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# Design of a galvanometer to be placed within a tubular antenna for the purpose of measuring antenna current distribution

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# DESIGN OF A GALVANOMETER TO BE PLACED WITHIN A TUBULAR ANTENNA FOR THE PURPOSE OF MEASURING ANTENNA CURRENT DISTRIBUTION

BY

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A

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# INTRODUCTION

The experimental methods heretofore used to measure the relative distribution of currents on antennas have, in the process of measurement, changed the original current distribution and thus introduced errors in the results. Since the radiation resistance and field pattern of an antenna element are highly dependent upon current distribution, a reliable method for its determination is desirable. Mathematical calculation of the latter can be made from a known distributed capacitance, but because of end effects, proximity to ground, or to other elements of an array, the distributed capacitance may not be uniform and such calculations would become extremely laborious. To avoid this and yet achieve results truly representative of actual conditions, it would be advantageous to find a more reliable experimental method for measurement of current distribution.

The initial attempts at the measurement of current distribution were made with antennas having resonant lengths in the broadcast frequency region. The first significant work was done in 1927 by R. M. Willmotte of the English National Laboratory.[(1)] This consisted of preparing cylindrical sections in the form of a cage and adding these in series to form an antenna. Thermo-ammeters were connected electrically between the sections and were placed inside them so as to be

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(1) Willmotte, R. M., The Distribution of Current on a Transmitting Antenna, Institution of Electrical Engineers, Vol. 66, pp. 617-627, June 1928.

shielded from the r-f radiation. The ammeters then indicated the longitudinal antenna currents at the points of insertion and were read from a remote point with a telescope. Correction of the readings was required to compensate for inductance of the meters.

A second method for use at these frequencies was introduced in 1937 by J. F. Morrison of Bell Laboratories. (2) A

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(2) Morrison, J. F., Simple Method For Observing Current Amplitude and Phase Relations in Antenna Arrays, IRE Proceedings, Vol. 25, pp. 1310-1326, October 1937.

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comparatively small rectangular steel loop was extended from a large transmitting antenna so as to be linked by the magnetic field of the antenna. The voltage induced in the pickup loop was proportional to the antenna current at the point adjacent to the loop. By applying this voltage to a coaxial cable, it could then be transmitted to a distant point for monitoring.

Such methods were satisfactory for application at broadcast frequencies, but because of the small physical size of VHF and UHF antennas, the conventional ammeters could not be placed inside them nor could the voltage from a small pickup loop be transmitted from the antenna to an external detector without having the conductor distort the antenna fields and the current distribution. For use at 150 mc, the pickup loop as used by Morrison was modified in 1948 by Giorgio Barzilai to a size of about 3/8 inch square. (3) The antennas used, whether parasitic or driven, were hollow

(3) Barzilai, Giorgio, Experimental Determination of the Distribution of Current and Charge Along Cylindrical Antennas, IRE Proceedings, Vol. 37, pp. 825-829, July 1949.

cylinders with a narrow longitudinal slot along one side. The pickup loop extended through the slot from a slug which lay inside and could travel the length of the antenna. This slug contained a rectifying circuit which delivered the rectified r-f voltage to a shielded pair which in turn was taken from the antenna to a galvanometer through a metal member meeting the antenna perpendicularly at its center.

Up to the present time, the most recent approach to the problem of antenna current measurement was reported in 1949 by Tetsu Morita. (4) The method of detecting the current,

(4) Morita, Tetsu, The Measurement of Current and Charge Distributions on Cylindrical Antennas, Office of Naval Research Technical Report No. 66, February 1, 1949.

by a traveling current loop, was the same as that used by Barzilai, however, a conducting ground plane was placed at the center of an antenna and perpendicular to it. This converted the antenna into an end-fed antenna above a ground plane. The current measured along this antenna was then assummed to be equivalent to that found on half of the antenna before the introduction of the ground plane. This instrumentation was accomplished by extending the hollow, slotted center conductor of a coaxial line through the ground plane to act as an antenna and then grounding the outside conductor of the line to the plane. In this way, the antenna could be a driven or a parasitic element, and all equipment along with the operator could be located behind the ground plane to reduce experimental errors.

The main precaution in measuring the current distribution on an antenna is to avoid to the highest degree any change in the currents which might be caused by proximity of the measuring equipment. If this precaution is observed, the data should be reliable, while otherwise it is meaningless. As was stated, the methods presented by Willmotte and Morrison are physically inapplicable to UHF problems. The metal support applied at the antenna center by Barzalai distorts the radial electric field and thereby causes some error. The method used by Morita appears very good in theory. However, to give accurate results, the ground plane must be of infinite extent and conductivity. A relatively good conductivity is attainable, but a ground plane of finite size can introduce more error than is immediately apparent. Because of the discontinuity at the ground plane boundary, the electric fields will be reflected, thereby changing the current distribution along the antenna.

While all of these methods introduce some error, the method by Morita appears most accurate. The latter has, however, three principle sources of error: (1) the longitudinal slot in the antenna, (2)presence of a pickup loop in the antenna fields, (3) error as caused by finite extent and conductivity of the ground plane. Since the conventional

UHF antenna is a hollow cylinder, it is highly possible that a very small and sensitive mirror galvanometer could be incorporated into one end of the element to measure the rectified loop voltage. In this way, only a beam of light need link the observer and the antenna, and the third source of error in Morita's method would be eliminated.

The object of this paper is to design such a galvanometer for application to cylindrical UHF antennas and to discuss the procedure involving its use. The galvanometer will then be placed inside a completely isolated parasitic antenna and the distribution of current along the antenna will be measured.

