THE DESIGN OF AN UNDERWATER METAL DETECTOR

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1958

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1959

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PREFACE

The detection of objects that have been lost in fresh water lakes is an interesting and perplexing problem. The presence of the many sedimentary particles near the bottom makes search by visual means practically impossible. In some cases there is total absence of light and a diver can only grope in the darkness in his attempt to locate the object. It is apparent therefore, that the effective detection of an object requires some means other than visual. The design of a device that would detect submerged metallic objects was selected as a thesis project. The device was to be self-contained and portable. It was to be operated by a diver and any indication made directly to him. A detector satisfying these conditions was designed and is described in this thesis.

The author wishes to thank Dr. Truet B. Thompson for his guidance and interest in the preparation of this thesis. He also wishes to extend thanks to Professor Paul McCollum and Dr. Herbert L. Jones for their suggestions and assistance. A debt of gratitude is also owed to Mr. John Tartar for his aid in construction of the detector and procuring of data.

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CHAPTER I

INTRODUCTION

General

Mine detectors and metal locators which have been designed to work in air function with little success over water. There has been very little effort directed toward the development of a portable detector that would function while submerged. For this reason it was first necessary to analyze the general problem of detection. The method by which a detector would function best was then determined from this general analysis.

Situations involving the detection of metallic objects not readily visible to the eye occur frequently. These include the detection of concealed weapons in penal institutions, the location of submarines far below the surface of the sea, and the removal of metal objects from hay.[1,2,3] There is a common fundamental linking these seemingly unrelated situations. In each it is necessary to detect the presence of a metallic object in a non-metallic medium. Due to the dissimilarity of

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[1] David G. C. Luck and Charles J. Young, "An Electromagnetic Metal Detector," RCA Review, Volume I (October, 1936), pp. 53-63.

[2] A. C. Keller, "Submarine Detection by Sonar," Bell Laboratories Record, Volume XXV (February, 1947), pp. 55-60.

[3] J. B. Dobie and F. C. Jacob, "Removing Tramp Iron from Chopped Hay," Electronics, Volume 27 (May, 1954), pp. 134-136.

the media to be searched and the particular situations involved, several different methods of detection have been developed. A comprehensive study of the characteristics of the medium and of the objects to be located is essential in order to determine what method should be employed by the particular detector.

The operation of all detection devices is based on the principle that the same properties of the medium and object have different values. The logical method of detection would therefore utilize the property having the greatest difference in value. If this difference is not readily detectable, or the situation in some other way precludes the use of this property, a less desirable characteristic must be used. Density, permittivity, permeability and conductivity are the properties utilized when detection is accomplished by electronic methods.

Just as each situation warrants the use of a certain property, there is a most favorable method of measuring the effects of this property. A summary of a few of the devices that have been developed to detect metallic objects is therefore presented. These devices are classified by the property on which the comparison or measurement is made.

Types of Detectors

Density

The relatively high value of the mass per unit volume of metals has been successfully employed in two different types of detectors.

Detectors have been built using the penetrating powers of the X-ray. They are quite successful even when the difference in density is small. Most of these detectors are found in the medical profession.[4] This type

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[4] Wayne T. Sproull, X-Rays in Practice, (New York, 1946).

has the highest resolution of any of the detectors due to the extremely high frequency. The volume to be examined is very limited since partial enclosure of the medium by the detector is required.

The second type was the result of intensive research to detect submarines during World War II and is known as sonar.[5] Detection is accomplished in the following manner. A directional sonic or ultrasonic wave is propagated through the water. Upon encountering the submarine, part of this energy is returned by reflection. The presence of the submarine is revealed by the reception of this echo.

Since the purpose of sonar is to locate metallic objects in water, it would seem to be the answer to the problem at hand. It does not prove to be adaptable for several reasons. All objects to be located in the present case are on the bottom, so the detector must be able to distinguish between a metallic object and a stone of similar size. The sonar wave is mechanical in nature and since a metallic object and a stone would have comparable densities, the response would be about equal. This disadvantage was not encountered in the primary use of sonar since most of the time the submarine was not on the bottom but at some intermediate depth. Other disadvantages are the power equipment required and the cost.

Permeability

Most of the early mine detectors were designed to give an indication upon a decrease in the reluctance of a magnetic circuit.[6] This change

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[5] J. W. Horton, Fundamentals of Sonar, (Annapolis, 1957).

[6] A. Butterworth, "Development and Use of Magnetic Apparatus for Bombs and Mine Location," Institute of Electrical Engineers Journal, Volume 95 (December, 1948), pp. 645-667.

in the magnetic reluctance was the effect of a ferromagnetic object in the volume being searched. Since this type detector would respond to a ferromagnetic material only, it was quite limited in application. Later model mine detectors, such as the English Mark IV, could discriminate between ferrous and non-ferrous materials.[7] This detector would function upon any change in its alternating magnetic field due to an induced magnetic dipole. Modifications of this detector determined this change by measuring the change in the output impedance of the field producing coil. This detector did not function on the effects of permeability alone since a response could be produced by a non-ferromagnetic conductor.

Permittivity and Conductivity

A mine detector utilizing the property of permittivity has been constructed.[8] It was designed primarily to detect non-metallic mines, although it would indicate the presence of a conductor. The principle of operation was based on the change in displacement current due to a change in the dielectric. The presence of moisture in the ground resulted in a large value for the conduction currents. This reduced the effectiveness of the detector to a marked degree.

Selection of Method

After considering the relative merits of the different detectors, an electromagnetic type operating on the effects of permeability appeared to

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[7] "Mine Detectors", Wireless World, Volume 52, (May, 1946), pp. 166-168.

[8] T. E. Stewart, "Non-Metallic Mine Detector", Electronics, Volume 18 (November, 1945), pp. 100-103.

be the most logical choice. This type detector was not limited to the ferromagnetic materials since it would also respond to any substance of high conductivity. This was important since it does not restrict the use of the device to only one type of metal. The cost of this type detector would be reasonable and the design requirements easily fulfilled.

CHAPTER II

THEORETICAL CONSIDERATIONS

Characteristics of Materials

A more accurate prediction of the behavior of the detector may be made by examining the characteristics of the materials involved. The properties of the medium are of particular interest, since an electromagnetic field will permeate the space to be inspected, and the reaction to this field must be known. A discussion of the characteristics of the medium and of the metals to be detected is therefore in order.

Permittivity

The relative dielectric constant of 80, generally given for water, is the static or very low frequency value.[1,2] This dielectric constant is not actually a constant but a function of several parameters, the important ones being temperature and frequency. An increase in temperature results in a decrease in the value of the permittivity. Some indication of the rate of change may be obtained from Table I. In the steady state, or with low frequencies, the time rate of change of the field is not rapid enough to affect the polarization of the dielectric. As the frequency

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[1] R. I. Sarbacher and W. A. Edson, Hyper and Ultrahigh Frequency Engineering, (New York, 1943), p. 3.

[2] Stephen S. Attwood, Electric and Magnetic Fields (New York, 1941), p. 57.

is increased, there are frequency spectrum regions in which there is a time lag in the attainment of equilibrium. This time lag is due to the relaxation of polarization and a thorough explanation may be found in the literature.[3,4] The accompanying loss in the dielectric gives rise to the introduction of a complex relative permittivity. It is defined as[5]

$$\epsilon_r^* = \epsilon' - \dot{j}\,\epsilon'' \tag{1}$$

where

ϵ_r^* is the complex dielectric constant,

ϵ' is the dielectric constant,

ϵ'' is the loss factor,

$\dot{j}$ is the complex operator $(-1)^{1/2}$.

The complex terms have been given as[6]

$$\epsilon' = \epsilon_s + \epsilon_H (\omega T)^2 \tag{2}$$

$$\epsilon'' = \frac{\omega T (\epsilon_s - \epsilon_H)}{1 + (\omega T)^2} \tag{3}$$

where

ϵ_s is the static dielectric constant in farads/meter,

ϵ_H is the dielectric constant at the high frequency end of the polar dispersion region, in farads/meter,

T is the relaxation time for water in seconds,

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[3] Ibid., pp. 95-98.

[4] Charles P. Smyth, <u>Dielectric Behavior and Structure</u> (New York, 1955), p. 52.

[5] Ibid., p. 54.

[6] J. A. Saxton, "Electrical Properties of Water," <u>Wireless Engineer</u>, September 1949, p. 289.

ω is the angular velocity in radians/second.

It should be emphasized that the values are valid only to approximately 10^6 megacycles. Above this frequency, atomic and electronic polarization result in similar losses, although not as large.

The relationships between temperature, static permittivity and relaxation time are given as Table I. By the use of equations 2 and 3 and the constants from this table, the complex dielectric constant may be found for different frequencies. The temperature for purposes here was considered to remain constant at 20° Centigrade. The results of these computations are given as Table II.

The permittivity values of metals are difficult to determine. Since the effects of conduction are so much greater than those of the permittivity, it is of little consequence and not discussed here.

