AN ELECTRONIC MAGNETOMETER

By

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1942

Submitted to the Faculty of the Graduate School of

the Oklahoma Agricultural and Mechanical College

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

1950

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PREFACE

For many years data have been compiled on the magnitude of the earth's magnetic field. With improved instrument technology, small variations in geomagnetism have been found. Some of the "micropulsations" have been attributed to local electric currents in the ionosphere. In conjunction with the current sferic research under the direction of Dr. H. L. Jones at the Oklahoma Institute of Technology, it was thought that an investigation should be made of the variations in the earth's magnetic field. As a basis for research in this field, the electronic magnetometer, described in this thesis, has been designed, constructed and subjected to elaborate operational tests.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation for the valuable suggestions and help offered by his friends and colleagues. He is greatly indebted to Dr. Clark A. Dunn, Director of the Division of Engineering Research and Experiment Station of the Oklahoma Institute of Technology, for the allocation of funds with which to purchase the component parts used in the construction of the magnetometer. Special thanks are due Dr. Herbert L. Jones, under whose supervision the work was done.

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CHAPTER I

INTRODUCTION

Since the ancient discovery of the magnetic properties of the lodestone, the complex nature of the earth's magnetic field has intrigued investigators. A slow secular variation of the field was first noted by Gellibrand in 1634.[1] Later studies of geomagnetism[2,3] have revealed diurnal, monthly, and annual variations of lesser degree, in addition to several small, short-period fluctuations of somewhat uncertain origin. The electronic magnetometer described herein was developed to facilitate measurement and recording of fluctuations as small as 2 gammas. The unit gamma, commonly used among geophysicists, is a measure of magnetic field intensity, the equivalent of 10^{-5} oersteds or approximately 8×10^{-4} ampere-turns per meter. Since the magnitude of the earth's magnetic field vector at Stillwater, Oklahoma, is approximately 55,000 gammas,[4] a 2-gamma variation would be about 0.0036% of the total field. This compares favorably with the optical-system type used by the Department of Terrestial Magnetism of the Carnegie Institution of Washington,[5] and has the advantage of instantaneous, continu-

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1 J. A. Fleming, _Terrestial Magnetism and Electricity_, p. 5.

2 _Ibid_., pp. 1-53.

3 Carnegie Institution of Washington, _The Geomagnetic Field, Its Description and Analysis_, pp. 1-6, 35, 93, 257-273.

4 _Ibid_., p. 20.

5 Fleming, _op. cit_., pp. 71-87.

ous reading and recording. Because it is electronic, sensitivity can be increased by means of additional amplification, but much greater sensitivity was not considered necessary. Figure 1 is a photograph of the magnetometer with the recording ammeter at the right, the power supply above, and the magnetic unit in front. Rear and bottom views of the main chassis are shown in Figure 2 and Figure 3.

Figure 1. Photograph of the Magnetometer, Power Supply, Recording Ammeter, and Magnetic Unit.

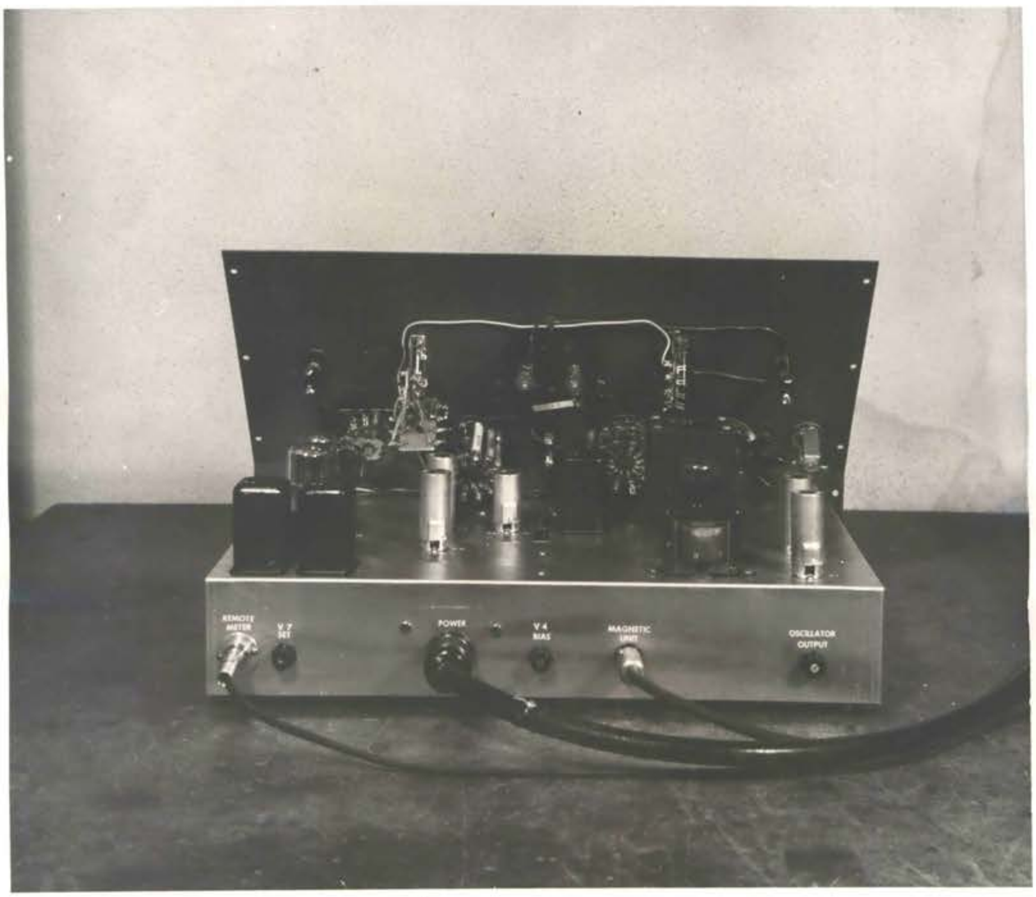

Figure 2. Rear View of the Main Chassis.

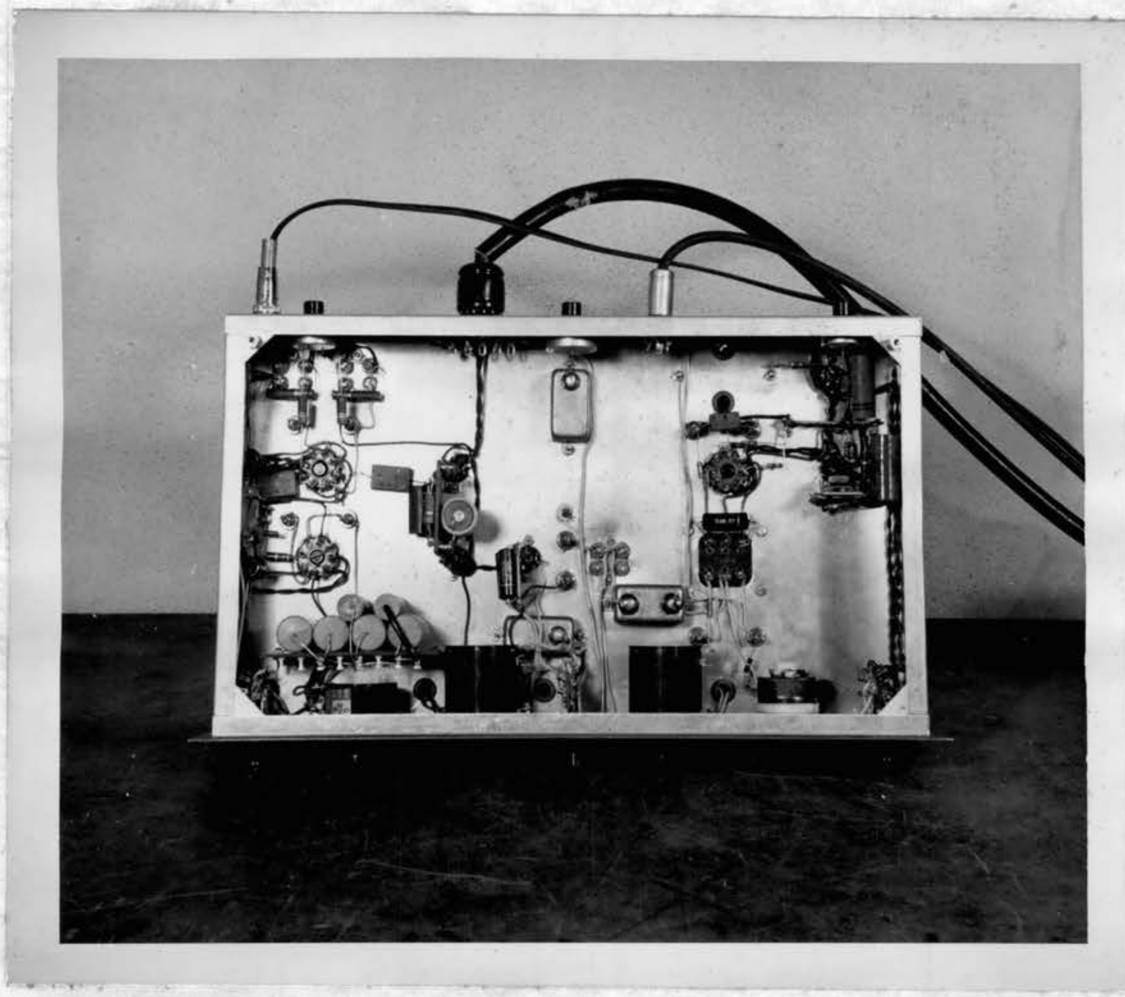

Figure 3. Bottom View of the Main Chassis.