## REVIEW OF LITERATURE

From literature available concerning measurement of the distribution of current on UHF antennas, nothing was found related to inclusion of the detecting meter within the antenna. The work of Willmotte, applied to antennas of broadcast frequency, is similar to the proposed method in that it includes meters within the antenna, but in the form given it is totally inapplicable to UHF antennas. There has been some work done on galvanometers of small size, but none which could be applied directly to the problem with which this paper is concerned.[5]

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(5) Laws, Frank A., Electrical Measurements, N. Y., McGraw-Hill, 1917, pp. 1-98.

## DISCUSSION OF CURRENT LOOP AND DESIGN OF GALVANOMETER

Several methods for measuring the relative distribution of current on UHF antennas have been developed, but the method to be used here incorporates a new and unique idea. The current distribution will be determined for an antenna the length of which is one-half wavelength at 400 megacycles (mc). The antenna is to be a slotted aluminum tube with an inside diameter of 1.41 centimeters (cm), which will allow a galvanometer to be built into one end.

### THE CURRENT LOOP CIRCUIT

The current pickup loop and the slug containing rectifying components are to be the same as used in previous work by Barzilai and Morita, but it is desirable to inspect some of the theory involved and the conditions imposed upon their use. It is the magnetic field about the antenna which induces an emf in the current loop, and the relation between this emf and the antenna current may be shown as follows. At a particular point on the antenna, let

$i = I_m \sin \omega t$ = instantaneous current on the antenna

$e$ = instantaneous voltage induced in the current loop

$H_\theta$ = magnetic field intensity about antenna at its surface

$\beta$ = flux density at the surface of the antenna

$\phi$ = flux through the current loop

$A$ = area of the current loop

$r$ = distance between centers of the loop and the antenna axis

Then

$$H_{\theta} = \frac{\beta}{\mu} = \frac{i}{2\pi r} \qquad (1)$$

from which

$$\beta = \frac{\mu i}{2\pi r} \qquad (2)$$

Also,

$$\phi = A\beta \qquad (3)$$

and substituting β of equation (2) into equation (3),

$$\phi = \frac{\mu A i}{2\pi r} \qquad (4)$$

For a loop such as this having only one turn,

$$e = \frac{d\phi}{dt} \qquad (5)$$

Replacing ∅ in equation (5) by that in equation (4),

$$e = \frac{d}{dt}\frac{\mu A i}{2\pi r} = \frac{\mu A I_m}{2\pi r}\frac{d}{dt}(\sin \omega t)$$

$$e = I_m\left[\frac{\mu\omega A}{2\pi r}\cos \omega t\right] \quad \text{volts} \qquad (6)$$

From this analysis, it is apparent that the voltage induced in the loop is proportional to the magnitude of the adjacent antenna current. Therefore, the relative current distribution may be determined by moving the current loop along the antenna and measuring the relative voltages induced in the loop.

Figure 1 shows the electrical circuit of the pickup slug connected to the galvanometer. Without the capacitor

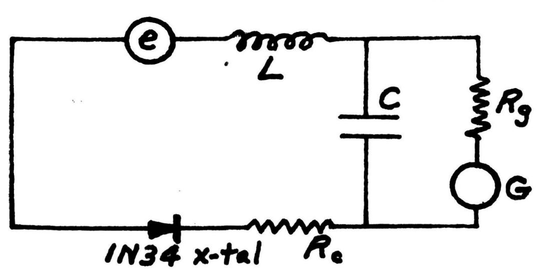



Fig. 1. Electrical circuit of pickup loop and galvanometer

L – inductance of current loop

C – capacitor

$R_c$ – resistance of 1n34 crystal

$R_g$ – resistance of galvanometer

G – galvanometer movement

e – voltage induced in loop

C in the circuit, the voltage across the galvanometer would be pulsating in form. If the capacitor is added, the properties of the $R_g$–C combination can filter the pulses so as to approach a d-c voltage. The space allotted and the capacitors available place an upper limit of approximately 25 μμfd on the capacitance to be used. It may be shown that choice of the $R_g$–C combination such that the product $R_gC$ is at least 4 times the period of the 400 mc wave would reduce the a-c ripple to about 2% of the d-c level. Since the actual value of capacitance to be used here is 28 μμfd, the magnitude of $R_g$ will now be calculated with the assumption that a 2% ripple factor is acceptable.

If P is the period, in seconds, and f is the frequency of a 400 mc wave, the above stated relations may be expressed symbolically as follows:

$$R_gC \geqq 4P \quad \text{seconds} \qquad (7)$$

and solving for $R_g$,

$$R_g \geqq 4\frac{P}{C} \quad \text{ohms} \qquad (8)$$

also

$$P = \frac{1}{f} = \frac{1}{4 \times 10^8} = 2.5 \times 10^{-9} \text{ sec} \qquad (9)$$

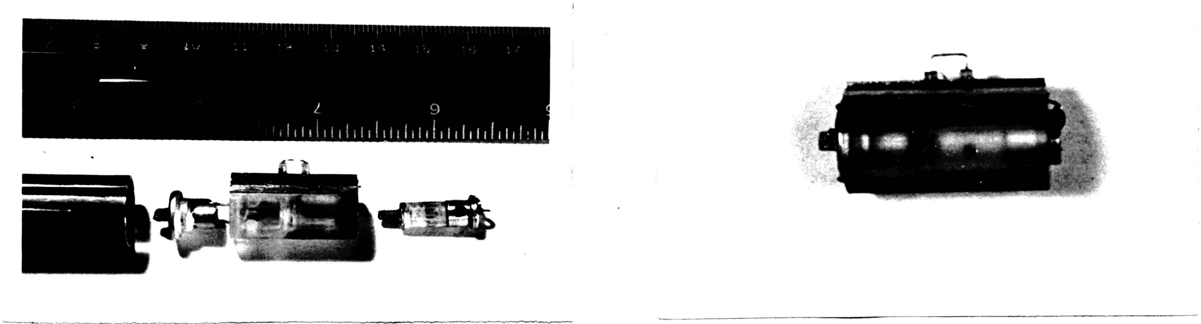
then

$$R_g \geqq 4 \frac{2.5 \times 10^{-9}}{28 \times 10^{-12}}$$

$$R_g \geqq 358 \text{ ohms} \qquad (10)$$

This indicates that the total galvanometer resistance should be at least in the order of 350 ohms.