Permeability

By a development similar to that for the permittivity the complex permeability is expressed. The imaginary term is zero for water however, and the real term a constant for all frequencies. Water is slightly diamagnetic[7], the relative permeability being on the order of .999991. For purposes here this may be considered as unity and the complex relative permeability equal to 1 for water.

The permeability of the metals to be detected is divided into two classes. In the first case are the ferromagnetic materials with a permeability that is dependent upon the applied magnetic field. The maximum relative permeability is much greater than unity for these materials.

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[7] K. Honda, "Paramagnetic and Diamagnetic Data," International Critical Tables (New York, 1937), VI, p. 354.

TABLE I

STATIC DIELECTRIC CONSTANT AND RELAXATION TIME FOR WATER AT DIFFERENT TEMPERATURES[8]

Temperature °C	Static Dielectric Constant Farads/Meter	Relaxation Time Seconds
0	88.0	19.05×10^{-12}
5	86.0	14.6×10^{-12}
10	84.0	11.85×10^{-12}
15	82.0	9.6×10^{-12}
20	80.0	8.1×10^{-12}
25	78.2	6.8×10^{-12}

TABLE II

COMPUTED VALUES FOR THE DIELECTRIC CONSTANT AND LOSS FACTOR OF WATER AT 20°C AT VARIOUS FREQUENCIES

Frequency Cyc/Sec	Dielectric Constant Farads/Meter	Loss Factor Farads/Meter
10	80	3.79×10^{-8}
10^2	80	3.79×10^{-7}
10^3	80	3.79×10^{-6}
10^4	80	3.79×10^{-5}
10^5	80	3.79×10^{-4}
10^6	80	3.79×10^{-3}
10^7	80	3.79×10^{-2}
10^8	80	.379
10^9	80	3.79
10^{10}	64.6	30.1
10^{11}	8.3	14.1
10^{12}	5.5	1.5

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[8] Saxton, p. 290.

The second class consists of the substances whose permeability is nearly equal to that of free space. These are the paramagnetic and diamagnetic materials. Since, in these materials, the variation in permeability is so small this difference is used only for the detection of ferromagnetic materials.

Conductivity

The ionic conductivity will of course vary between bodies of water. The magnitude depends upon the quantity of dissolved salts and minerals in the water. Sea water has a conductivity of 3 to 5 mhos/meter. Different average values are given for lake water, most of them around 10^{-3} mhos/meter.[9,10] This will be the assumed value for computations here.

The conductivities of metals are extremely large compared to those of water. One of the poorest, nichrome, has a conductivity of 10^6 mhos/meter. The principal ones involved here, aluminum, copper, iron, etc., are on the order of 10^7 mhos/meter. This is a 10^{10} ratio when compared to fresh water.

Frequency Response of Lake Water

The dielectric constant and loss factor for water were computed for 20° Centigrade and given in Table II. Much about the frequency response of water may be shown by examining this table and the ionic conductivity in the light of Maxwells first curl equation. The curl equation in sinusoidal time function form is:

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[9] Saxton, p. 288.

[10] A. B. Bronwell and R. E. Beam, Theory and Application of Microwaves (New York, 1947), p. 462.

$$\bar{\nabla} \times \bar{H} = (\sigma + j\omega\epsilon^{*})\bar{E} \qquad (4)$$

The terms $\bar{H}$ and $\bar{E}$ are the magnetic and electric field intensities, and σ is the conductivity of the material. The symbol $\bar{\nabla}$ is a differential operator. Since the permittivity is complex, expanding it results in:

$$\bar{\nabla} \times \bar{H} = (\sigma + \omega\epsilon'' + j\omega\epsilon')\bar{E} \qquad (5)$$

The two conductivity terms may be added arithmetically. This is permissable since both $\sigma\bar{E}$ and $\omega\epsilon''\bar{E}$ are conduction current density values.[11] The sum of the two would give the total conduction current density.

The manner in which the water behaves may be divided into three classes; that of conductor, that of a dielectric, and a combination of the two, which will be referred to as a quasi-conductor.

The ionic conductivity of the water is much larger than $\omega\epsilon''$ from 0 to 50 kilocycles, so the conduction currents predominate and the water is acting as a poor conductor. From 50 kilocycles to 50 megacycles $\omega\epsilon''$ has become significant and the reaction is complex. The water is a quasi-conductor for this frequency range. From 50 to 100 megacycles the displacement current is much larger and the characteristics of a dielectric predominate. Above this frequency the reaction returns to that of the complex region since the real and imaginary terms are again comparable. Above 10^4 megacycles the field is changing too rapidly to allow molecular polarization and the dielectric constant has been greatly reduced.

Considering the dielectric properties of the water alone, would point to the use of frequencies from 50 to 100 megacycles for greatest efficiency. This is because the water is acting as a dielectric and the

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[11] Saxton, p. 290.

attenuation due to conduction currents would be a minimum. Due to limitations imposed by circuit components the frequency selected was considerably below this value and no experimentation was done in this range. The frequency selected was as high as possible under the existing conditions although it was still in the conduction range.

Attenuation Due to Conductivity

Since water was acting as a conductor at the selected frequency, it was of interest to determine how much an electromagnetic wave would be attenuated due to this conductivity. A transverse electromagnetic wave, traveling in a direction designated "X", in a conducting medium, would be attenuated by the factor $e^{-\alpha x}$. The term α is known as the attenuation constant and is the real part of the propagation constant. This was the rate at which the intensity of the field was decreasing. There was a phase shift also taking place but this was not of interest here. A much more elaborate discussion may be found in any discourse on electric waves.[12] The attenuation constant is given by [13]

$$\alpha = \sqrt{\sigma f \mu \pi} \tag{6}$$

where

α is the attenuation in nepers/meter,

f is the frequency in cycles/second,

μ is the permeability in henrys/meter,

σ is the conductivity in mhos/meter, taken as 10^{-3} for lake water.

It was found that even at 50 kilocycles, the upper limit of the conduction

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[12] Sarbacher and Edson, p. 160.

[13] Ibid.

range, the attenuation was only .014 nepers per meter. The distance at which the wave will be reduced to 1/e of its original value would be $1/\alpha$ or 71.5 meters. Since the frequency used by the detector was much below this, the attenuation would also be much lower.

A confirmation of the rate of decrease of the magnetic field in water was obtained by experimental methods. The voltage induced in a coil is a function of the magnetic intensity at that point. The voltage induced in a closely wound coil by a uniform sinusoidal magnetic field may be shown as[14]

$$v = j\omega H_m \mu A N \cos\theta \, \epsilon^{-j\omega t} \qquad (7)$$

where

v is the induced voltage in volts,

A is the area of the coil in meters^2,

N is the number of turns,

H_m is the peak magnetic flux intensity in ampere-turns/meter,

θ is the angle between the flux and plane of coil,

other terms are as defined before.

For a constant frequency the induced voltage will be a direct function of the magnetic intensity and the position of the coil. By producing such a magnetic field and measuring the voltage induced in a coil at different points, a measure of the decrease of magnetic intensity was determined.

The test equipment was arranged as shown in Figure 1. The primary coil was 300 turns of No. 22 gauge, cotton covered copper wire. The coil was 12 inches in diameter. Current and frequency were both maintained

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[14] Nathaniel H. Frank, _Introduction to Electricity and Optics_ (2d ed., New York, 1950), pp. 149-150.

at a constant value. The frequency selected was 13 kilocycles, since this was the approximate value to be used for the detector. The secondary coil was 1000 turns of No. 28 gauge, enamel coated copper wire. This coil was 2½ inches in diameter. The ratio of the two coil diameters was large so a more uniform flux distribution would be realized. The secondary coil was arranged so all voltage measurements were made when the coils had a common axis. This kept the flux field components normal to the plane of the secondary coil. Only when the resultant flux was normal to the plane of the coil would the induced voltage be related to the magnetic intensity by a constant.