CHAPTER II

PRINCIPLE OF OPERATION

Saturable-Core Inductors

The electronic magnetometer detects the geomagnetic field by the use of saturable-core inductors.[1] A number of modern magnetic materials[2] have hysteresis loops similiar to that shown in Figure 4, characterized by very high permeability at low flux densities, saturation at a relatively low value of magnetizing force, and low hysteresis loss. This last property is evidenced by the small area enclosed by the loop. Between the points a' and a, the permeability is very high, but in the regions of saturation b'-a' and a-b the relative permeability is equal to one. If the magnetizing force H is caused by current-carrying coils surrounding a core of the magnetic material, H is directly proportional to the value of the

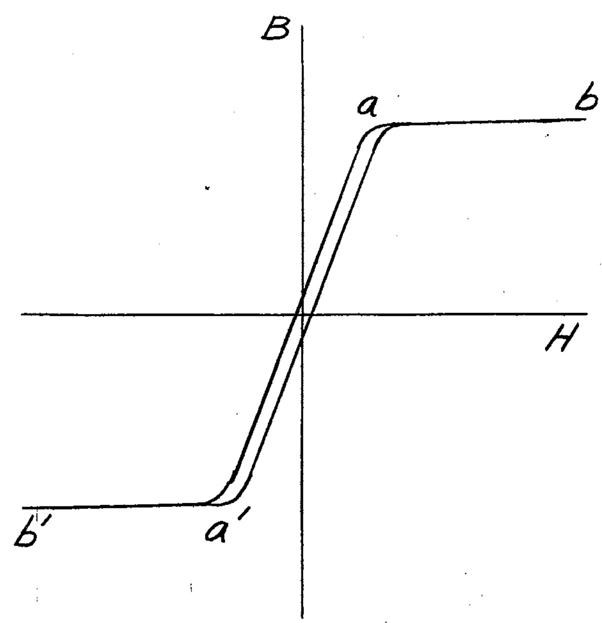

Figure 4. Hysteresis Loop.

[1] W. E. Tolles, "Applications of the Saturable-Core Magnetometer," Proceedings of the National Electronics Conference, III (1947), 504-513.

[2] Stephen S. Attwood, Electric and Magnetic Fields, 3d Edition, pp. 325-355.

current I and to the number of turns in the coil. The magnetic flux is equal to the product of the flux density B and the cross-sectional area of the core.

A variety of circuits may be employed with saturable-core coils. If the core is driven into saturation, the sudden change in flux will produce a voltage pulse. One simple basic circuit uses a sinusoidal source of very high internal resistance connected to a saturable-core coil. The current flow in the coil, as shown in Figure 5, is approximately sinusoidal since the impedance of the coil is relatively low. If peak current were considerably greater than the value necessary to saturate the core, flux would be as indicated in Figure 5.

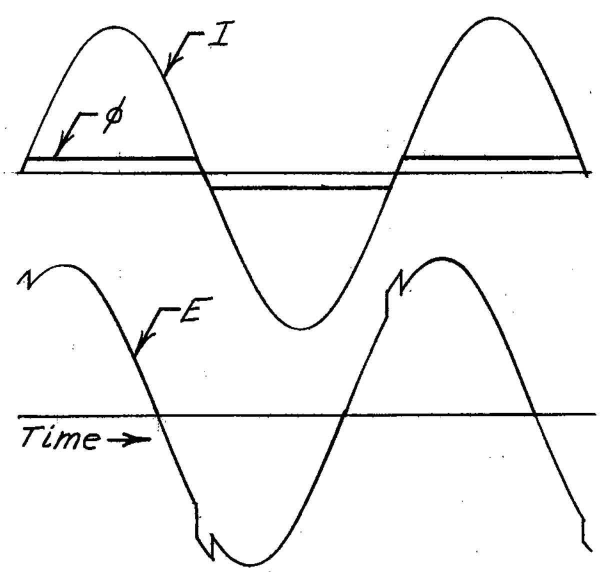

Figure 5. Current, Flux, and Voltage for a Saturable-Core Coil.

Although the ordinary concept of impedance does not apply to nonlinear parameters, the circuit may be analyzed in terms of impedance as long as only saturated conditions are considered. During saturation, coil inductance is the value the coil would have with an air core so that, considering the resistance of the winding, the voltage across the coil would be expected to lead the current by an angle less than 90 degrees. Neglecting the period of non-saturation, a sinusoidal variation of voltage would be expected. During the brief interval around the instant of zero current, however, the change in flux will produce a counter e.m.f., resulting in the net voltage waveform shown in Figure 5.

If the core should be magnetically biased a small amount due to an external field, the pulse portion of the voltage curve would occur slightly earlier or slightly later, depending upon the direction of the externally caused flux. A measure of the instant during the cycle when the pulse starts could thus be used for detection of an external magnetic field.

A more satisfactory scheme is the use of the bridge circuit[3] shown in Figure 6. Two coils are fed from a push-pull source and so connected that fluxes produced by current flow in them will be opposing in the common magnetic core. If the push-pull source is perfectly balanced and the coils are identical, there can be no net flux in the core due to coil currents. If, however, a slight unbalance is introduced by the addition of resistance across one arm of the bridge, a small net flux will result. With fairly high amplitude of source voltage and many turns on the coils, there will be ample net flux to drive the core well

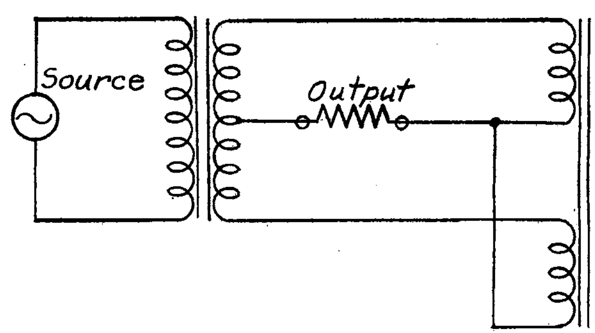

Figure 6. Bridge Circuit.

3 Tolles, op. cit., pp. 506-507.

into saturation. Figure 7 shows voltage, current, and flux waveforms that might result. Phase relations have been exaggerated in order to enlarge the magnitude of net current so that it will show on the scale used for individual currents.

Actual mathematical analysis of the bridge circuit is difficult because some circuit parameters are nonlinear, others are of indefinite value, and there is a high coefficient of coupling between coils. However, the graphical picture agrees well with the photographs of the waveforms of coil voltages, shown in Figures 14 and 15. Output of the bridge will be a series of alternately positive and negative pulses whose magnitudes will be alike if no externally caused magnetic field exists in the core. The positive-pulse amplitude will exceed the negative-pulse amplitude if the core is magnetically biased due to any average field which exists within the core in the proper direction. A measure of the difference in amplitudes will therefore indicate the magnitude of the field. In order to measure small variations of a magnetic field like that of the earth, it is necessary to cancel out its average value. This can be done by sending a direct current through the coils such that the flux produced thereby will oppose the flux due to the geomagnetic field. Connection of a d-c source across the output terminals of Figure 6 will cause current flow through the coils in such a direction that flux produced by one coil will aid that produced by the other coil. The magnitude of the net flux of the two coils can then be adjusted to exactly cancel that of the earth's field.