Two major reasons present themselves as to why the low ripple factor should be attained: (1) the d-c component of voltage received by the galvanometer is increased, and (2) a large component of a-c voltage applied to the galvanometer might be rectified by contact points in the measuring system, thus tending to produce inaccuracy. Figure 2 (a) provides an exploded view of the pickup slug showing the polystyrene case, current loop, crystal, and capacitor. The completed slug is then shown in Figure 2(b). As seen in the photographs, the metal strip, through which the current loop projects, is for the purpose of providing continuity across the antenna slot in the vicinity of the current loop.

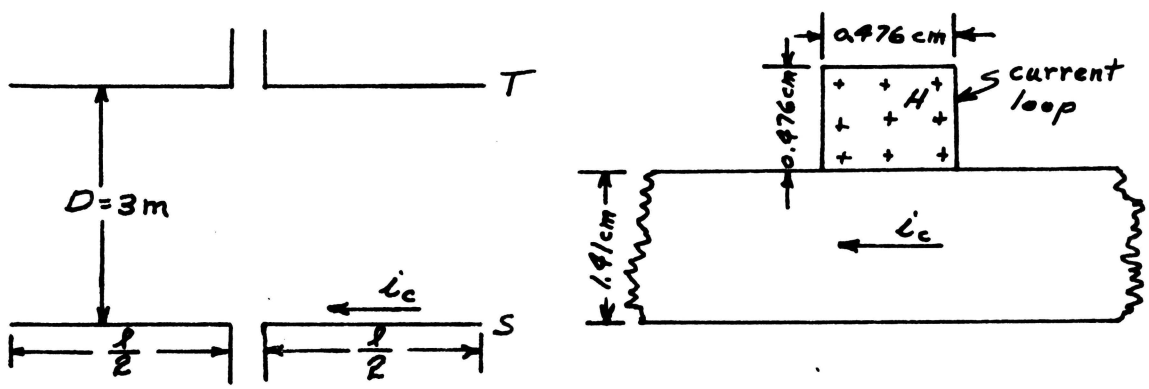


(a) (b)

Fig. 2. (a) exploded view of pickup slug, (b) pickup slug in completed form

GALVANOMETER SENSITIVITY REQUIREMENTS

Having found a lower limit for galvanometer resistance, the next logical step is determination of the required sensitivity. As shown in Figure 3, let a 400 mc transmitting antenna T radiating an average power $P_{ave}$ of 10 watts, be placed 3 meters from the half wavelength parasitic antenna S. Assumptions will be made that power is radiated equally in all directions from the driven element, and that the parasitic element is equivalent to a short circuited half wave dipole having a radiation resistance $R_r$ of 72.3 ohms and a sinusoidal current distribution. The current will then be maximum at the center of the antenna and sensitivity calculations will be based on the current at that point.




(a) (b)

Fig. 3. (a) a parasitic element in the vicinity of a driven antenna, (b) a section of the parasitic antenna with the current loop projecting

$\bar{E}$ = rms value of electric field intensity at S

$\bar{H}$ = rms value of magnetic field intensity at S

$v_{oc}$ = rms open circuit voltage at center of antenna S

$i_c$ = current at the center of the parasitic antenna

$\ell$ = length of the parasitic antenna

$\eta$ = intrinsic impedance of free space ($120\pi$ ohms)

The relation for power delivered per unit area at a distance D from the antenna T is;

$$\bar{E} \times \bar{H} = \frac{P_{ave}}{4\pi D^2} \quad (\text{watts/m}^2) \qquad (11)$$

also

$$|\bar{H}| = |\bar{E}|/\eta \qquad (12)$$

so that

$$|\bar{E}|^2/\eta = \frac{P_{ave}}{4\pi D^2} \qquad (13)$$

and

$$|\bar{E}|^2 = \frac{P_{ave}}{4\pi \eta D^2} = \frac{10}{4\pi(120\pi)(3)^2} \qquad (14)$$

$$|\bar{E}| = 1.53 \times 10^{-2} \text{ volt/m} \quad \text{(rms)} \qquad (15)$$

The open circuit voltage for the parasitic antenna when considered as a dipole would be,

$$v_{oc} = |\bar{E}|\ell = (1.53 \times 10^{-2})\left[\frac{1}{2} \times \frac{3 \times 10^8}{4 \times 10^8}\right] \qquad (16)$$

$$v_{oc} = 5.74 \times 10^{-3} \text{ volt} \quad \text{(rms)} \qquad (17)$$

The current on a dipole antenna is limited by the radiation resistance of the antenna together with the load resistance. The parasitic antenna is shorted at its center so that the load resistance is zero and the current at center may be calculated as follows.[(6)]

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(6) Jordan, Edward C., Electromagnetic Waves and Radiating Systems, N. Y., Prentice-Hall, 1950, pp. 331-333