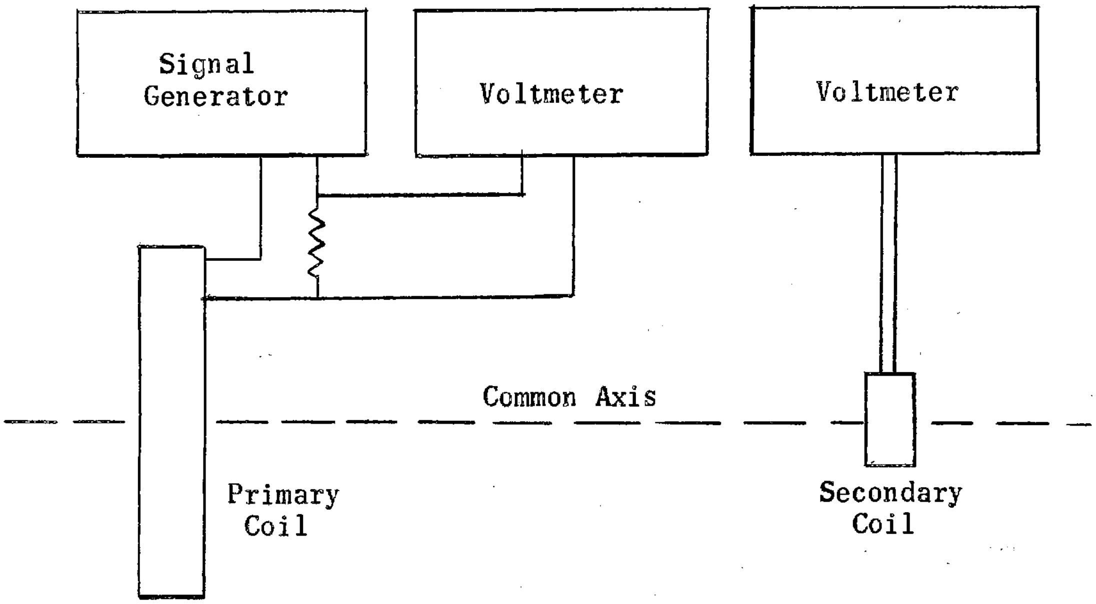

Figure 1. Block Diagram of Test Equipment Arranged to Determine Magnetic Field Intensity in Water

The magnetic intensity would vary by two factors. There was the decrease due to the separation given by

$$\overline{H}_o = \frac{N r^2 I \epsilon^{j\omega\tau}}{2(x^2 + r^2)^{3/2}} \qquad (8)$$

where

r is the radius of the primary coil,

x is the axial separation of the coils,

I is the peak primary current,

$\overline{H}_0$ is the magnetic intensity in free space along the axis.

There was also the decrease due to the conduction of the water. This was shown to be

$$\overline{H}_w = \overline{H}_0 e^{-\alpha x} \qquad (9)$$

where

$\overline{H}_W$ is the magnetic intensity at point x.

The theoretical value of the magnetic intensity is shown in Figure 2 with experimental values between 0 and 4 meters displayed as isolated points. No attempt was made to isolate the conduction current loss, since the purpose of the experiment was to determine the total decrease of magnetic intensity.

The Field Produced by a Coil

The electromagnetic field could best be generated by a current carrying coil and this form was selected for the detector. In order to determine the response of an object or spherical target it was necessary to know the magnetic intensity at the target point. It is of interest then to examine the magnetic field produced by a circular coil.

The fields produced by an alternating current carrying loop may be classed in two categories; the induction field and the radiated field. The radiated field is known as the far field or Fraunhofer region. In

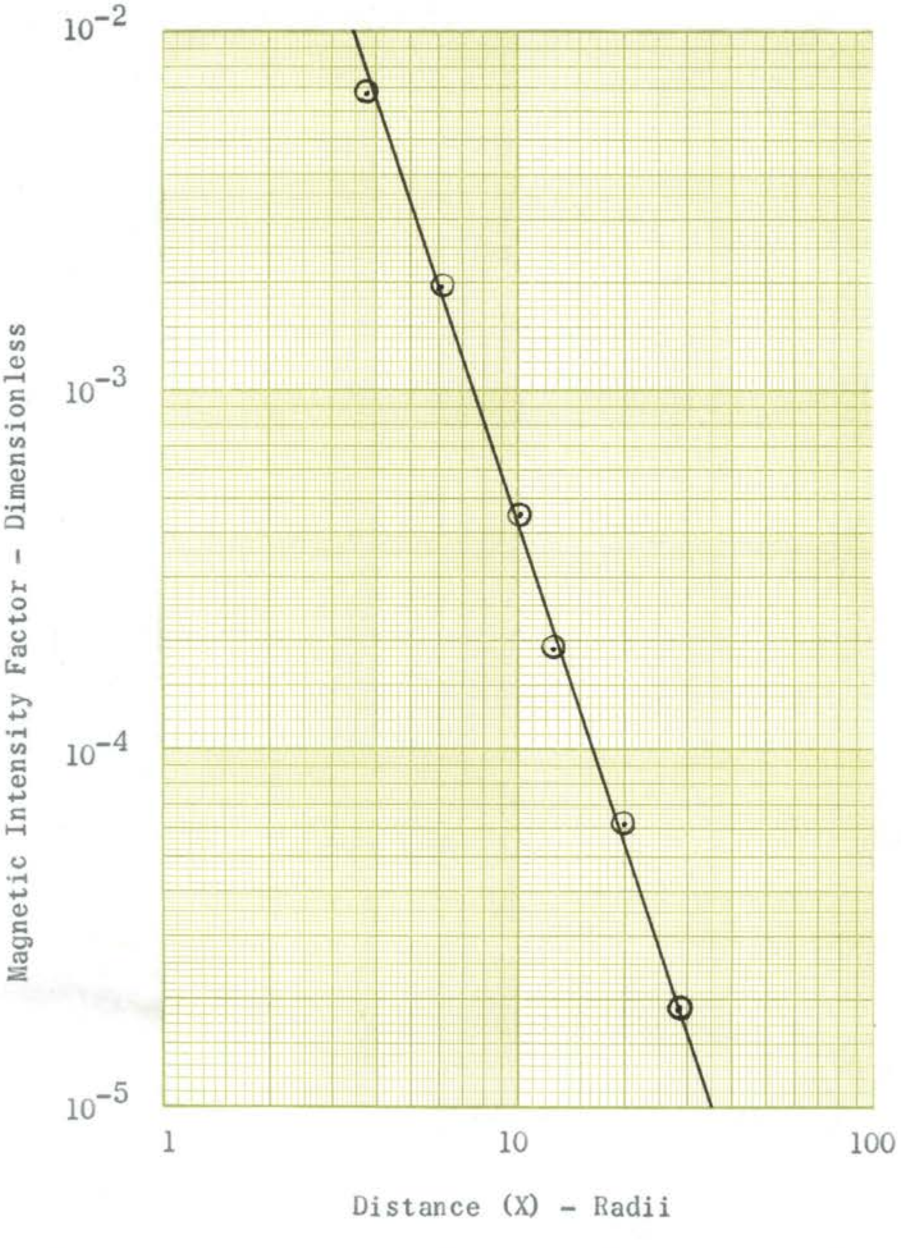

Fig. 2. Variation of Magnetic Intensity in Lake Water As a Function of Distance

this region the electric and magnetic components are transverse to the direction of propagation, which is radially outward. These components are related by the intrinsic impedance of the medium. Radiation is dependent upon the finite time or velocity of propagation. When this is not considered the quasi-stationary solution results. This is the induction field or Fresnel region. This region may be described as a sphere with radius small compared to the wave length, the conductor being at the center of the sphere. The derivations and theory may be found in any treatise on antennas.[15,16]

The equations for the magnetic field intensity for an incremental dipole antenna contain the terms[17]

$$\frac{j2\pi}{\lambda r} + \frac{1}{r^2} \tag{10}$$

where

r is the distance from a point to the dipole,

λ is the wave length of the frequency.

This clearly describes the relative magnitudes of the magnetic intensities of the near and far fields. The near field, being the $1/r^2$ term, decreases as the inverse square of the distance. It may be seen that the fields would have equal intensities when r equals $\lambda/2\pi$. The wave length would be less in any conducting material than it would be for the same frequency in free space. At low frequencies the water was acting as a conductor and, therefore, the wave length was decreased. It

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[15] J. D. Kraus, Antennas, (New York, 1950), p. 155.

[16] Bronwell and Beam, p. 400.

[17] Ibid., p. 403.

may be determined by[18]

$$\lambda = 2\sqrt{\frac{\pi}{f\mu\sigma}} \qquad (11)$$

where

all terms and values are defined as before.

At 13 kilocycles the wave length would be 877 meters. The equal intensity point would occur at 140 meters. Since the induction field is decreasing inversely as the square of the distance, and the area involved is only a few meters from the loop, it certainly follows that the induction field is the principal one of interest. This provides the simplification that the quasi-stationary method of analysis will be adequate for the solution.

The Induced Dipole

When a metallic particle is subjected to an alternating magnetic field an induced magnetic dipole is formed.[19,20] This effect is due either to the eddy currents, the magnetic polarization, or a combination of both. The induced magnetic dipole possesses a magnetic field that is added vectorally to the primary field.

For ease in computation a spherical particle was selected to determine the response. For the experimental portion circular disks were used. These are treated as degenerate spheroids with a zero minor axis and have a magnetic moment along this axis .425 times that of a sphere of equal

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[18] Bronwell and Beam, p. 270.

[19] Leslie F. Curtis, "Detectors for Buried Metallic Bodies," Proceedings of the National Electronics Conference, (Chicago, 1946), II, p. 341.

[20] Thomas L. Martin, Physical Basis for Electrical Engineering (New York, 1957), p. 353.

diameter.[21]

The magnetic dipole moment of a sphere that has been induced by a sinusoidal varying magnetic field, is found to be[22]

$$\overline{m} = \frac{3}{8\pi}\left(\frac{2\mu_r + 1 - W}{\mu_r - 1 + W}\right) V \overline{H} \tag{12}$$

where

$$W = \frac{(\gamma - j\gamma)^2 \ \mathrm{TANH}\ (\gamma + j\gamma)}{(\gamma + j\gamma) - \mathrm{TANH}\ (\gamma + j\gamma)} \tag{13}$$

$$\gamma = r\alpha \tag{14}$$

and

r is the radius of the sphere in centimeters,

α is the attenuation constant as defined by (6),

V is the volume of sphere in meters^3,

$\overline{H}$ is the magnetic intensity in ampere-turns/meter,

$\overline{m}$ is the complex moment in ampere-turns/meter^2.