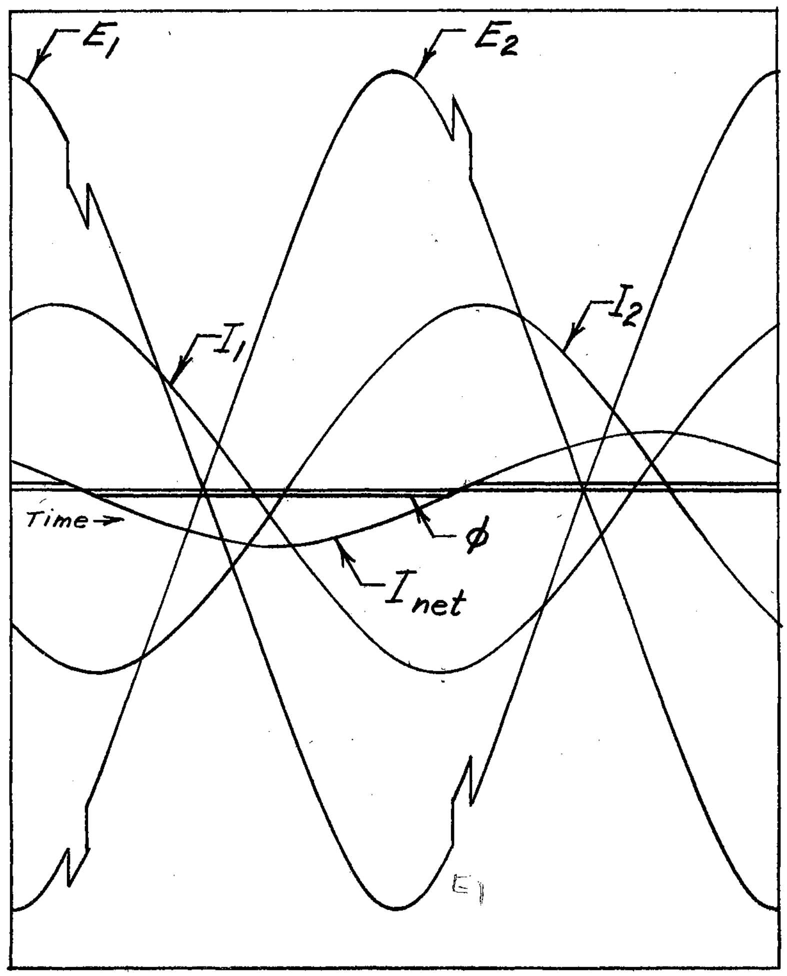

Figure 7. Voltage, Current, and Flux Waveforms for a Bridge Circuit.

Circuit Diagrams

Figure 8 shows a block diagram of the magnetometer. The oscillator, buffer and power amplifier section supplies push-pull sinusoidal output to the magnetic unit. The output from the magnetic unit is passed through a biased diode to clip out certain undesired portions of its waveform. Signal voltage is then amplified in the pulse amplifier before being applied to the balanced detector, where the difference between positive and negative pulse magnitudes is detected. The amount of this difference is registered on meters in the output of the balanced-bridge vacuum-tube voltmeter.

The circuit diagram of the main chassis of the magnetometer is shown in Figure 9, that of the power supply is drawn in Figure 10. A cabling diagram for connections to the power source, remote meter and magnetic unit, and for interconnection of the two chassis is shown in Figure 11. A list of parts is given in Table I.

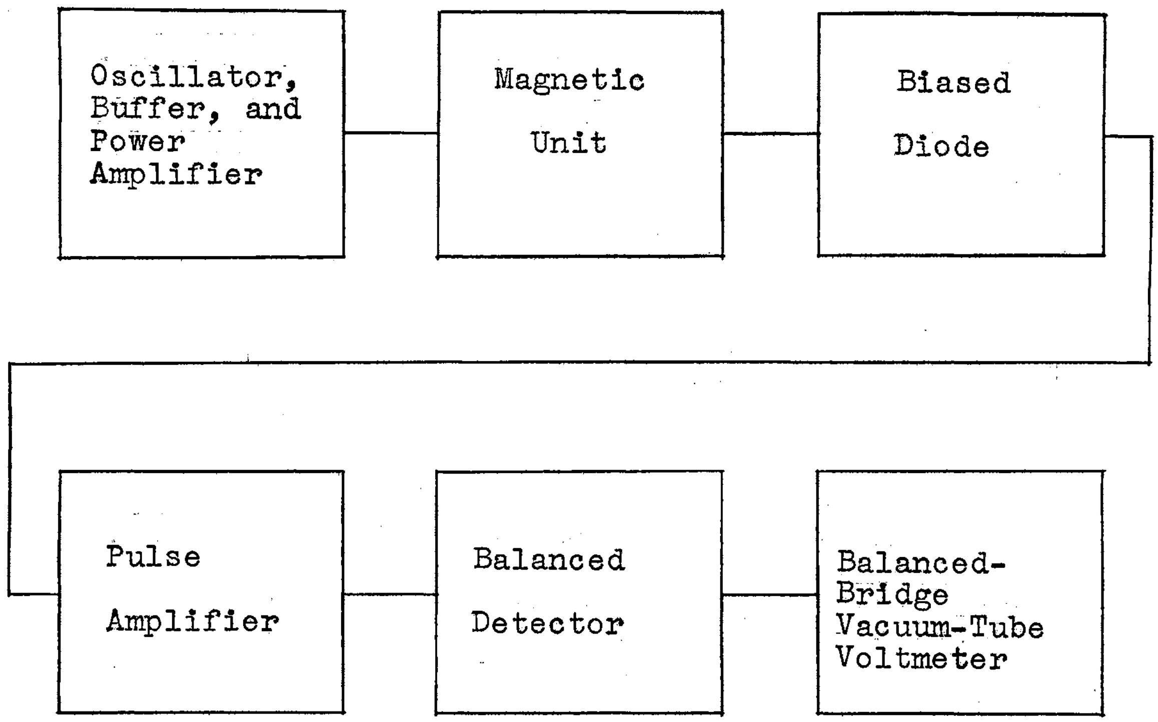

Figure 8. Block Diagram of the Magnetometer.

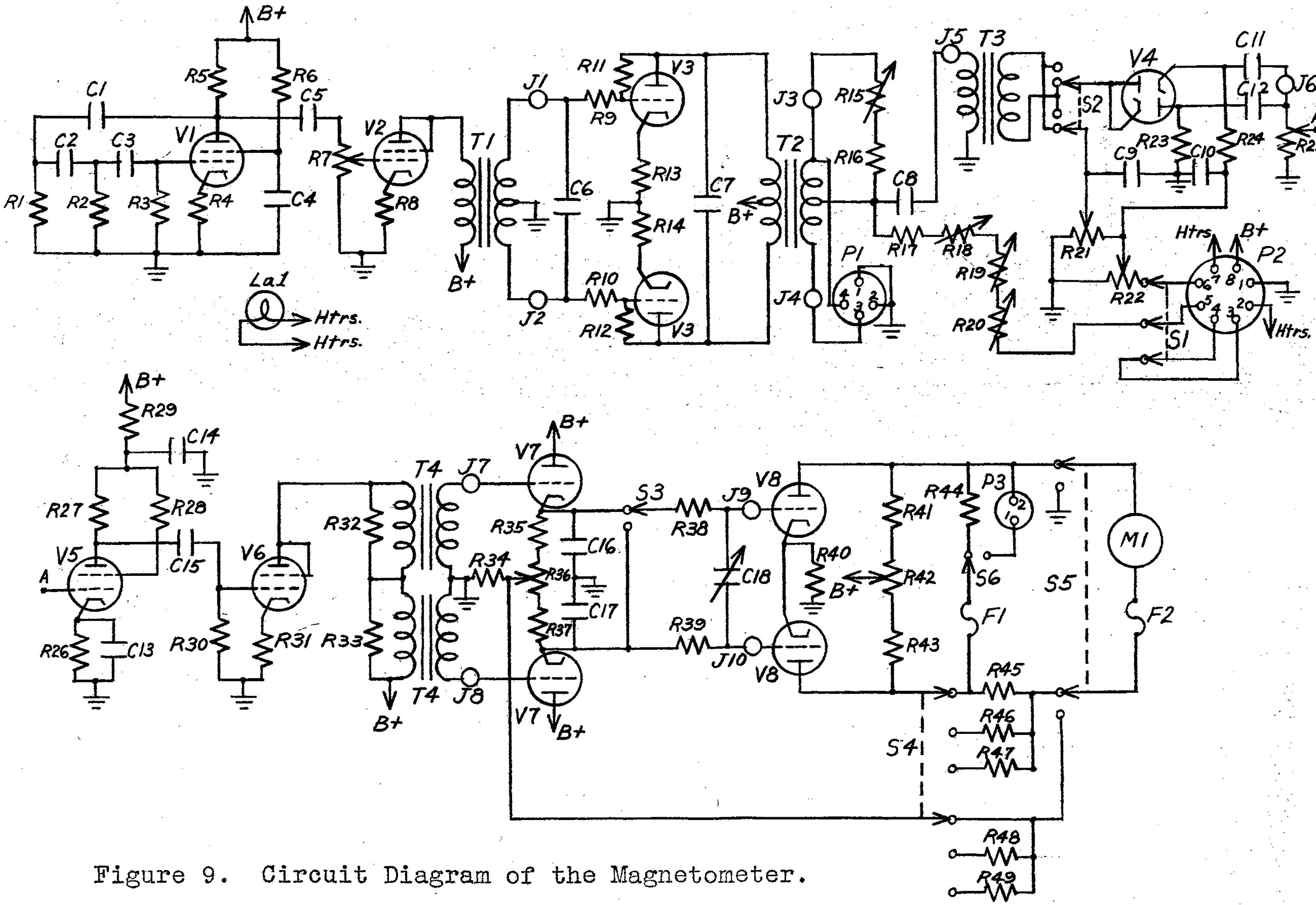

Figure 9. Circuit Diagram of the Magnetometer.