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$$i_c = \frac{v_{oc}}{R_r} = \frac{5.74 \times 10^{-3}}{72.3} \qquad (18)$$

$$i_c = 7.94 \times 10^{-5} \text{ amp} \quad \text{(rms)} \qquad (19)$$

The magnetic field intensity at the center of the loop can be expressed as

$$H_{\bullet} = \frac{i_c}{2\pi r} = \frac{3.97 \times 10^{-5}}{2\pi \times \left[\frac{1.41 + 0.476}{2} \times 10^{-2}\right]} \qquad (20)$$

$$H_\theta = 1.34 \times 10^{-3} \text{ amp/m} \qquad \text{(rms)} \tag{21}$$

and the flux density in the loop can be expressed in terms of $H_\theta$ as

$$\beta = \mu H_\theta \tag{22}$$

Since

$$\phi_{max} = \sqrt{2}\,\beta A = \sqrt{2}\,\mu A H_\theta \tag{23}$$

then

$$\phi_{max} = \sqrt{2}\, 4\pi \times 10^{-7} \times (0.476 \times 10^{-2})^2 \times 1.34 \times 10^{-3}$$

$$\phi_{max} = 5.40 \times 10^{-14} \text{ weber} \tag{24}$$

$$\phi = \phi_{max} \sin \omega t \tag{25}$$

and e as a function of $\phi$ becomes,

$$e = \frac{d\phi}{dt} = \omega\, \phi_{max} \cos \omega t \tag{26}$$

then

$$e_{max} = \omega\, \phi_{max} = 2\pi f\, \phi_{max} \tag{27}$$

$$e_{max} = 2\pi \times 4 \times 10^{8} \times 5.40 \times 10^{-14}$$

$$e_{max} = 136\ \mu \text{ volts} \tag{28}$$

Assuming that the rectified voltage wave is filtered adequately to produce a d-c voltage equal to the maximum value of e, then the galvanometer design should provide a maximum desired deflection with 136 microvolts applied at the galvanometer terminals. This maximum deflection will be designated later, but it may be assumed at present to be less than one-half radian.

## GALVANOMETER TYPE

The tubing to be used for the antenna has an inside diameter of 1.41 cm and being a half wavelength at 400 mc, the antenna must be 37.5 cm long. Since the galvanometer is to be placed inside the antenna element at one end, the current loop cannot be moved over the total length of the element. Therefore, the assumption must be made that the current is distributed symmetrically over the antenna length. With this assumption, the galvanometer length can be 18.75 cm, less enough room for galvanometer leads and half of the pickup slug or about 15 cm.

Having established a minimum inherent resistance, minimum sensitivity, and maximum size, a specific type of galvanometer may now be chosen. The galvanometer is not limited by mass nor volume so much as by the shape to which it must conform. Examination shows that a movement suspended perpendicular to the axis of the antenna would be highly impractical because of the extremely short length of suspension that would be required together with an accompanying high torsion. This leaves only one alternative, that is a suspension along the antenna axis. But with such a suspension, the movement will sag if the antenna lies horizontally. Thus the parasitic antenna must be vertically supported, which in turn requires that the driven element lie in the same position so that the electromagnetic fields will be vertically polarized.

All galvanometer movements except the suspended magnet, string, thermo, and moving coil (D'Arsonval) may be easily eliminated by virtue of the limited space available.[7] The

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(7) Ibid. pp. 24-48

suspended magnet and string galvanometers acquire their fields from electromagnets which are excited by the current or voltage to be measured. Because of the position of the suspension, these electromagmets would be required to lie with their axes along the antenna diameter. Since the galvanometer must be voltage sensitive, with the space available there could not be enough turns wound on the core to provide the required strong field for good sensitivity.

The thermo-galvanometer requires for its field, a source other than the current or voltage to be measured. This source would have to be permanent magnets since wires leading into the antenna are undesirable. However the efficiency of the heater and thermocouple combination would be so low that loss in sensitivity could not very well be compensated by a larger magnetic field strength. It is of interest to note that vacuum tube amplifiers are often used to increase the overall sensitivity of a galvanometer system, but would be impractical in this case because of limited space for a power source. All galvanometers have now been eliminated except the popular moving coil type with permanent magnet field the deflection of which can be obtained by causing a light beam to fall incident upon the galvanometer mirror and be reflected through the antenna slot. The following design will show how this type of galvanometer can be constructed so as to meet the requirements which have already been stipulated.

MAGNETIC CIRCUIT DESIGN FOR THE GALVANOMETER FIELD

Thus far the MKS rationalized system of units has been used for all derivations and calculations, but since the cgs system is used in most data available for magnetic circuit design, the latter system will be used in the designs to follow. The characteristics portrayed in the second quadrant of a hysteresis loop are those which are of interest in permanent magnet design. If a permanent magnet is operating with a flux density and demagnetizing force of $B_d$ and $H_d$ respectively, as in the second quadrant of Figure 4, then $B_d \times H_d$ is proportional to the energy available at the air gap and is called the energy product.[8] If magnets are to

(8) Permanent Magnet Design Manual, General Electric Co. Chemical Department, Pittsfield, Mass., pp. 6-7

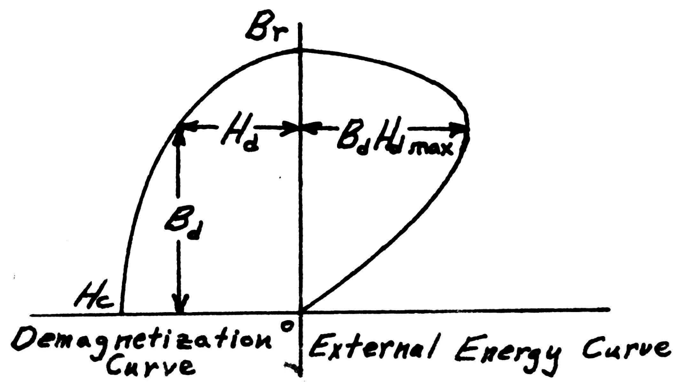



Fig. 4. Generalized demagnetization and energy product curves for permanent magnets

be utilized to best advantage, it is desirable that they be operated on the demagnetization curve at the point where this energy product is maximum. The general relation between the demagnetization curve and external energy curve is shown in Figure 4 where also $H_c$ is the coercive force, $B_r$ is the residual flux density, and $B_dH_{d}max$ is the maximum energy product.