The complex moment is then a function of the frequency of the field as well as of the conductivity, permeability, and radius of the sphere. Its direction will be parallel to that of the primary field due to the symmetry of the assumed particle. If the sphere has high resistivity, or the frequency approaches zero, the equation (14) approaches zero. The substitution of zero in equation (13) results in an indeterminate form. The limit of the equation may be determined by the application of L'Hospitals rule. The limit is found to be the interger 3. The limiting dipole moment then becomes

$$\overline{m} = \frac{3}{4\pi}\left(\frac{\mu_r - 1}{\mu_r + 2}\right) V \overline{H} \tag{15}$$

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[21] Curtis, p. 344.

[22] C. W. Clapp, "Detection of Tramp Metal", Proceedings of the National Electronics Conference (Chicago, 1950), VI, p. 195.

when μ_r is 1

$$\overline{m} = \frac{3}{4\pi}\left(\frac{1-1}{1+2}\right)V\overline{H} = 0 \tag{16}$$

when μ_r is large

$$\overline{m} \longrightarrow \frac{3}{4\pi} V \overline{H} \tag{17}$$

So for a direct current field, the induced moment would vary from zero for a sphere of unit permeability, to $3/4\pi \; V\overline{H}$ for a ferromagnetic sphere of the same size. The value would vary expotentially between these limits. Since the value is real and positive the induced moment will be in phase with the primary field.

The detector was to indicate the presence of any type of metal so the direct current field is not the solution. Only objects with an effective diameter of several inches were of interest. This fact, coupled with the high conductivity of the metals, makes the term g (Equation 14) quite large for all but the lowest frequencies. This could be designated the high frequency case since for high frequencies g becomes large for particles of any size. For this situation it may be shown that for values of g greater than 6, tanh(g - jg) equals 1 and

$$W = \frac{(g - j g)^2}{(g - j g) - 1} \tag{18}$$

when g is much larger than 6 then

$$W \cong g - j g \tag{19}$$

and

$$\overline{m} \longrightarrow -\frac{3}{8\pi} V \overline{H} \tag{20}$$

The induced dipole for a conducting sphere of any permeability, when the flux penetration is small compared to the radius, is then

$$\overline{m} \cong -\frac{3}{8\pi} V \overline{H} \qquad (21)$$

Since it is real and negative the direction of the dipole is opposite to that of the primary field. It should be noted that the absolute value of the maximum induced dipole for ferromagnetic materials is double that for the limiting case of an equal sized sphere of unit permeability.

The Induced Voltage in the Secondary

The induced magnetic moment due to the alternating magnetic field was shown in the previous section. This magnetic moment will in turn induce a voltage in a passive secondary coil. This can be given by[23]

$$V = -j\,\omega\,\overline{m}\,(4\pi)^2 \times 10^{-2} \qquad (22)$$

where

v is the induced voltage in microvolts

$\overline{m}$ is the moment as defined in Equation 12, with $H = \overline{H}_p \cdot \overline{H}_s$.

The magnetic intensity in the moment equation is the scalar product of the magnetic field intensities at the point of the target. The two magnetic fields are the result of unit current in the primary and secondary coils.

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[23] Ibid., p. 197.

CHAPTER III

DESIGN OF COMPONENT PORTIONS

General

The detector was to be composed of a transmitter section to generate an alternating current of proper frequency and a receiver system to amplify and indicate minute voltages. A search coil system was included as a method of creating an electromagnetic field and detecting slight changes in this field. The manner in which they were constructed is described in this chapter.

The Search Coil System

The three search coils were wound on octagonal forms constructed of wood. The distance between opposing sides of the forms was 1 foot. The width of the secondary forms was 1 inch and that of the primary 1¼ inches. The forms were constructed of 3 layer plywood sides separated by pine blocks. Each of the coils contain several cubic inches of air space. This space provides the necessary bouyancy to bring the detector to the surface if it is released by the diver while submerged. Each coil, when completed, was coated with fiberglass for waterproofing.

The two receiver coils were constructed as nearly alike as possible. If the coils were identical, any change in the physical or electrical characteristics of one would also occur in the other. Since the coils are connected in opposition in the circuit, any voltage change would be

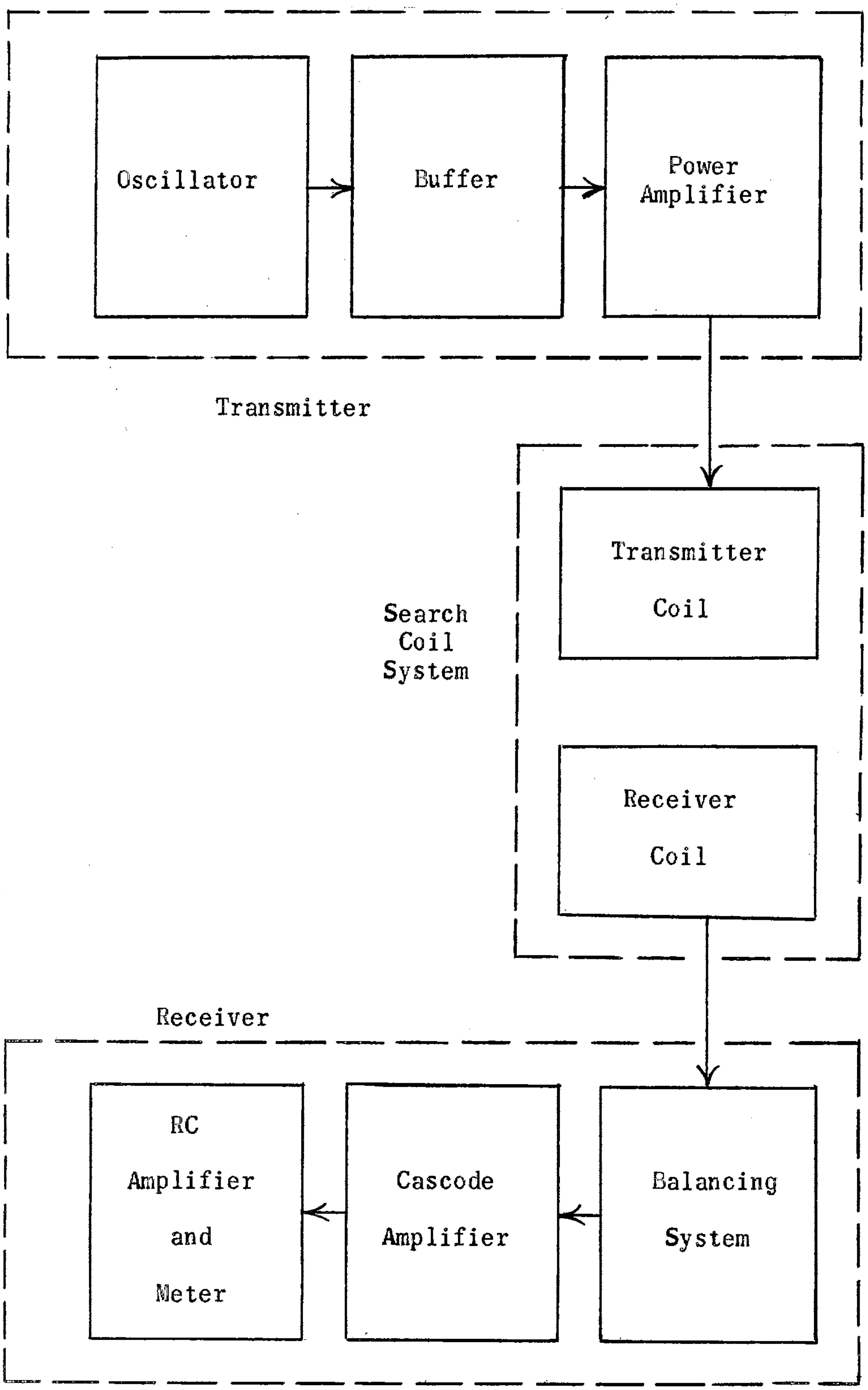

Fig. 3. Block Diagram of Metal Detector

balanced or canceled out. Any voltage induced in the coils by an external electromagnetic field would likewise be nullified.

The secondary coils were composed of 300 turns of enamel coated 22 gauge hard drawn copper wire. The wire was wound 30 turns per layer with kraft paper separating the layers. The ends of the wire were terminated in amphenol connectors for watertight integrity and ease of connection.

The primary coil had the same specifications as the secondary except the wire was cotton coated.