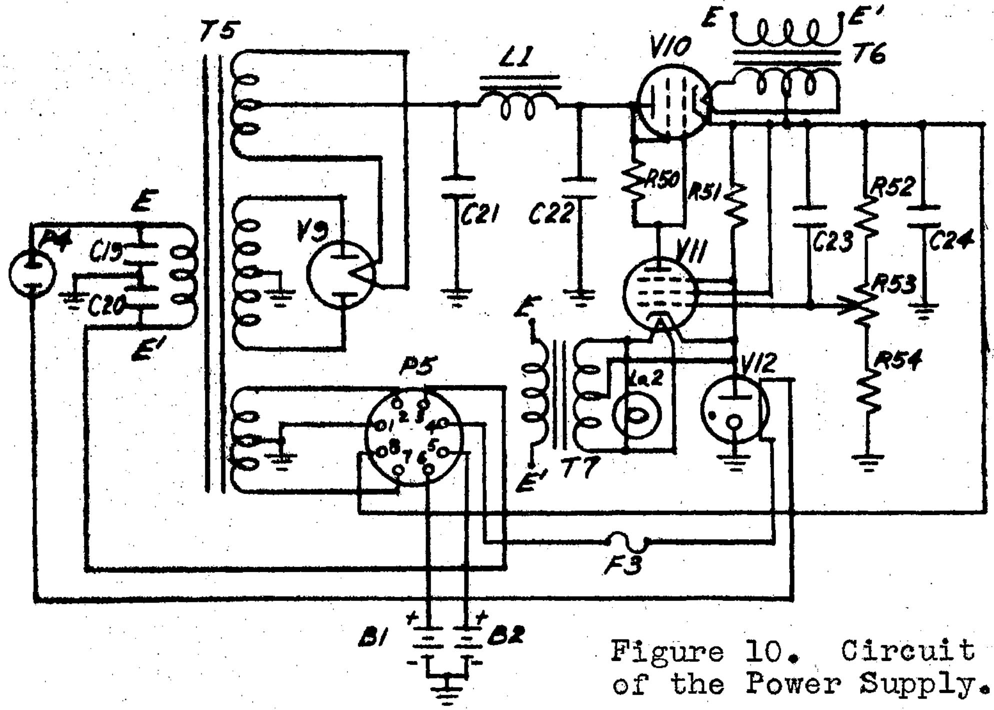

Figure 10. Circuit Diagram of the Power Supply.

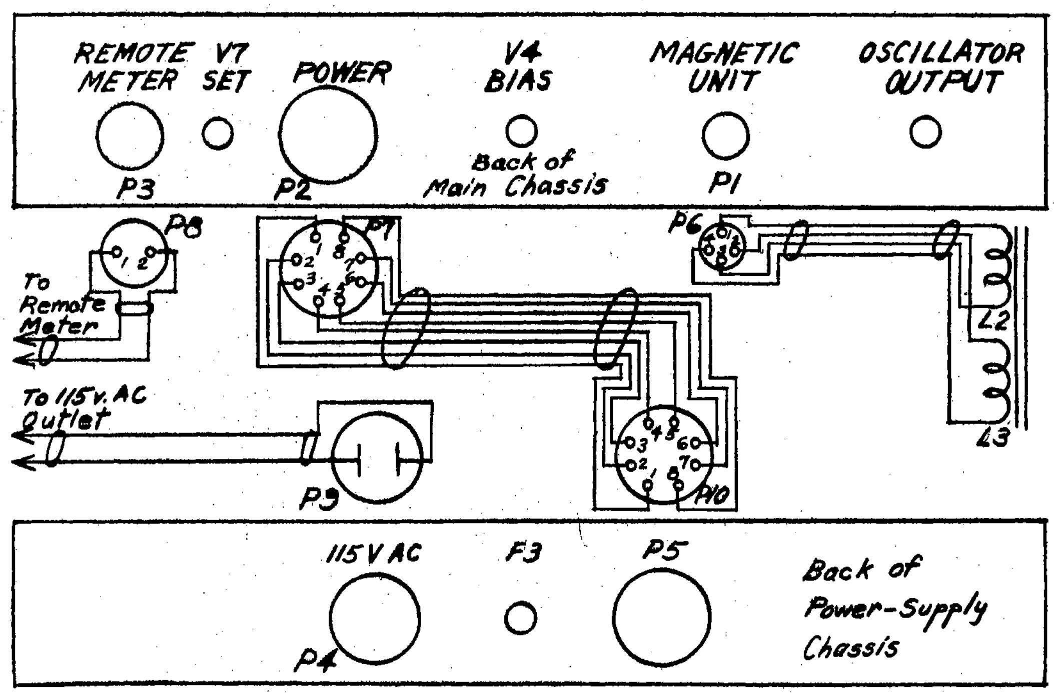

Figure 11. Cable Connections.

TABLE I

LIST OF PARTS

Batteries

B1	6 v. lantern battery, F4BP		
B2	7 Mallory RM3 cells		

Capacitors (All capacitances are in microfarads. All capacitors are paper unless otherwise specified.)

C1	0.0002 mica	C13	20, 25 v. electrolytic
C2	0.0002 mica	C14	16, 450 v. electrolytic
C3	0.0002 mica	C15	0.01
C4	8, 400 v. electrolytic	C16	0.005 mica
C5	0.1	C17	0.005 mica
C6	0.001	C18	0.1-1.0 decade
C7	0.02	C19	0.05
C8	0.5	C20	0.05
C9	0.5	C21	8, 600 v. electrolytic
C10	0.5	C22	8, 600 v. electrolytic
C11	0.02	C23	1
C12	0.02	C24	8, 600 v. electrolytic

Fuses

F1	1/100 a., 8AG	F3	5 a., 3AG
F2	1/200 a., 8AG		

Jacks

J1 - J10 Phone tip jacks

Inductors

L1	15 h., 75 ma. choke	L2, L3	Magnetic-unit coils (See text.)

Lamps

La1, La2 6.3 v., 0.25 a. bayonet-base lamps

Meters

M1	50-0-50 microammeter	M2	0-1 ma. recording ammeter

Plugs and sockets

P1	Four-contact socket	P6	Four-contact plug
P2	Octal plug	P7	Octal socket
P3	Two-contact socket	P8	Two-contact plug
P4	A-C plug	P9	A-C socket
P5	Octal socket	P10	Octal plug

TABLE I

(Continued)

Resistors (All resistances are in ohms. K represents 1000; meg. represents megohms. All resistors are 1/2 watt unless otherwise specified.)