When used with the proper ratio of length to cross-section, Alnico 5 alloy has the highest energy product of any magnetic material commercially available at the present time. In any type of permanent magnet circuit, the leakage flux should be kept to a minimum by locating the magnets as near the air gap as possible. This eliminates, in this case, the possibility of locating the magnets at a remote point and then providing an iron flux path to the galvanometer coil since the flux leakage would be unduly high. Also, because the length to area ratio must be large to get a maximum energy product with Alnico 5, the flux density of the gap would be low if the magnets were placed on each side of the coil and magnetized along the antenna diameter.

At best, magnetic circuit design is a trial and error or empirical process, and the exactness with which it can be carried out is largely dependent on the experience of the designer. With the preceding facts in mind, the magnetic circuit of Figure 5 was chosen in striving for a maximum energy product with a minimum of undesirable flux leakage. The notations $M_1$ and $M_2$ refer to the two magnets providing excitation, G is the region of usable air gap, and W is a wrought iron bar which completes the magnetic circuit. The

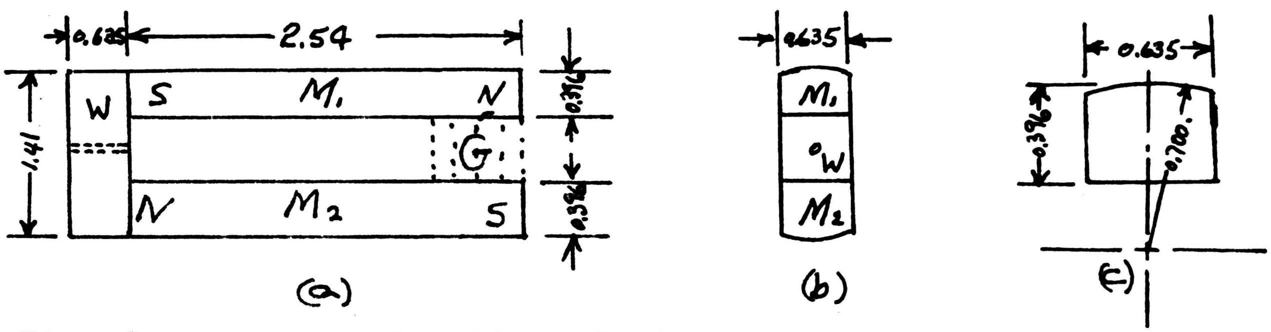



Fig. 5. Magnetic circuit used with Alnico 5 permanent magnets (Dimensions are in cm, but drawings are not to scale)

portion of the figure labeled (a) is a plan view of the circuit, (b) is a right side view, and (c) is an enlarged end view of magnet $M_1$. The magnets were obtained as 1/4" x 1/4" cast Alnico 5 stock and were ground very slowly and carefully to the given dimensions in an attempt to avoid loss of magnetism. Part W was made of wrought iron because the latter has a lower magnetic reluctance than most any of the basic irons. The hole in W permits passage of the coil suspension in order that its length will not be limited by the length of the magnets.

The magnetic circuit components were held in place as shown in Figure 5 (a), then a piece of thin paper was placed over the whole, and iron filings were sprinkled on the paper. Figure 6 shows the resulting flux distribution as indicated by the filings. The most noteworthy point here is that between the magnets, the flux is fairly concentrated in the air gap up to a point 0.95 cm from the magnet ends. It is


Fig. 6. Flux distribution in the air gap and about the Alnico 5 magnetic circuit as indicated by iron filings

then obvious that maximum flux linkage could be obtained if a coil 0.95 cm long would be placed in this region.

The galvanometer, being of the mirror type, will produce a satisfactory deflection at 3 meters distance with a small angle of coil rotation. A narrow band of high flux density would then be both sufficient and desirable as a medium for the coil. Having determined the region of maximum flux density, the method shown in Figure 7 was used to concentrate the flux through the region in which the coil lies. Plates or pole shoes $P_1$ and $P_2$ were added to the magnet faces while an armature A was mounted in the air gap in such way that the coil could rotate about it. All of these additions were of wrought iron in order to again provide a low reluctance path.

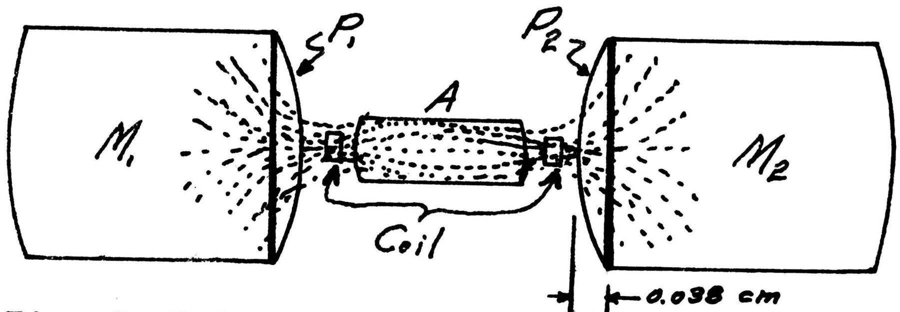



Fig. 7. End view of magnetic circuit showing pole shoes and armature in position

The operating point of the magnets should now be determined, and if that point is not in the optimum region of the demagnetization curve, some modification of the circuit may be required. Let the following quantities be defined in cgs units;

$B_g$ = average flux density in useful portion of air gap

$H_g$ = magnetizing force in useful air gap

$L_m$ = total length of magnets

$L_g$ = total length of air gap

$A_m$ = cross sectional area of magnets

$A_g$ = effective area of air gap

$\phi_m$ = total flux through the magnets

$\phi_g$ = total flux through the effective gap

$$K_1 = \frac{\text{total flux required for circuit}}{\text{useful air gap flux}}$$

$$K_2 = \frac{\text{magnet magnetomotive force}}{\text{air gap magnetomotive force}}$$