Each of the two secondary coils were adjusted for minimum mutual inductance with respect to the primary. This was done by overlapping the coils until the voltage induced in the secondary was a minimum. The coils were then secured in this position by fiberglass. This balance could not be expected to hold indefinitely so it was necessary to provide some method of readjusting the coils for minimum output. Since they could not be physically moved this was accomplished by a balancing circuit. This circuit consists of the two front panel control potentiometers R_{20} and R_{21} and the fixed components R_{23} and C_{14}. The potentiometers function as variable tap voltage dividers. A high value of resistance was therefore selected to maintain the high Q of the coil circuit. Quadrature voltages are obtained by the use of R_{23} and C_{14}., the magnitude of these voltages being regulated by the front panel controls. A voltage of proper magnitude and phase may be established to cancel any unbalance in the receiver coils by the proper adjustment of these controls.

The Receiver

The receiver section of the metal detector consists of a cascode amplifier input stage followed by two identical stages of voltage amplification. The output of the receiver section is fed to a meter which is used to indicate the degree of unbalance produced in the receiver coils by a metallic object.

The input amplifier used in the receiver section is a cascode circuit. The cascode amplifier circuit is basically a grounded cathode stage followed by a grounded grid stage with the plate of the first stage directly connected to the cathode of the second stage.

The cascode amplifier circuit was chosen for three principal reasons.[1,2]

First, the cascode circuit is extremely stable. The grounded cathode stage is presented with a large conductance by the succeeding grounded grid stage making the input stage very stable.

Second, the circuit is capable of a gain approaching that of a pentode stage. A constant current is maintained through both tubes by the grounded grid stage. The current gain of the grounded cathode stage is then g_m and the voltage gain for both sections is $-g_m R_p$ as in a pentode.

Third, the cascode circuit is a low noise amplifier with its noise figure showing a 2 to 10 db improvement over that of conventional circuits. The noise figure is reduced by obtaining pentode gain without having to rely on the noise generating screen circuit.

The cascode amplifier used here was designed by following the eight steps as outlined by Wirth.[3] This circuit requires identical triode stages.

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[1] H. J. Wirth, "Cascode Auto Preamplifier," <u>Electronics</u> (October, 1957), pp. 234-240.

[2] R. Lee Price, "Cascode Audio Amplifier has Low Noise Level," <u>Electronics</u> (March, 1954), p. 156.

[3] Wirth, p. 234.

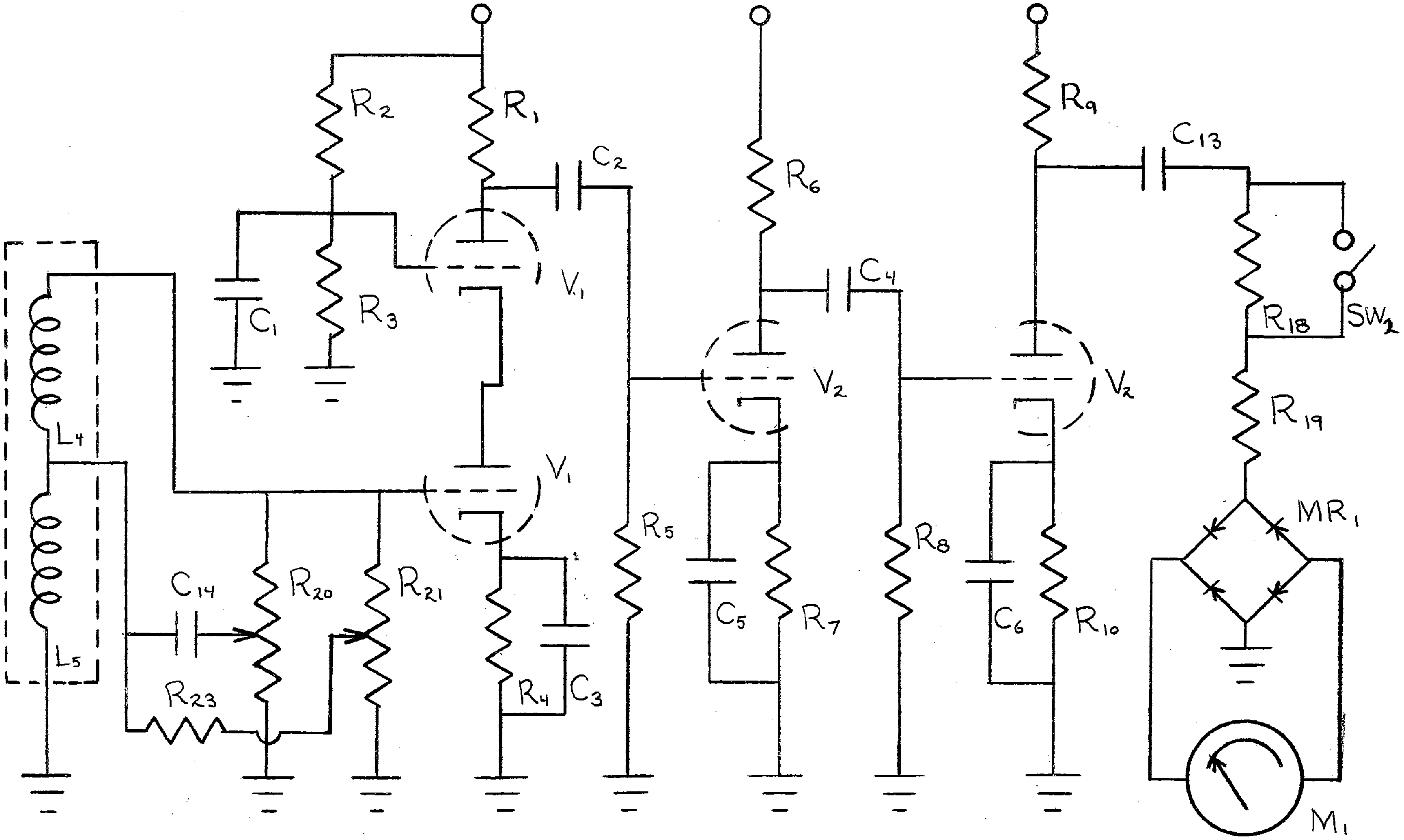

Fig. 4. Schematic Diagram of Receiver

The potential across R_3 of the bleeder R_2 and R_3 maintains the grid of the grounded grid section at a constant d.c. potential while C_1 places the grid at r.f. ground. The combination of R_4 and C_3 provide a steady bias for the grounded cathode section. The input to the cascode is the voltage from the receiving coils. This input is coupled through a short length of coaxial cable.

The output of the cascode is coupled through C_2 to the grid of one section of a 12AX7 tube. This tube was selected for its exceptionally high gain. Both sections of the 12AX7 tube serve as identical, resistance-capacitance coupled cascade amplifiers. These are quite conventional voltage amplifiers designed for the frequency range of 10 to 20 kilocycles.[4] Cathode bias is developed for each stage across bypassed resistors R_7 and R_{10}. The output signal of the first stage is developed across R_6 and applied to the grid of the second stage through C_4. The final output signal from the receiver amplifier is developed across R_9 and fed to the meter circuit through C_{13}.

The meter movement is connected across a bridge type rectifier which is mounted inside the meter case. Resistors R_{18} and R_{19} serve as multipliers to decrease the deflection and protect the meter when the coil system is unbalanced to any great degree. To increase the receiver sensitivity, R_{18} can be shorted out by Sw_2 after the coils have been balanced.

The Transmitter

The transmitter section of the metal detector consists of an oscillator stage followed by a buffer amplifier and a power amplifier stage.

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[4] Herbert J. Reich, Theory and Application of Electron Tubes (New York, 1944), p. 144.