R1	680 K	R28	100 K
R2	680 K	R29	5.6 K, 1 w.
R3	360 K	R30	560 K
R4	100	R31	560
R5	27 K	R32	25 K
R6	82 K	R33	25 K
R7	500 K potentiometer	R34	1.8 K
R8	4.7 K	R35	680 K
R9	100 K	R36	1 meg. potentiometer
R10	100 K	R37	680 K
R11	1 meg.	R38	1 meg.
R12	1 meg.	R39	1 meg.
R13	3.3 K	R40	4.7 K
R14	3.3 K	R41	10 K, 10 w.
R15	200 potentiometer	R42	2 K, 3 turn potentiometer
R16	100	R43	10 K, 10 w.
R17	180	R44	1.33 K
R18	200, 10 turn potentiometer	R45	33 K
R19	7 x 4.15 K steps	R46	330 K
R20	23 x 180 steps	R47	3.3 meg.
R21	5 K, 10 turn potentiometer	R48	1 K
R22	5 K potentiometer	R49	8 K
R23	62 K	R50	1 meg.
R24	62 K	R51	22 K, 2 w.
R25	1 meg., 10 step attenuator	R52	100 K
R26	820	R53	50 K w.w. potentiometer
R27	33 K	R54	68 K

Transformers

T1	3:1 interstage	T5	Power transformer: 750 v. c.t., 150 ma.; 5 v., 3 a.; 6.3 v., 5a.
T2	AX 773 (See text.)	T6, T7	Filament transformers: 6.3 v., 1.2 a.
T3	901737-501 (See text.)		
T4	2 901737-501 (See text.)		

Tubes

V1	6AG5	V7	6SL7
V2	6AG5	V8	6SN7
V3	6SN7	V9	5Y3
V4	6AL5	V10	6L6
V5	6AG5	V11	7C7
V6	6AG5	V12	OD3

CHAPTER III

DESCRIPTION OF EACH MAJOR UNIT

Oscillator, Buffer, and Power Amplifier

To drive the magnetic unit to saturation requires a source of sinusoidal voltage with the following characteristics: amplitude as constant as possible, frequency approximately 400 cycles per second, and push-pull output adjustable to give at least 12 volts r.m.s. when connected to the magnetic unit. A phase-shift oscillator[1] seemed to satisfy best the requirements of constant amplitude and fixed frequency. In the circuit diagram, Figure 9, V1 is the oscillator tube with C1 R1, C2 R2, and C3 R3 forming the phase-shifting network.

The output of V1 is fed through C5 and R7 to the grid of V2, the buffer amplifier tube. Adjustment of potentiometer R7 controls the amplitude of voltage delivered to the magnetic unit. This potentiometer, marked Oscillator Output, is mounted at the back of the main chassis so that adjustment may be made with a screwdriver.

V2 has as its plate load an ordinary audio interstage transformer T1, which provides push-pull signal voltage to the dual-triode power amplifier V3. It is coupled to the magnetic unit through a special audio transformer T2, the secondary of which is very carefully center-tapped within an accuracy of 0.1%. To improve the waveform of the output both the secondary of T1 and

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[1] Frederick E. Terman, Radio Engineers' Handbook, p. 506.

the primary of T2 are tuned to approximately 400 cycles. Figures 12 and 13 show the output waveforms of T1, from J1 to ground and J2 to ground.

Magnetic Unit

The magnetic unit, shown in front of the main cabinet in Figure 1, consists of two coils L2 and L3 surrounding a core of magnetic material. Each coil is carefully wound of 2000 turns of number 32 enameled wire. Each has approximately 115 ohms of d-c resistance and 13 millihenrys of inductance without the magnetic core. The magnetic core is a strip of high-permeability material approximately 1/8 inch wide and 5 inches long. The core and coils are mounted in a machined strip of linen bakelite to which is attached a terminal strip to facilitate electrical connection between coil leads and the conductors of the cable that plugs into P1 on the main chassis. Rheostat R15, marked Amplitude Adjust on the front panel of the main chassis, provides an adjustment of the unbalance of the push-pull circuit of the magnetic unit. The output of the magnetometer is a function of the degree of unbalance. R16 serves as a limiting resistance to prevent shorting one half of the secondary of T2 should R15 be turned to zero resistance.

As explained in Chapter II, operation of the magnetic unit requires that the average value of the earth's magnetic field be canceled by the flow of direct current through the coils of the magnetic unit. Since the magnetometer is to record variations as small as 2 gammas out of a total of 55,000 gammas, it is essential that the source supplying the biasing current shall

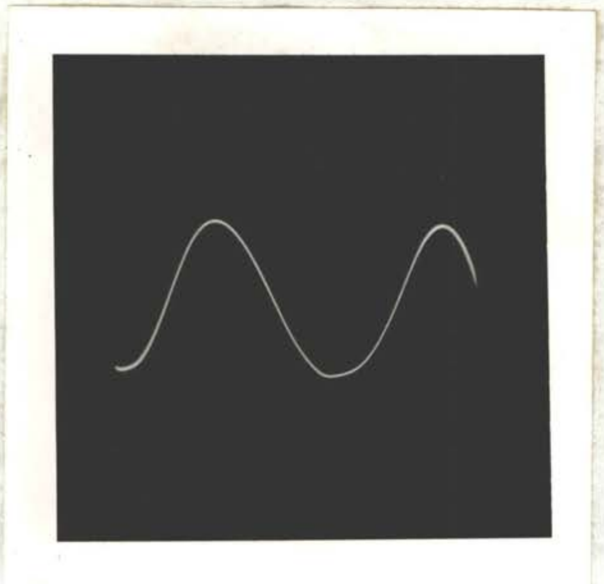

Figure 12. Waveform at J1.

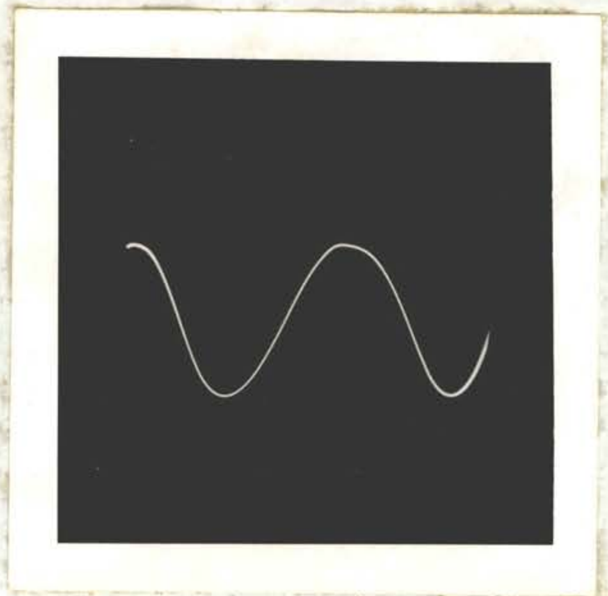

Figure 13. Waveform at J2.

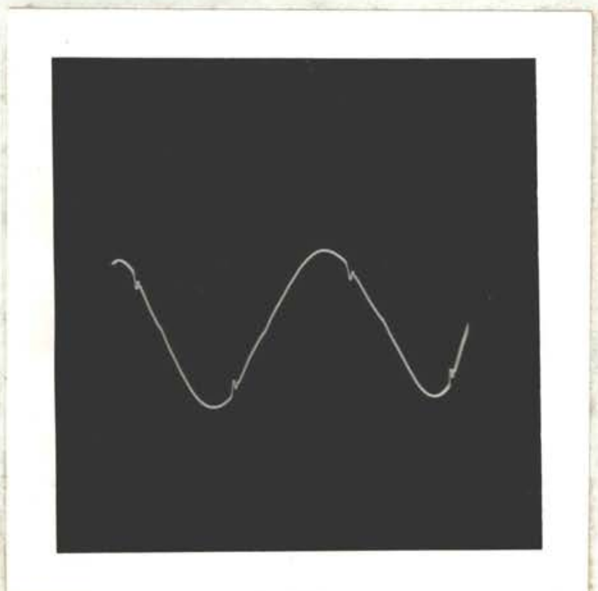

Figure 14. Waveform at J3.

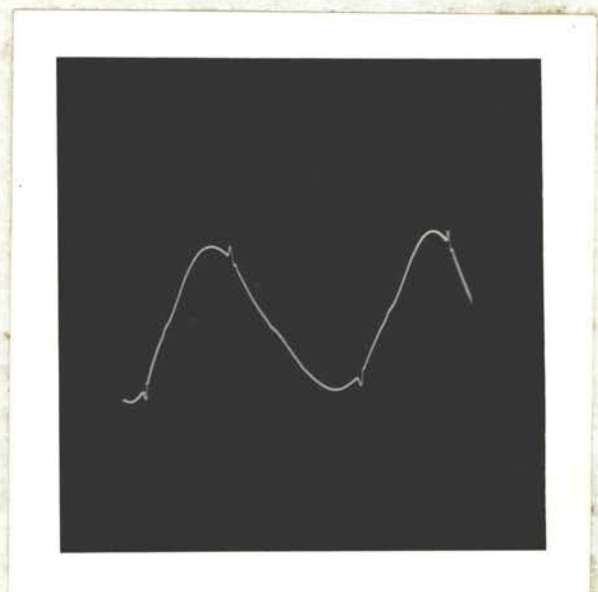

Figure 15. Waveform at J4.

have a regulation better than 0.0036%. Ordinary dry cells are not stable enough; even standard cells, with their limited current ratings, are not satisfactory. A new type of cell, the Mallory RM mercury cell,[2,3] does have very excellent regulation. Terminal voltage starts at 1.345 volts at no load. With small current drain, it decreases to 1.250 volts after about 0.1 ampere-hour and remains constant until the end of the cell's life when it drops quickly to zero. Seven of these cells are connected in series to supply the magnetic biasing current.