In air,

$$H_g = B_g \tag{29}$$

and since

$$\phi_m = K_1 \phi_g \tag{30}$$

then,

$$B_d A_m = K_1 B_g A_g \tag{31}$$

Also

$$H_d L_m = K_2 H_g L_g = K_2 B_g L_g \tag{32}$$

and combining equations (31) and (32),

$$\frac{B_d}{H_d} = \frac{K_1 L_m A_g}{K_2 L_g A_m} \tag{33}$$

The constants $K_1$ and $K_2$ are dependent upon the degree of flux leakage in a magnetic circuit and are often determined from flux leakage plots with a resultant accuracy which is largely dependent upon the skill of the designer. Sometimes a mathematical approach can be used, particularly when the air gap lies between two magnets the axes of which are on a straight line. However, the magnets for this design lie parallel to each other, and a good engineering approximation of $K_1$ and $K_2$ can be obtained with the aid of Figures 6 and 7 while avoiding any long calculations that would in themselves require a certain degree of approximation.

There is somewhat of an interrelationship between $A_g$, $L_g$, $K_1$, and $K_2$ in a magnetic circuit of this type, and having chosen $A_g$ and $L_g$ first, consideration of these latter values was given when determining $K_1$ and $K_2$. The following values were chosen for the magnetic circuit which has been outlined.

$A_m = 0.227 \text{ cm}^2$

$L_m = 5.08 \text{ cm}$

$K_1 = 1.5$

$A_g = 0.318 \times 0.950 = 0.302 \text{ cm}^2$

$L_g = 2 \times 0.0795 = 0.159 \text{ cm}$

$K_2 = 3.0$

By using equation (33), the operating point of the magnets on the demagnetization curve can be determined since there is only one point on the curve corresponding to a particular value of $B_d/H_d$.

$$\frac{B_d}{H_d} = \frac{K_1 L_m A_g}{K_2 L_g A_m} = \frac{1.5 \times 5.08 \times 0.302}{3.0 \times 0.159 \times 0.227} = 21.2 \text{ gausses/oersted}$$

Plate 1 presents the demagnetization curve and external energy curve for Alnico 5. If a straight line having a slope of $B_d/H_d = 21.2$ is drawn from the origin and through the demagnetization curve, the point of intersection is found to be so near the point corresponding to maximum energy product that the magnetic circuit may be considered entirely satisfactory as far as having maximum energy available in the air gap. The flux density $B_d$ in the magnets is 9.7 Kilogausses at that point and the air gap flux density $B_g$ may be obtained from equation (31).

$$B_g = \frac{B_d A_m}{K_1 A_g} = \frac{9.7 \times 0.227}{1.5 \times 0.302} = 4.87 \text{ Kilogausses}$$

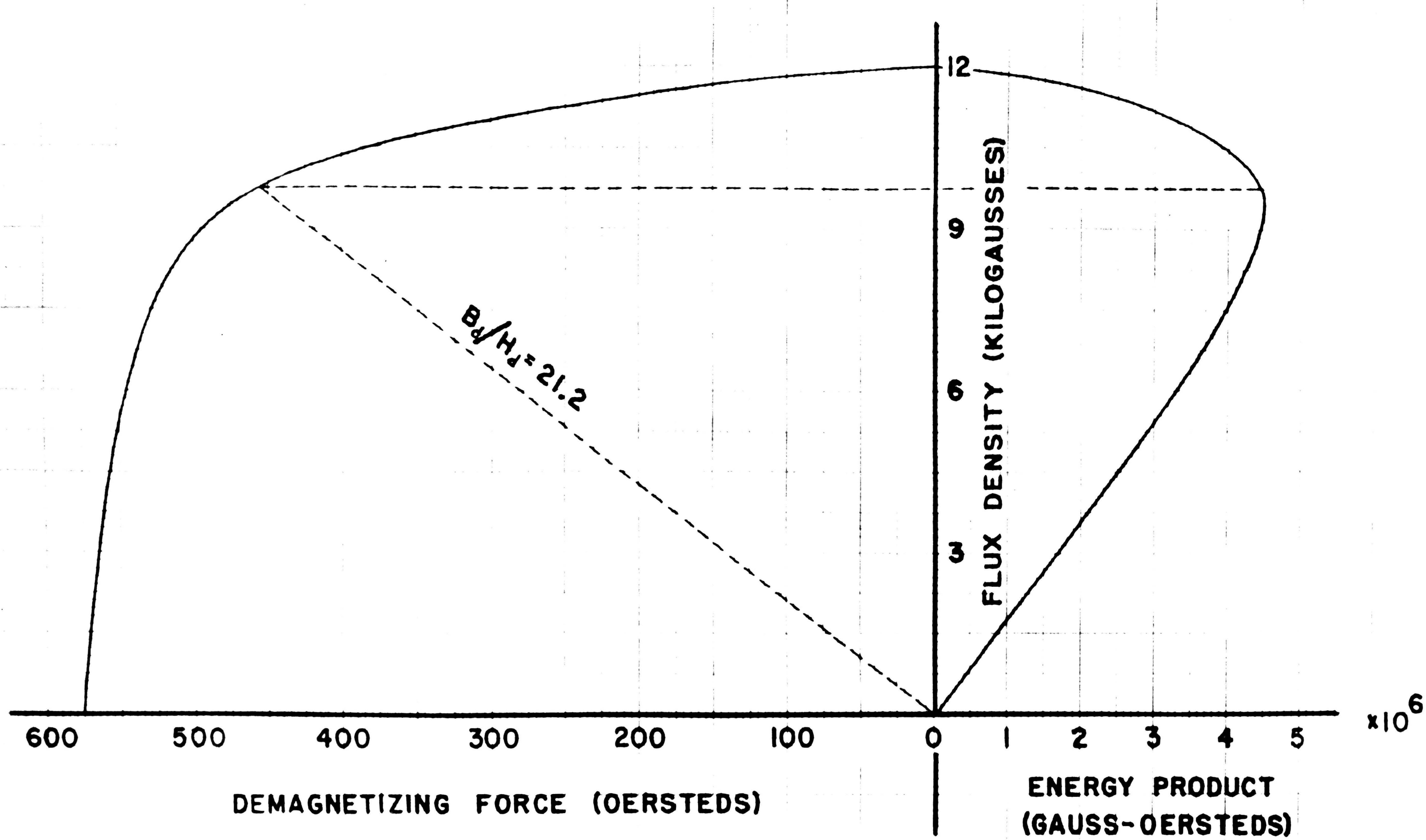
If the values chosen for the magnetic circuit are representative of actual conditions, then 4.87 Kilogausses should be the flux density in the useful air gap.