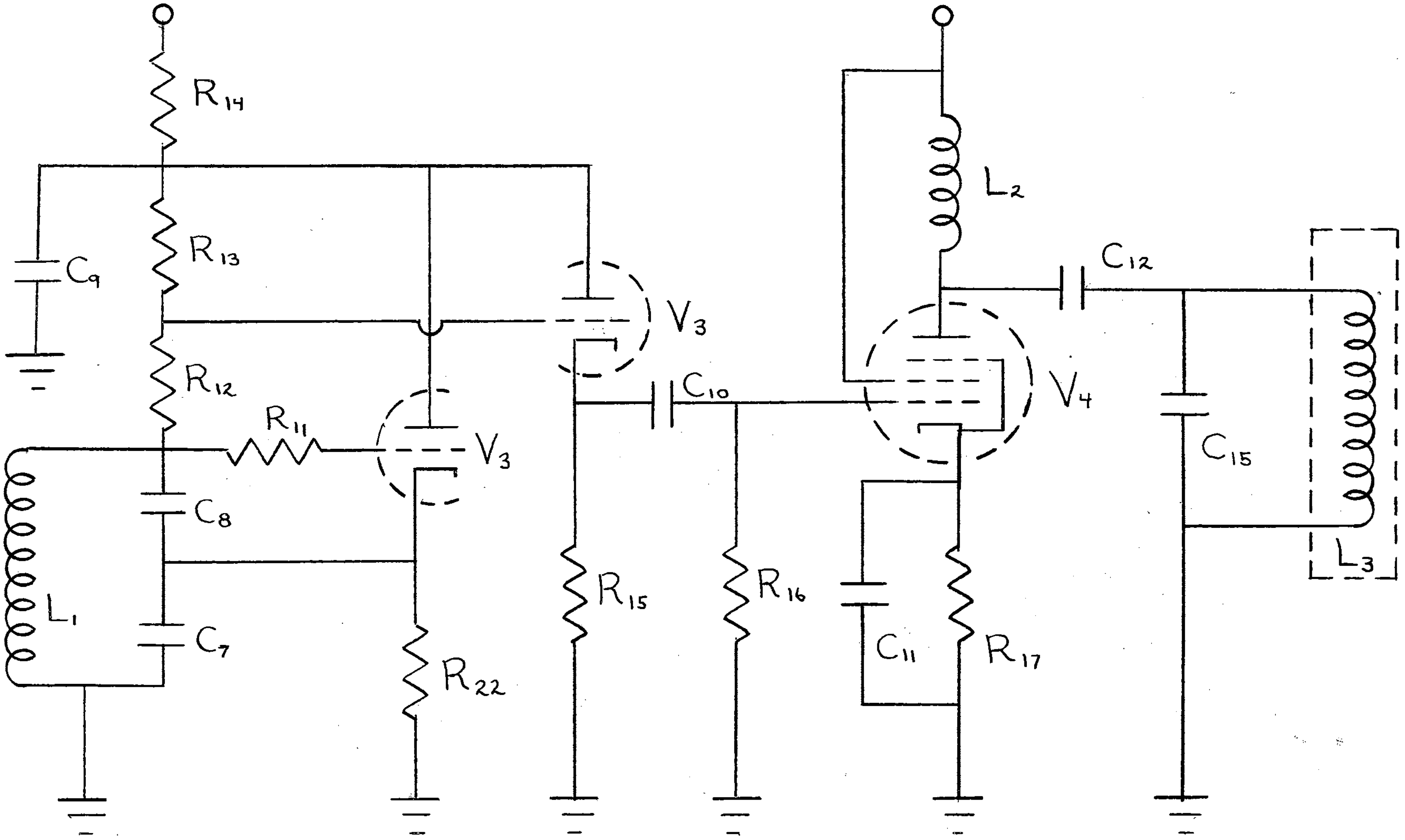

Fig. 5. Schematic Diagram of Transmitter

The output of the power amplifier is coupled to the transmitter coil through a short length of coaxial cable.

The oscillator circuit chosen was originally designed by Harris as a Q multiplier.[5] The circuit was shown to be oscillatory by Clapp,[6] and modified as a low frequency oscillator by Fleming.[7] The circuit was chosen for its unusual simplicity, its stability at the lower frequencies, and the fact that only one untapped choke was required.

The actual circuit used in this transmitter was modified from a circuit by Fleming and Follin[8] to oscillate at approximately 16 kilocycles. The frequency determining elements in the circuit are L_1 and C_8. The capacitor C_7 has little effect on the frequency and the best stability and waveform are obtained when C_7 is approximately 100 times larger than C_8.[9]

The output signal from the oscillator is taken from the grid circuit and directly coupled to the grid of a cathode follower buffer amplifier. The oscillator and buffer consist of the two sections of a 12AT7.

The output signal of the buffer is developed across R_{15} and coupled to the grid of the 12AQ5 power amplifier. The 12AQ5 tube was chosen for its high power handling capabilities and the 12 volt filament is compatible with the other tube filaments in the set. This is a conventional

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[5] H. E. Harris, "Simplified Q Multiplier," <u>Electronics</u> (May 1951), pp. 130-134.

[6] J. K. Clapp, "Frequency Stable LC Oscillators," <u>Proceedings of the Institute of Radio Engineers</u> (August 1954), p. 1299.

[7] L. Fleming, "Fixed LC Oscillator Without Taps," <u>Electronics</u> (March 1955), pp. 216-224.

[8] L. Fleming and W. W. Follin, "Subaudio Oscillator Tunes 0 to 50 Cycles," <u>Electronics</u> (October 1955), pp. 144-145.

[9] Fleming, p. 220.

self biased power amplifier having L_2 for its plate load. The output signal is coupled from the plate load of the power amplifier to the transmitter coil by C_{12} and a short piece of coaxial cable.

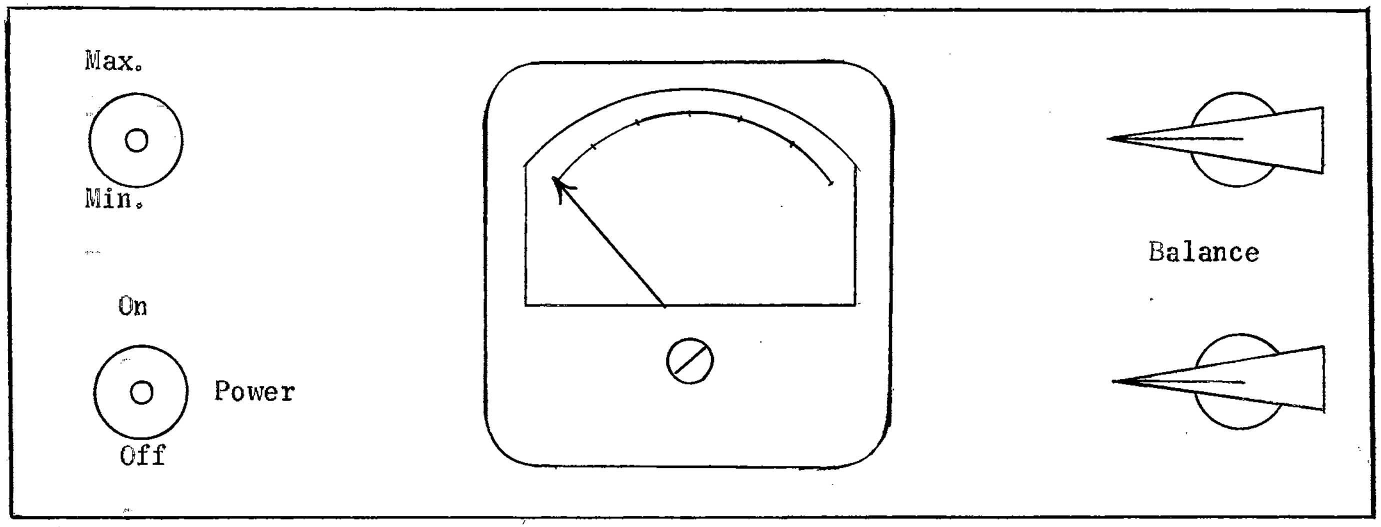


Fig. 6. Front Panel Layout Showing All Operating Controls

TABLE III

METAL DETECTOR PARTS LIST

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

C1	0.1
C2	0.1
C3	25 elect.
C4	0.1
C5	25 elect.
C6	25 elect.
C7	0.1 mica
C8	.001 mica
C9	10 elect.
C10	.25
C11	25 elect.
C12	0.1
C13	0.1
C14	0.1
C15	.0005 mica

Resistors (All resistances are in ohms. K represents 1,000; M represents 1,000,000. All resistors are ½ watt unless otherwise specified)

R1	47K
R2	220K
R3	100K
R4	1.2K 1 watt
R5	470K
R6	100K
R7	2.2K 1 watt
R8	470K
R9	100K
R10	2.2K
R11	1.0M
R12	1.0M
R13	2.2M
R14	10K 1 watt
R15	22K 1 watt
R16	270K
R17	250 1 watt
R18	100K
R19	1.0K
R20	1.0M pot.
R21	1.0M pot.
R22	15K 1 watt
R23	10

Vacuum Tubes

V1	12AU7
V2	12AX7
V3	12AT7
V4	12AQ5

Rectifiers

Mr1 Meter Rectifier, full wave

Meters

M1 D'Arsonval meter movement

Switches

Sw1	DPST	Toggle
Sw2	DPST	Toggle

Inductances

L1	100 millihenry (modified iron core choke)
L2	1.7 henrys iron core
L3	50 millihenrys air core
L4	50 millihenrys air core
L5	50 millihenrys air core

