to inhomogeneities in the field within the laboratory and to misbalance in sensitivity of the two sensors. The signal is less than 10 percent of that from a single sensor in the earth's field.

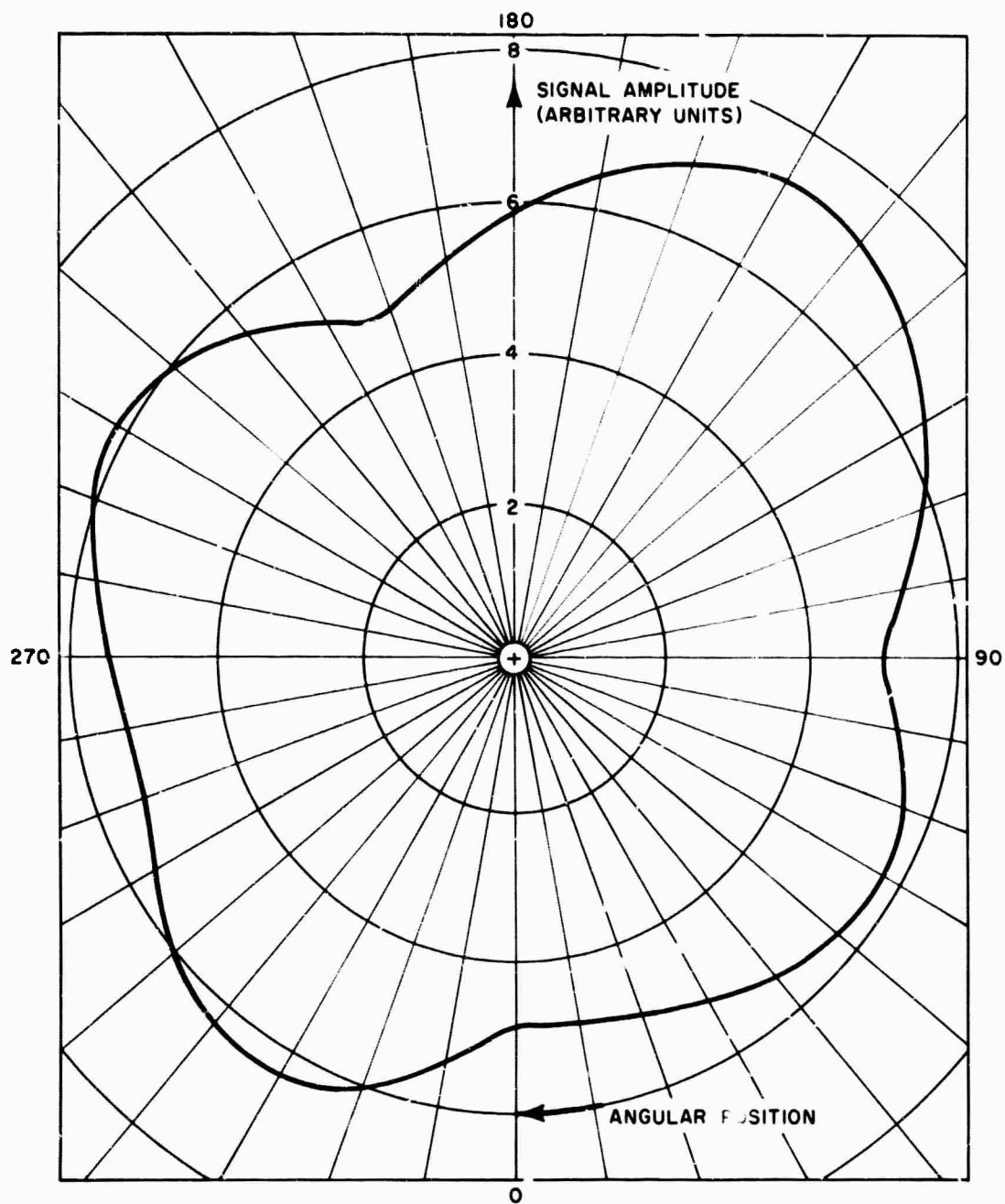


FIGURE 17. Summed Output of Two Hall-Effect Field Sensors at Right Angles as a Function of Position in the Horizontal Component of the Earth's Field