## GALVANOMETER ENCLOSURE

At this stage of construction, it becomes necessary

PLATE I

MINIMUM VALUE DEMAGNETIZATION AND ENERGY PRODUCT CURVES FOR ALNICO 5 PERMANENT MAGNET ALLOY



to encase the magnetic circuit in a manner that will allow the components to maintain their desired relative positions while at the same time providing a mount for the coil suspension. The enclosure must be constructed in such a way that the galvanometer can be easily put into the antenna or removed for adjustment or repair. With these requirements in mind, the design given in Figure 9 was adapted. The region A is an open rectangular volume in which the coil, suspension, and mirror may be placed while the opening B, as seen edgewise in the elevation view, provides a position for

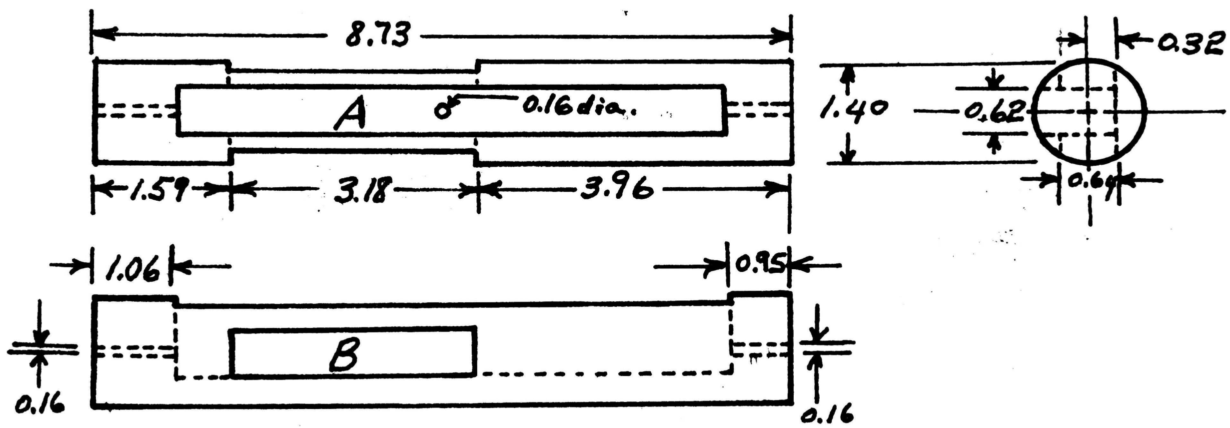



Fig. 9. Top, front, and right-side views of the galvanometer enclosure (Dimensions given in cm, not to scale)

the magnetic circuit. The holes at the ends of the enclosure are present so that the suspension may pass through them and be fastened at their outside ends. The 0.16 cm hole at the center of the top view is present so that a short length of number 16 wire may be soldered to the lower side of the armature and forced into the hole, thus holding the armature in the correct position. The enclosure was fabricated from polystyrene plates cemented together with the magnetic circuit in place and with a soft fiber material filling the region A. The whole was then turned down on a lathe to the specified dimensions and the fiber was removed from the center section leaving it open.

## THE GALVANOMETER MOVEMENT

The mean coil length for the galvanometer has been specified as 0.95 cm, and in order that the coil may move freely between the pole shoes, its mean radius can be only 0.238 cm. A short circuited turn of low resistance is often included in a galvanometer coil to aid in damping. In this case it was considered advisable to expend damping in order to use all available space to increase the number of coil turns and as a result the sensitivity.

By trial, it was found that a coil wound to the above dimensions with number 38 B & S gage enameled wire could contain no more than 45 turns and yet maintain sufficient clearances. Since the area of number 38 wire is found to be $7.97 \times 10^{-5}$ cm$^2$, it would appear that the cross section of the coil could be no greater than $45 \times 7.97 \times 10^{-5}$ or $3.59 \times 10^{-3}$ cm$^2$ if the small area in the coil not filled by conductors is neglected. In choosing the largest wire which will give at least the minimum required galvanometer resistance and still be within the limits of coil area, two equations must be satisfied. Letting N equal the number of coil turns, these equations become;

$$N \cdot (\text{cross section of the wire in cm}^2) = 3.59 \times 10^{-3} \text{ cm}^2$$

$$N \cdot (\text{mean length of one turn})(\text{resistance of wire/cm}) \geqq 358 \text{ ohms}$$

Under such circumstances, the solution of these two equations must be made by trial and error from copper conductor tables. It is found that number 49 B & S gage enameled copper wire is the largest which will satisfy the conditions, and 574 turns of this may be used with a resultant coil resistance of 469 ohms. A coil cross section having a width to thickness ratio of 2 was found most satisfactory and such an arrangement permits 34 turns per layer and 17 layers of wire on the coil giving a total of 578 turns.