PLATE I

View of Detector with Laboratory Power Supply

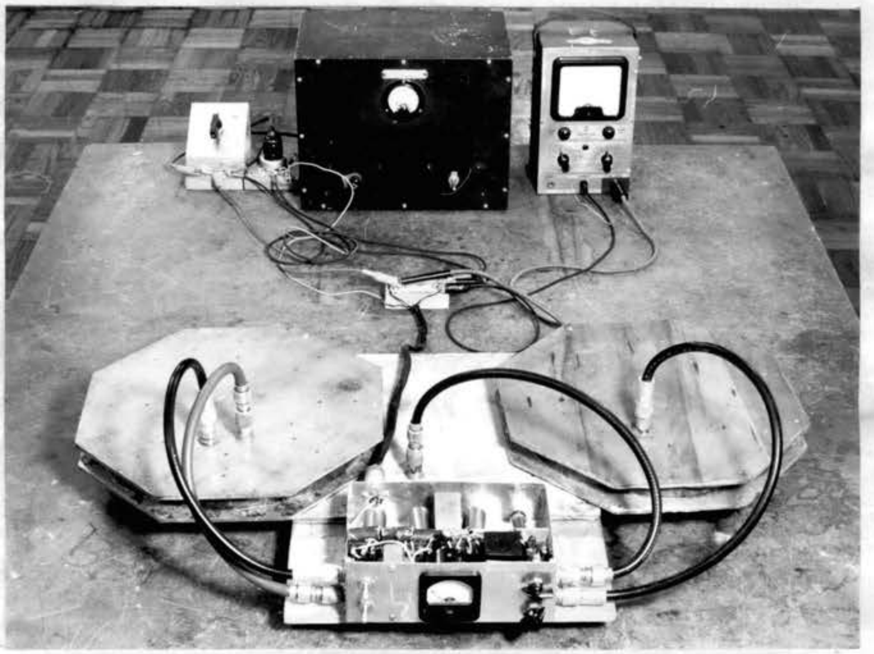


PLATE II

Top View of Detector Showing Chassis Interior

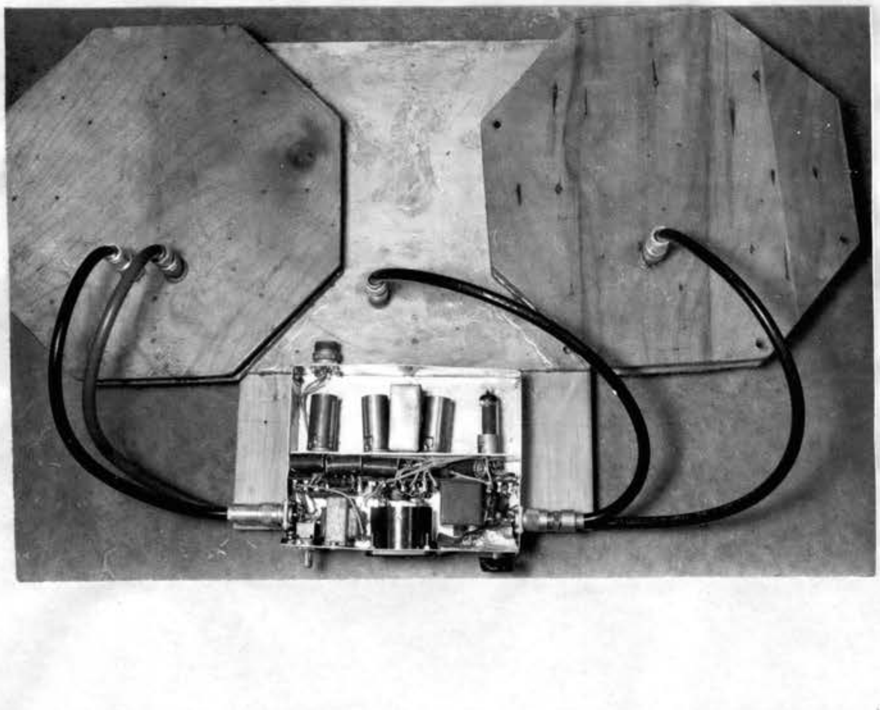


PLATE III

Front Panel View of Metal Detector

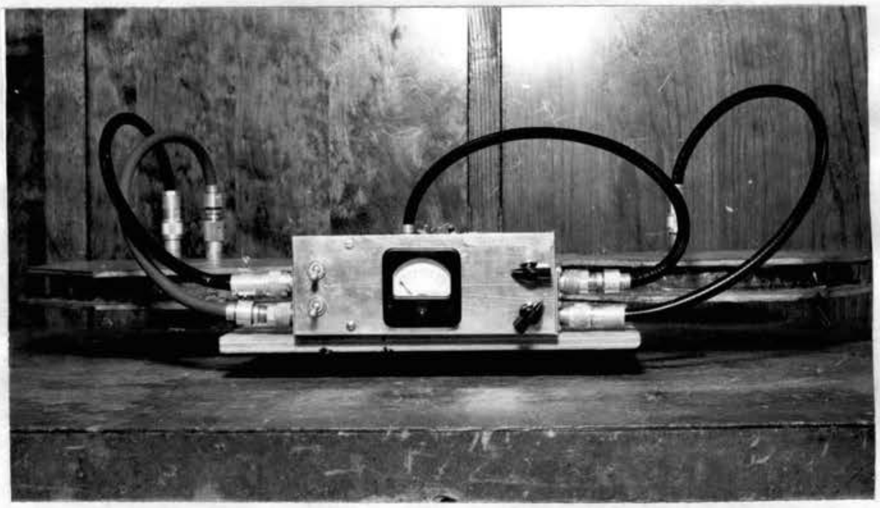
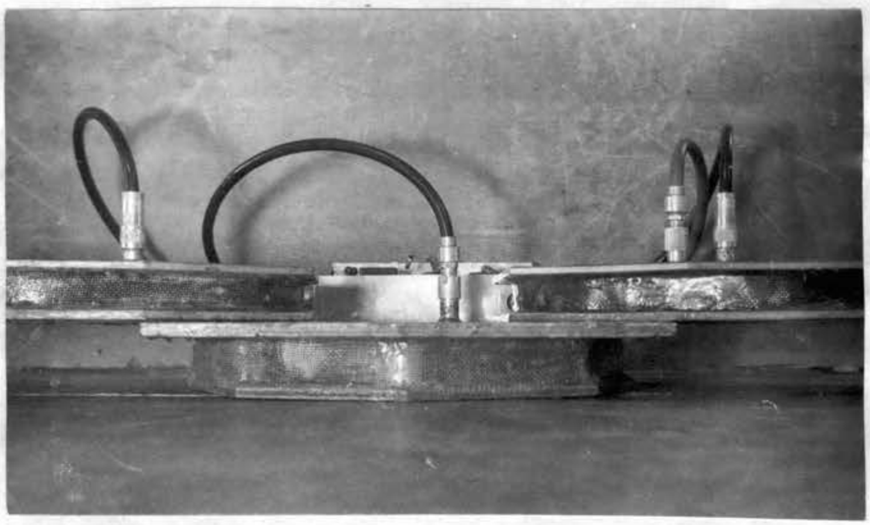


PLATE IV

Rear View of Metal Detector Displaying
Overlapping Coils



CHAPTER IV

PERFORMANCE

Sensitivity and Response Pattern

The coil configuration of the detector produces a sensitivity pattern as displayed by Figure 7. These contours are equal response lines for any conducting object in the plane of the coils. The line dividing the symmetrical families is one of zero response. A particle or target along this line results in voltages of equal magnitude being induced in the receiver coils. These voltages cancel since they are 180° out of phase and the net effect is one of no response.

In determining the theoretical response, only spherical targets were considered. This idealized case would, of course, be seldom found in practice. When evaluating non-spherical targets it would be necessary to consider the shape of the target and its position in the magnetic field, in addition to the previously considered factors. The detector will give a minimum indication to the presence of a conducting sphere 3 inches in diameter at a distance of 2½ feet. The presence of an object the size of an outboard motor at a distance of 4 to 6 feet will also result in a minimum indication. These distances are measured from the center of the transmitter coil along the major axis of detection. This axis is perpendicular to the zero sensitivity line and is illustrated in Figure 7. Since the detector will respond to objects on either side, this will result in a detection band 8 to 12 feet wide for the larger objects.