To give range and accuracy of the biasing current, three adjustable resistances R18, R19, and R20 are provided. R19, marked Coarse Bias Switch on the front panel, provides seven steps of 4,150 ohms each. R20, marked Fine Bias Switch on the front panel, provides twenty-three steps of 180 ohms each. R18, labeled Bias Vernier on the front panel, is a ten-turn 200-ohm potentiometer for accurate adjustment of the magnetic bias.

The output pulses from the magnetic unit are fed to the primary of T3 through capacitor C8 to block direct current from the primary of T3. Figure 16 shows the wave shape of the voltage appearing across this primary. An ordinary audio transformer can not be used for handling sharp pulses of this type because of its inability to transform the high frequency harmonics of

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[2] Maurice Friedman and Charles E. McCauley, "The Ruben Cell - A New Alkaline Dry Battery," Transactions of the Electrochemical Society, XCII (1947), 183-193.

[3] Samuel Ruben, "Balanced Alkaline Dry Cells," Transactions of the Electrochemical Society, XCII (1947), 195-215.

the pulses and because of the tendency for oscillation under pulsed conditions. The transformers T3 and T4 are special pulse transformers built by R.C.A. for pulse circuits. The ground connection to one winding is through internal connection to the case of the transformer.

Biased Diode

As evidenced in Figure 16, the output from the magnetic unit contains not only the desired pulses but also undesired variations about the time axis. To eliminate these undesired variations, the signal is fed through a double diode V4 which passes only positive and negative voltages whose magnitudes are greater than the bias voltage on the diodes. Moreover, since ultimately the difference between positive and negative magnitudes of the pulses is to be compared, a greater differential will exist if a fixed amount is subtracted from the magnitude of each. As shown in Figure 9, signal voltage is applied between ground, through the 1/2-microfarad capacitor C9, and both the plate of the upper diode and the cathode of the lower diode. Positive d-c voltage on this plate and this cathode with respect to ground is established by the setting of R21. The cathode of the upper diode is still more positive with respect to ground by an amount established by the setting of R22. Thus, should R22 be adjusted for +4 volts and R21 for +2 volts, the upper diode would pass positive signal amplitudes greater than 2 volts and the lower diode would pass negative signal amplitudes greater than 2 volts. R22, marked V4 Bias, is a screwdriver adjustment on the back of the main chassis, and R21, labeled Meter Center

Figure 16. Waveform at J5.

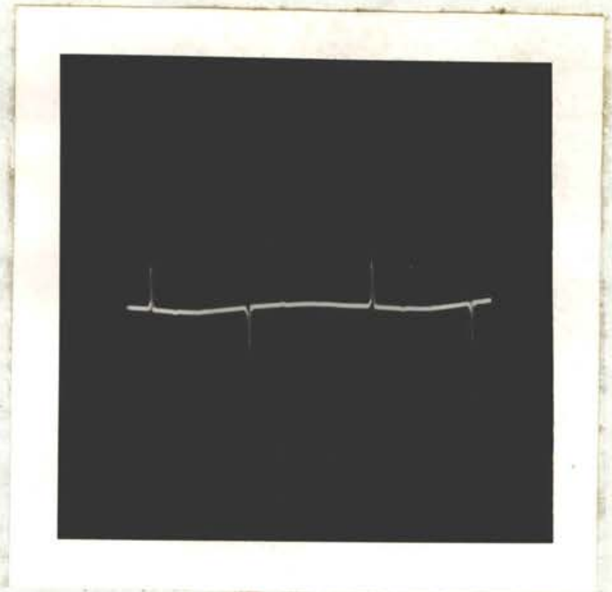

Figure 17. Waveform at J6.

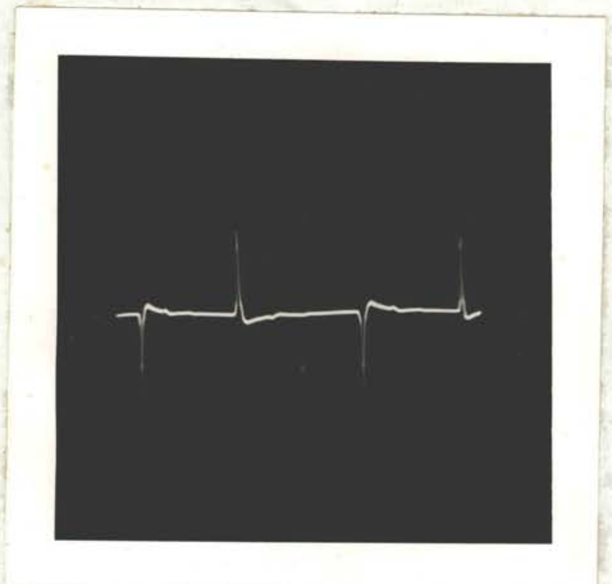

Figure 18. Waveform at J7.

Figure 19. Waveform at J8.

on the front panel, is a ten-turn potentiometer with which to adjust for equality of the thresholds of conduction of the diodes. The waveform of the signal output of V4 is shown in Figure 17.

Because a difference between the magnitudes of positive and negative pulses, evidenced by a deflection on the output meter, will result from either an improper amount of direct current in the coils of the magnetic unit or an improper adjustment of R21, there is a need for an indication as to which of these two is the cause. The indication is provided by manipulation of a spring-return reversing switch S2, marked Invert on the front panel. If depressing S2 causes a negative deflection equal to the positive deflection when it is released, R21 is properly adjusted. The deflection is therefore due to the fact that the bias current in the magnetic unit is not causing a flux exactly equal and opposite to the flux in the magnetic core due to the earth's field.

Pulse Amplifier

Because the output of V4 is relatively low in magnitude, it is necessary to amplify it through the two-stage amplifier V5 and V6. V5 is used as ordinary resistance-coupled pentode voltage amplifier.[4] C14 and R29 form a decoupling network to avoid the possibility of regeneration.[5] R25 labeled Gain on the front panel, is a one-megohm ten-step attenuator for controlling

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4 Terman, op. cit., pp. 354-366.

5 Ibid., pp. 406-410.

signal amplitude at the grid of V5. V6 is connected as a triode for the transformer-coupled amplifier stage. Because push-pull output is desired, T4 actually consists of two pulse transformers like T3, with primaries connected in series. R32 and R33 are used as damping resistors to suppress the tendency of the transformers to oscillate. The output of the pulse amplifier at J7 and J8 is shown in Figure 18 and Figure 19.

Balanced Detector

The amplifier pulses now must be compared in such a manner as to develop a d-c voltage that is a function of the difference between the magnitudes of the positive and negative pulses. Dual triode V7 serves this purpose as a push-pull infinite input impedance detector.[6,7] Resistance between cathodes and ground are large enough to bias the triodes close to cutoff. The magnitude of the d-c component of voltage between cathodes depends upon the difference between the magnitudes of positive and negative signal peaks, with polarity controlled by the larger.

Because it is difficult to obtain 6SL7 dual-triode tubes in which the two sections are identical, it may be found that even with no signal input a small d-c voltage will exist across the output of the balanced detector circuit. V7 must be carefully selected for minimum meter deflection when R25 is turned to zero. Some compensation is possible through adjustment of R36, labeled V7 Set at the back of the main chassis.

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6 Ibid., pp. 563-564.

7 Austin V. Eastman, Fundamentals of Vacuum Tubes, 3d Edition, pp. 573-574.

Balanced-Bridge Vacuum-Tube Voltmeter

The vacuum-tube voltmeter circuit[8,9] consists of a bridge circuit with arms composed of the two sections of dual triode V8, R41, and R43 with a portion of R42 added to each of the resistors. Direct voltage from plate to plate is metered. With no signal input to V8, the plates are at the same potential. If V7 drives the upper half of V8 in a positive direction and the lower half in a negative direction, the meter will deflect upward due to the difference in plate potentials. If the input is reversed in polarity, the meter will deflect downward. To compensate for dissimilarity in the two sections R42, labeled Meter Zero on the front panel, is adjusted for meter balance when both grids of V8 are receiving identical signal voltages. Identical signals are applied to the two grids by throwing switch S3, marked Operate-Zero on the front panel, to the Zero position. Normal position for S3 is on Operate. R38, R39, and C18 form a time-delay circuit which prevents sudden changes of voltage on the grids of V8. Since this delay effectively damps the meter swing, the decade-capacitance switch is labeled Meter Damping on the front panel. Between J9 and ground there is a d-c voltage with a small amount of ripple superimposed. The voltage between J10 and ground is of the same form, with the d-c voltage equal to that of J9 if the positive and negative

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8 Keith Henny, The Radio Engineering Handbook, p. 207.