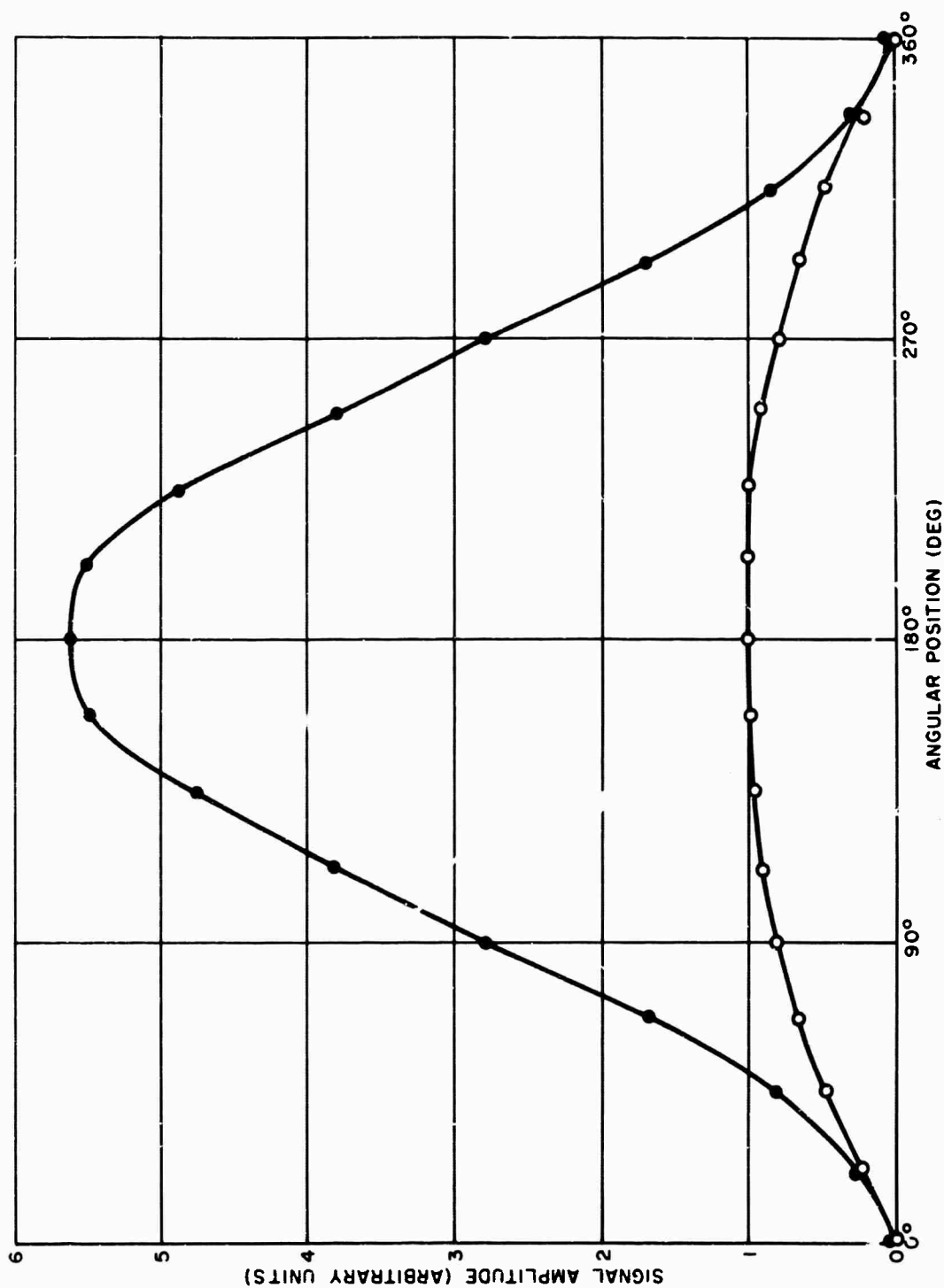


FIGURE 18. Output of a Hall-Effect Field Sensor as a Function of Position in the Earth's Field. Solid circles indicate response without feedback, and open circles indicate response with feedback applied to the magnetometer.

of improvements in the technique of deposition, which is likely to raise the electron mobility to $\mu = 5 \times 10^4 \text{ cm}^2/\text{volt-sec}$.

2. The detection of linear displacement by transducers based on the Hall effect. Such transducers would be especially useful as seismic detectors.

3. Temperature compensation of Hall sensors. A temperature-stabilized Hall generator requiring small amounts of power could act as an effective magnetic compass over long periods of unattended operation.