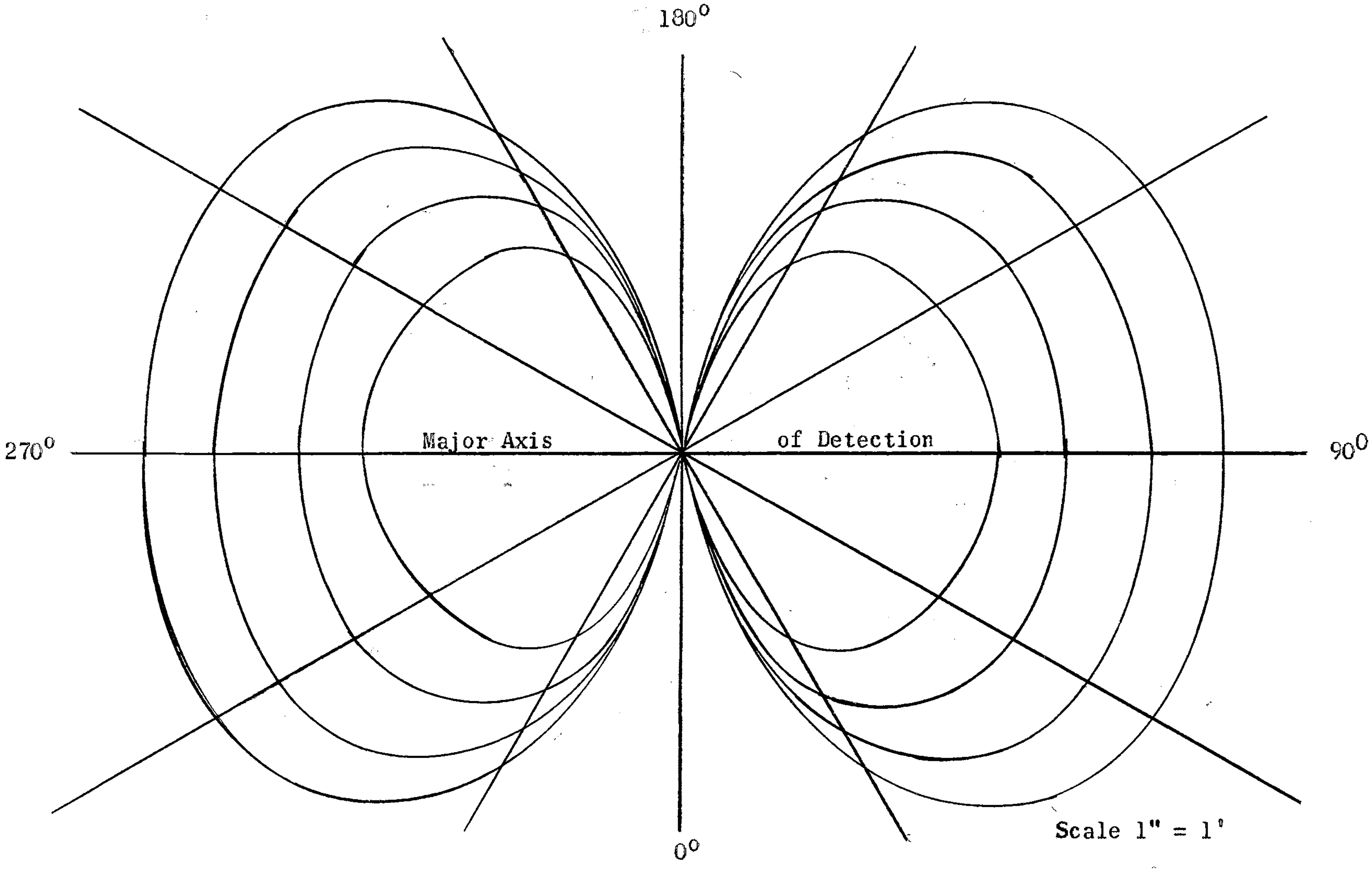


Fig. 7. Response Pattern of Detector

Calibration of the meter was not deemed logical or necessary, since a nearby small object would produce the same response as a more distant large object.

The problem of the divers metallic equipment giving a false indication of a target was solved by positioning the operator along the line of zero response. The largest objects involved, the air tank and regulator on the diver's back, would be symmetrical with the pattern and produce no response. Any other equipment effects would be nullified by the proper adjustment of the balancing circuit.

Operating Procedure

The controls of the detector have been simplified and reduced in number as much as possible. There are two reasons for this being done: First, in any type of equipment a minimum number of controls is desirable, but in this case it is necessary. The operator will probably be working under rather difficult conditions, complete darkness being one of the more severe handicaps. Any adjustments to be made under these circumstances must be done easily and quickly. For this reason the controls and adjustments must be few in number and not at all complicated. Second, for each external control, a fitting must be used to maintain watertight integrity. The possibility of water leaking into the electronic portion of the detector becomes greater as the number of fittings increase. The controls have been limited to an off-on switch, a maximum-minimum sensitivity switch, and the two balancing circuit potentiometers. The two switches could be incorporated into a single rotary switch to reduce the total number of waterproof fittings to three.

The procedure for placing the detector in operation is quite simple

PLATE V

Metal Detector Arranged to Determine
Response of a Copper Disk

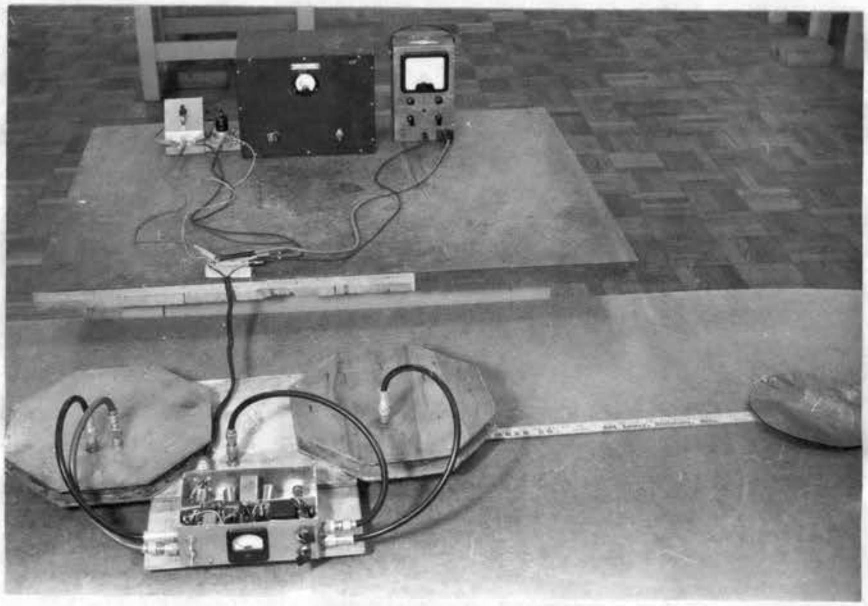
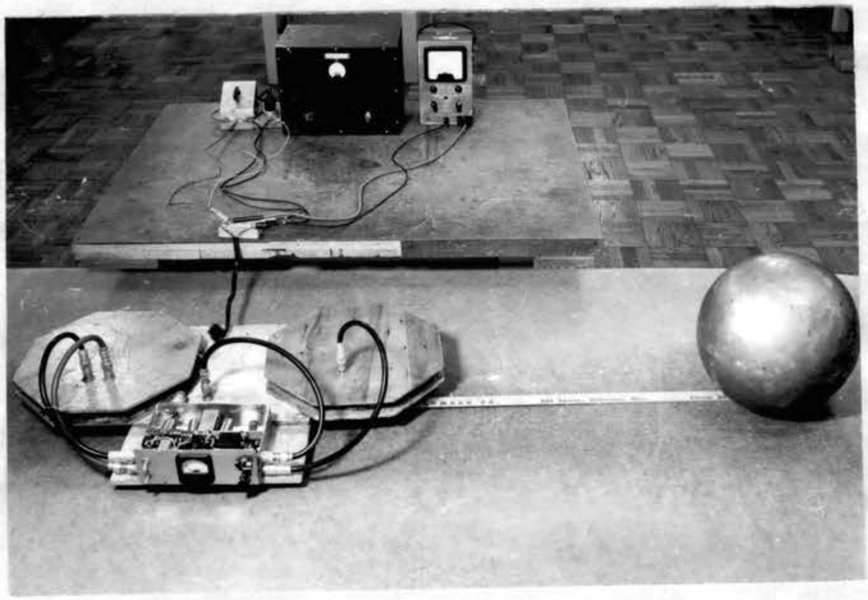


PLATE VI

Metal Detector Arranged to Determine
Response of an Iron Sphere



and no difficulty should be experienced in its operation. The proper sequence of steps in using the detector is as follows:

1. After the diver descends to the area to be investigated, the off-on switch is turned on. The meter becomes illuminated when this switch is closed.
2. With the detector in the operating position, the two balancing circuit controls are adjusted for a minimum or zero indication on the meter.
3. The sensitivity switch, which should be in the minimum position, is now switched to maximum sensitivity.
4. A slight readjustment of the balancing circuit may be required to give minimum meter indication. The detector is now in operating condition. A lane several feet wide may be examined for metallic objects by now moving about the bottom.

The possibility of detection of an object is greatly enhanced by establishing a definite search procedure rather than by one of random. This assures the complete coverage of the bottom without duplication of effort. The operator will develop different techniques and procedures through normal use of the equipment.

The machine will not give any indication of the position of an object, only that one exists. This hindrance may be reduced to a certain extent by a readjustment of the balancing circuit. A condition of unbalance is first created by the introduction of a voltage from the balancing circuit. This results in an indication by the meter. Now if the object is nearer to the coil with the predominant voltage it will cause a further increase in the meter reading. If it is on the other side the induced voltage cancels part of the original error voltage and the meter reading will decrease. The meter will reveal immediately to the operator which side the object is on. The sensitivity of the detector is not as great when operating in this manner as when it has been completely balanced.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

In general the detector should function as a useful tool in underwater salvage work. The sensitivity of the device was not quite as good as theoretically possible. This was primarily due to the search coils. With the present search coil arrangement it is not possible to obtain zero voltage at the input grid. Although the coil output voltage is only in the order of a few microvolts is is comparable with weak signals. As previously stated, it is necessary for this voltage to be zero for maximum sensitivity. An increase in the sensitivity and extension of the range would follow from an improvement in the search coil arrangement. It is felt that a concentric coil configuration would bear investigation.

Spillover and coupling also provide serious engineering problems with a high gain, low level amplifier such as the one used here. In any production model it would be advisable to completely isolate the receiver and transmitter sections. This could be done without increasing the physical size of the electronic portion appreciably. By making these two alterations the range of the device would be extended to a marked degree.

The theoretical considerations also indicated that the use of higher frequencies would be advantageous. A large increase in the operating frequency would require different techniques in construction, especially in the method of generating the electromagnetic field.

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