9 P. Popper and G. White, "Analysis of Bridge-Type Valve Voltmeters," Wireless Engineer, XXV (December, 1948), 377-384.

pulse magnitudes are the same, unequal if not.

Metering Circuits

Meter M1, a 50-0-50 microampere instrument mounted in the center of the front panel, serves two functions. If S5, labeled Meter Selector Switch on the front panel, is in the Output position, M1 is connected through a multiplying resistor from plate to plate of V8. Meter reading is then a function of the difference in amplitudes of positive and negative pulses. When S5 is in the Amplitude position, M1 is connected across R34 and therefore indicates the amplitude of signal voltage at the grids of V7. The Meter Sensitivity Switch S4 inserts appropriate values of resistance in series with M1 for low, intermediate or high sensitivity. Since the meter must measure output voltage that is much larger than the amplitude voltage, two different banks of multiplier resistors are employed. Partial protection against excessive current through the meter is provided by F2, a 1/200-ampere fuse.

Provision is made for recording the output by means of a 1-milliampere recording ammeter connected to P3. If recordings are to be made, S6, marked Remote Meter on the front panel, must be turned to On position. When S6 is in Off position R44, which has the same resistance as the recording meter, is connected instead of it. A 1/100-ampere fuse F1 provides protection for the recording meter. Because resistances of different fuses of this rating are large and vary considerably, F1 is always in the circuit so that switching S6 from the remote meter to R44, which has resistance identical to that of the remote meter, will not vary the reading of M1. Multiplier resistor R45 has been so selected that full-scale deflection of M1 will accompany full-scale deflection of the recording meter. To circumvent the possibility of turning on the recording meter when excessive output voltage is being monitored by M1 on intermediate or low sensitivity, the recording-meter circuit is such that essentially no current will flow in it unless S4 is in High position where sensitivities of M1 and the remote meter are approximately equal.

Power Supply

The power supply, the circuit of which is shown in Figure 10, consists primarily of a standard voltage-regulated power supply circuit.[10] V9 rectifies the high voltage output of T5; L1, C21, C22 and C24 filter it. V10 is a series control tube, V11 amplifies any variation in output voltage and adjusts the voltage on the grid of V10 to minimize the variation. V12 is a voltage-regulator tube which establishes a reference voltage for V11. Because the cathodes of V10 and V11 are considerably positive with respect to ground, their heaters are powered by individual filament transformers rather than by the filament winding on T5. B1 is a 6-volt dry battery to supply bias voltage for V4. Because any change in the voltage of B1 will affect the bias on both halves of V4, minor variations have neglible effect on the output readings of the magnetometer. B2 consists of seven mercury cells to supply an extremely stable source for the

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[10] Ivan A. Greenwood, J. Vance Holdam and Duncan Macrae, Electronic Instruments, pp. 548-567.

current that biases the magnetic unit. When the power switch S1 on the front panel of the main chassis is turned to On position, the primaries of the power and filament transformers are energized and batteries B1 and B2 are connected to the proper circuits.

<u>Cabling</u>

Cable connections to the various units of the magnetometer are shown in Figure 11. The power supply is connected to a 115-volt a-c source through a conventional power cord. An 8-conductor cable carries power from the power supply to the main chassis. Two other cables plug into the back of the main supply, one to the remote recording meter, the other to the magnetic unit. Correct connection is facilitated by clear labeling of sockets and plugs on the two chassis and by the use of different types of connectors so that no plug can be inserted into the incorrect socket.

CHAPTER IV

OPERATING THE MAGNETOMETER

Placing the Equipment in Operation

Because there are fourteen controls on the front panel, most of which are interdependent, starting the magnetometer is an insurmountable task unless a definite plan is adopted. If the controls on the magnetic unit have been moved since the preceding operation of the equipment, the procedure outlined below must be very carefully followed. To aid in understanding the process, Table II lists the controls, the positions into which each may be put, its number on the circuit diagram of Figure 9, its function, and the page on which it is described.

1. Start with:

   Meter Selector Switch on Amplitude
   Meter Sensitivity Switch on Low
   Coarse Bias Switch on 4
   Fine Bias Switch on 12
   Remote Meter on Off
   Gain on 9
   Meter Damping on 9
   Power on Off
   Amplitude Adjust on 70
   Bias Vernier on 500
   Invert untouched
   Meter Center on 500
   Meter Zero on 150
   Operate-Zero on Operate

TABLE II

CONTROLS

NAME	POSITIONS	NO. ON DIAGRAM	FUNCTION	DESCRIBED ON PAGE NO.
Meter Selector Switch	Output Amplitude	S5	Selects voltage read by meter M1	26
Meter Sensitivity Switch	High Intermediate Low	S4	Selects multipliers for meter M1	26
Coarse Bias Switch	1-8	R19	Sets coarse range of magnetic bias	20
Fine Bias Switch	1-24	R20	Sets fine range of magnetic bias	20
Remote Meter	On Off	S6	Turns remote meter on and off	26
Gain	Off 1-10	R25	Varies gain of pulse amplifier	23
Meter Damping	1-9	C18	Varies C in RC time-delay circuit	25
Power	On Off	S1	Turns power on and off	28
Amplitude Adjust	0-100	R15	Adjusts unbalance of magnetic unit	18
Bias Vernier	0-1000	R18	Sets exact magnetic bias	20
Invert	Normal Invert	S2	Inverts signal to V4	23
Meter Center	0-1000	R21	Adjusts V4 bias for balance	21
Meter Zero	0-300	R42	Balances V8 VTVM bridge	25
Operate Zero	Operate Zero	S3	Applies same signal to grids of V8	25
V7 Set (On back)	0-270°	R36	Balances 2 halves of V7	24
V4 Bias (On back)	0-270°	R22	Sets level of V4 conduction	21
Oscillator Output (On back)	0-270°	R7	Varies output of oscillator	17

2. Switch Power to On.

3. Adjust Coarse Bias Switch for minimum meter deflection.

4. Put Meter Selector Switch on Output.

5. Adjust Coarse and Fine Bias Switches for minimum meter deflection.

6. Put Meter Sensitivity Switch on Intermediate.

7. Adjust Fine Bias Switch and Bias Vernier for minimum meter deflection, moving Coarse Bias Switch one step if dictated by the limits of Fine Bias Switch.

8. Adjust Meter Center control so that the meter deflection is the same magnitude when Invert switch is depressed and released, at the same time adjusting Fine Bias Switch and Bias Vernier for zero meter deflection. Meter Damping may be turned to a lower setting if more rapid movement is desired.

9. If deflection is less than 4 microamperes, put Meter Sensitivity Switch on High and readjust Bias Vernier and Meter Center controls for zero reading whether Invert button is depressed or released.

10. Put Operate-Zero switch on Zero and adjust Meter Zero for Zero meter reading. Return Operate-Zero switch to Operate.

11. Put Meter Sensitivity Switch on Low and then put Meter Selector Switch on Amplitude.

12. Turn Amplitude Adjust for a meter reading of 8.

13. Put Meter Sensitivity Switch on Intermediate and turn Amplitude Adjust for a meter reading of 23.

14. Put Meter Sensitivity on High and turn Amplitude Adjust for a meter reading of 30.

15. Put Meter Sensitivity Switch on Low and then put Meter Selector Switch on Output.

16. Repeat parts 5 through 14 until the meter reads zero on Output and 30 on Amplitude when Meter Sensitivity Switch is on High.

Unless the operator has familiarized himself with both the circuit and the operation of the magnetometer, it will probably be best to follow the procedure outlined above each time the equipment is turned on. Fortunately, if no radical changes have occurred in the magnetic field to be measured since the last operation of the equipment, the procedure is not as tedious as it might appear to be. With familiarization will come speed in adjustment and possible omissions of some steps.

Selection of Operating Positions of Controls

When the magnetometer has been put into operating condition, there are certain controls to be adjusted to positions dependent upon the results desired. If maximum sensitivity is desired, Gain should be placed on 10. If, on the other hand, the magnetometer must be operated in a location close to a street, this sensitivity may be too great since the passing of cars 50 feet away from the magnetic unit can give at least half-scale deflection.