4. Development of station magnetometers based on the Hall effect. Such magnetometers could act as remote-area sensors of temporal variations in the local earth's field; hence, they might be useful as oceanographic research tools.

Appendix A

OPERATING INSTRUCTIONS FOR THE HALL-EFFECT MAGNETOMETER

Operating Procedure

The Hall-effect magnetometer is a sensitive electronic instrument. No attempt has been made to waterproof the instrument nor to provide fungus protection. Because of its sensitivity, the operation of the magnetometer is somewhat critical. The following operating procedure is recommended:

1. Locate the field sensor so that it will not move in the earth's field. (Anchor it securely.)
2. Set the controls as follows:
 - a. FINE BALANCE at 5.00
 - b. Switch S2 at BRIDGE
 - c. GAIN at minimum (clockwise)
 - d. METER SENSITIVITY at minimum (clockwise)
3. Turn on power switch S1, and adjust COARSE BALANCE to give minimum reading.
4. Increase GAIN to give full-scale reading; readjust COARSE BALANCE to give minimum response, and lock dial.
5. Adjust REACTIVE BALANCE to give minimum reading.
6. Increase GAIN to give full-scale reading and adjust FINE BALANCE and REACTIVE BALANCE to give minimum response.
7. Repeat step 6 until maximum gain is reached.
8. Turn S2 to SYNC. DEM. and increase METER SENSITIVITY to maximum.

9. Adjust response to zero with FINE BALANCE.

NOTE

If the REACTIVE BALANCE is disturbed, the sensitivity will be decreased. To readjust, turn switch S2 to BRIDGE and repeat steps 6 through 9; decrease the GAIN and METER SENSITIVITY if necessary.

The field sensor is color-coded to match the detector. Be sure to use the correct detector with the sensor. The red-coded unit uses a thin-film InSb Hall generator. The green-coded unit uses an F. W. Bell Model BH-200 InAs Hall generator.

A circuit diagram is located on the inside of the back panel of each detector.

Battery Replacement

The magnetometer is designed to operate from a 12- to 15-volt source. The current generator and the detector amplifier are powered separately, each by three series-connected 4.2-volt Mallory TR-233 mercury cells. Access to the batteries is gained as follows:

CURRENT GENERATOR BATTERY - remove the top panel.

DETECTOR AMPLIFIER BATTERY - remove the bottom panel.

Magnetometer Capability

These magnetometers will measure full-scale deflection for magnetic fields on the order of 10 gamma (10^{-4} gauss) at their maximum sensitivity. The sensor measures only field components parallel to the flux concentrator rods. During operation, the earth's field component (tenths of a gauss) must be balanced out. The magnetometer is sensitive to the magnetic fields of ferromagnetic objects in its proximity, to variations and fluctuations in the earth's magnetic field, to changes in the position of the sensor in the earth's field, and to temperature changes in the sensitivity of the Hall generator. Since the concern is to detect the presence of ferromagnetic objects, the other factors are all forms of noise and should be kept to a minimum.

Environmental Factors

Environmental problems that may be detrimental to the operation of the magnetometer are outlined below:

1. Alternating magnetic fields such as from power lines can be large enough to overload the amplifier at maximum sensitivity. The 1-kc band-pass filter of the amplifier prevents reasonably small fields from being a problem; however, large enough alternating fields can disrupt the operation of the magnetometer. The presence of large alternating fields is indicated by the inability to obtain a minimum reading at high gain with the switch S2 in BRIDGE position.

2. Variations in the ambient field cause a drift in the null of the magnetometer that is impossible to differentiate from field variations due to the presence of a ferromagnetic object or to positional variation of the sensor in the ambient field. The earth's field has short-term variations typically on the order of 1 gamma, and over a period of an hour the variation is tens of gammas.

3. Temperature drift in the Hall sensor sensitivity will cause shifting of the null so that the magnetometer must be rebalanced if there is a change in ambient temperature. Any temperature change of the balancing circuit will also affect the null; however, the temperature coefficients of resistance of the components is small compared to Hall sensor sensitivity change. The temperature coefficient of sensitivity for the thin-film InSb Hall generator is typically about 1 percent per degree Centigrade. The InAs bulk material Hall generator has a temperature coefficient of 0.1 percent per degree Centigrade. If the field sensor is aligned in the earth's field with the Hall voltage balanced to provide a null, it would require only a 0.04-percent drift in sensitivity to drive the meter off scale.

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