Observation of the deflection of the meter on the front panel may be adequate. If, however, a permanent record of magnetic field variations is desired, the remote recording meter should be used. This necessitates checking for an adequate paper and ink supply in the recording meter, starting the flow of ink and the movement of the paper, and setting the Remote Meter switch to On. For this type of recording, it would be advisable to adjust the Bias Vernier control for an average deflection of about half scale on the recording meter.

If observation of sudden changes in the magnetic field is desired, the Meter Damping switch should be turned to position 1. If, on the contrary, rapid swings of the meter needle are not desired, the switch should be put at its maximum setting, position 9. It should be noted that a damping device built into the recording meter will prevent it from moving as rapidly as the one on the front panel of the magnetometer.

Orientation of the magnetic unit will depend on which component of the earth's magnetic field vector is to be measured. Since very minor variations can be read on the magnetometer, it is essential that the magnetic unit be rigidly mounted. Otherwise, even a small change in the direction in which the unit is pointed would cause the meter to go off scale. If the value of the component to be read is much larger or much smaller than that of the horizontal component, some difficulty may be encountered in obtaining the correct magnetic bias. Even though R18, R19 and R20 provide for a large variation, the total variation could not be made extremely great and still provide a fine adjustment on the Bias Vernier. The value of R17 could, however, be altered to shift the range.

Laboratory Adjustment and Servicing

No adjustment of the screwdriver controls at the back of the main chassis and no attempt at major servicing should be attempted except in a laboratory supplied with adequate test equipment. Adjustment of R36, V7 Set, would normally not be made unless V7 were replaced. Proper balance of V7 is indicated by identical d-c voltages read on a vacuum-tube voltmeter from J9 to ground and from J10 to ground when Gain is set at 0 and the Operate-Zero switch is on Operate. As explained in Chapter III, should V7 need replacement several 6SL7 tubes may need to be tried before one is found with two sections enough alike. R36 can then be used to balance the stage.

The adjustment of R22, V4 Bias, is quite critical since it determines the level at which the two halves of the biased diode start to conduct. Too little bias will mean that the output of the stage will overdrive the pulse amplifier. Excessive bias would mean that no signal would reach the pulse amplifier. Observation of the waveform at J6 should be made with an oscilloscope of good quality while adjustments are being made. Even an oscilloscope of high input impedance may disturb the circuit enough to cause an appreciable change in meter reading. Waveforms at points farther along the circuit may indicate whether the pulse amplifier is being overdriven. Another indication of excessive signal would be the absence of the proper change in meter reading to half value when the Gain control is turned from 10 to 9.

The Oscillator Output adjustment R7 should be set at a value that gives best pulse waveform, necessitating ample output for saturation but not enough to endanger the coils. The voltage from J3 to J4 as measured on an a-c vacuum-tube voltmeter should be set at 12 volts r.m.s.

Location of faults in the equipment can probably best be done by using a good oscilloscope to trace waveforms starting at the oscillator. This procedure coupled with a knowledge of the function of each stage should minimize any servicing difficulties that might arise.

CHAPTER V

SUMMARY AND CONCLUSION

Summary

The goal of this project was to design and construct an electronic magnetometer capable of measuring minor variations of the earth's magnetic field, with a sensitivity of approximately 2 gammas out of 55,000 gammas. The magnetometer described herein fulfills that purpose. A description of the basic principle of operation of saturable-core inductors is presented, along with circuit diagrams of the complete equipment and a description of each major unit. Because of the large number of controls involved, a set of instructions is given on the proper procedure for placing the equipment in operation. Selection of the operating position of certain controls is discussed, along with instructions for adjusting other critical controls.

Plan of Action

Plans for the immediate future call for location of the magnetometer in a relatively isolated area. So far, operation of the equipment has been confined to a laboratory in the School of Electrical Engineering at Oklahoma A. and M. College. The passing of automobiles on the street in front of the building causes at least half-scale deflection of the meter. Changes of the number and positions of parked cars during the intermission between classes can drive the meter completely off scale. Although the instrument is insensitive to sixty-cycle fields and can be adjusted to compensate for steady d-c fields, starting of electrical machinery on the floor below completely disrupts the meter readings.

Two buildings have just been moved to an isolated spot near a corner of the College airport. One of these is to house the magnetometer. Here, with almost no man-made magnetic disturbances, the instrument can be calibrated, checked for drift, and set into operation successfully.

Calibration can be done in one of two ways. One method[1] involves the use of a Helmholtz coil or a long solenoid to produce an increment of flux. Its value will be a readily computed function of the current and of the physical dimensions and the number of turns of the coil. Accuracy will depend largely on the ability to measure the flow of current. Because this accuracy will apply to the increment of flux rather than the total flux, it is a factor of the actual quantity the magnetometer is measuring. It should therefore be more than adequate. The other method involves calculation of the flow of d-c biasing current through the actual coils of the magnetic unit. A coil factor must be established by determining the value of current for a known magnetic field, for example, the established value of the horizontal component of the earth's field. The value of coil current can be calculated for a given setting by dividing the voltage of B2 by the sum of the values of R17, R18, R19, and R20. In reading the dials, note that clockwise rotation of R18,

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[1] Arthur Whitmore Smith, Electrical Measurements in Theory and Application, pp. 393-398.

R19, and R20 decreases the value of resistance. Since the calculation involves these resistance values it will not be exceedingly accurate but should be within 5%. The change in R18, Bias Vernier, necessary to produce a definite increment in the reading of the meter on the front panel can now be noted. Calculation of the increment of flux can thereby be made.

It is planned to investigate the possibility of correlation between variations in the geomagnetic field and the sferic studies of tornadoes currently being carried on under the direction of Dr. H. L. Jones of the School of Electrical Engineering at Oklahoma A. and M. College. Because the current in a lightning discharge can be as high as 130,000 amperes[2] the magnetic field produced thereby should be readily detectable by the magnetometer at a remote distance. A Swedish scientist[3] has made an analysis of a lightning stroke in terms of its magnetic field, using a shielded loop as an antenna, but measurement of the result of distant discharges was not attempted. Examination of the literature reveals that relatively little work has been done on recording the magnetic effects of lightning discharges. The Carnegie Institution of Washington in speaking of short-period magnetic fluctuations states:[4]

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[2] John Stanley Hutchison, "A Study of Tornado Identification," Master's thesis, Oklahoma A. and M. College, p. 65.

[3] Harold Norinder, "Some Aspects and Recent Results of Electromagnetic Effects of Thunderstorms I and II," Journal of the Franklin Institute, CCXLIV (August and September, 1947), 109-130 and 167-207.

[4] Carnegie Institution of Washington, op. cit., p. 270.

> A brief mathematical analysis showed that lightning occurring vertically above the ocean's surface can yield fields of several gauss in horizontal intensity enduring about 0.001 second, in a neighborhood within the ocean some tens of meters away from the point of discharge. Magnetograms for the Huancayo Magnetic Observatory, where the incidence of thunderstorms is high, do not reveal deflections in excess of 30 gammas per three-month interval due to lightning; it is to be noted that the period of free oscillation of the magnet system of the variometer is of the order of a few seconds. Because the area of influence is small and the discharges infrequent, the effects of lightning discharges are rarely recorded at observatories.

There is some possibility that magnetic fields may be produced by thunderstorms or tornadoes even in the absence of visible lightning. Fleming[5] speaks of observed "micropulsations" that seem to be the result of rather local electric currents in the ionosphere. With the distribution of electric charges in a thunderstorm cloud, as discussed by Hutchison,[6] it is conceivable that rapid cloud movement could be detected by the magnetometer. If such a charge distribution exists in a tornado, the relatively greater velocities involved may result in a characteristic magnetic indication. Investigation of these possibilities definitely seem warranted.

Another future project, as an outgrowth of the development of the magnetometer, would be an investigation of saturable-core inductors. Although some work has been done, much more should be undertaken. An accurate mathematical analysis of the nonlinear balanced bridge with its high coefficient of coupling between coils would be a definite contribution to scientific

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[5] Fleming, _op_. _cit_., p. 430.

[6] Hutchison, _op_. _cit_., pp. 4-20.

knowledge. The whole subject of proper core materials should be investigated, to discover exactly what magnetic properties are desirable: highest permeability, highest rate of change of permeability at the point of saturation, minimum hysteresis loss, lowest value of saturation flux density, or minimum coercive force. Such an investigation should be valuable and interesting.

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