The suspension is the next part of the movement to be considered. Maximum sensitivity can be attained with a suspension which will bare the weight of the coil, conduct the required current, and still have a minimum torsion constant. The suspension of smallest torsion constant available from Leeds and Northrup Company is of 24K gold having a diameter of 0.00178 cm and a torsion of 0.06 dyne-centimeters per radian for a one cm length.

It is common practice in precision galvanometers to suspend the coil from above with conventional suspension material and then to use as the lower conductor a fine helical spring which acts to hold the movement somewhat in tension. Also, galvanometers of that type have provision for removing the weight of the coil from the upper suspension when not in use, because the helical spring is not strong enough to keep the coil from jolting and breaking the upper suspension when the galvanometer is moved. Removal of the coil weight from the suspension is not very practical for the galvanometer under consideration and so the spring will be replaced by conventional suspension material with the whole movement placed slightly in tension to avoid breakage.

The beam of light reflected from the mirror is limited by the edges of the antenna slot as to the maximum angle over which an indication can be obtained. The mirror will be on the longitudinal axis of the antenna, placing it 0.705 cm from the antenna slot which is 0.238 cm in width. The maximum angle of sweep will then be the angle subtended by an arc of length 0.238 cm on a circle of radius 0.705 cm or approximately 1/3 radian.

The torsion of a given suspension material is inversely proportional to its length. However, when a rotational torque source is placed between two suspensions of equal length, the restoring torque is twice that of one suspension or the effective suspension length is 1/4 of the total length of both suspensions. Using the dimensions and data that have been previously given, calculations of the expected galvanometer sensitivity can be made.[9] Let the

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(9) Ward, R. P., Introduction to Electrical Engineering N.Y., Prentice-Hall Inc., 1947, pp. 79-80

---

galvanometer current (I) be expressed in amperes and the other terms to follow in cgs units.

$T_d$ = deflecting torque $T_r$ = restoring torque

L = length of the coil R = radius of the coil

$l_s$ = effective length of suspension = 7.60/4 = 1.90 cm

$R_c$ = resistance of coil plus suspension

$K_T$ = torsion constant of the suspension

$\theta$ = angle of deflection (radians)

The deflecting torque produced by the coil may be expressed as

$$T_d = 2 N B_g L R I \times 10^{-1} \tag{34}$$

while the restoring torque of the suspension is

$$T_r = K_T \theta / \ell_s \tag{35}$$

The opposing torques must be in equilibrium so that

$$T_r = T_d \qquad \text{and also} \qquad I = e / R_c$$

Then equating the torques in terms of the galvanometer constants,

$$2 N B_g L R \frac{e}{R_c} \times 10^{-1} = K_T \theta / \ell_s \tag{36}$$

and solving for e,

$$e = \frac{K_T R_c \theta}{2 N B_g L R \ell_s} \times 10 \tag{37}$$

$$e = \frac{(0.06) \times (469 + 7.60 \times 0.9) \times 1/3 \times 10}{2(578\ ) \times (4.87 \times 10^3) \times (0,95) \times (0.238) \times 1.90}$$

$$e = 39.3\ \mu \text{ volts} \tag{38}$$

By calculation, the galvanometer should then require 39.3 microvolts to obtain a 1/3 radian deflection. This sensitivity is nearly three and one-half times that which was calculated to be required with the transmitting antenna 3 meters from the parasitic element. If it is desired to take measurements with the antennas separated by that distance or less, then a series resistor can be added to decrease the galvanometer sensitivity. However, full advantage may be taken of the maximum sensitivity be placing the antennas even farther apart.

Since the coil and suspension are small, the mirror can not have very much mass if excess weight on the suspension and possible misalignment are to be avoided. A telescope is often used to read a scale which is reflected from the galvanometer mirror, or sometimes a hairline on the lens of a light source is focused on the mirror and then reflected on an opaque scale in order to get numerical values corresponding to the deflections. These methods require a comparatively large plane mirror, so they were eliminated in favor of a very small mirror which would reflect a light beam so small that it could be used itself as an indication when incident upon an opaque scale. A mirror capable of doing this was found to be of very thin glass having a mercuric backing and measured 1/64 by 3/64 inches. This mirror was cemented onto the suspension at a point as near the coil as possible, having the 3/64 inch dimension along the suspension.

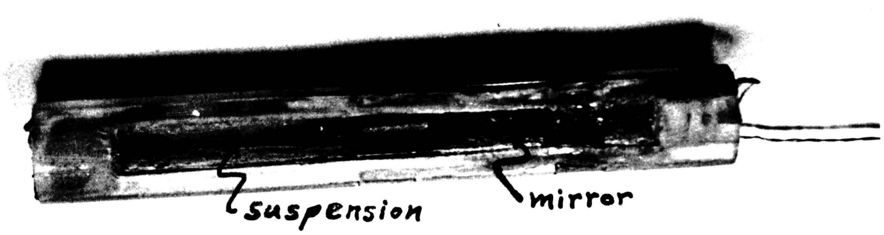



Fig. 10. The assembled galvanometer

The completed galvanometer is shown in Figure 10. The resolving power of the film, used in making the picture, was not sufficient to make the suspensions distinguishable nor is the mirror easily seen, but each of these is indicated by arrows in the photograph.

## THE ANTENNA MOUNT

It may be recalled that one of the prime objectives of this thesis is to measure, after construction of the galvanometer, the current distribution along a half wavelength isolated parasitic element. The objective then in mounting such antenna should be to avoid having in the vicinity of the element any materials which would distort the near fields. The mount shown in Figure 11 was built to accomplish this goal. The base and vertical support are made

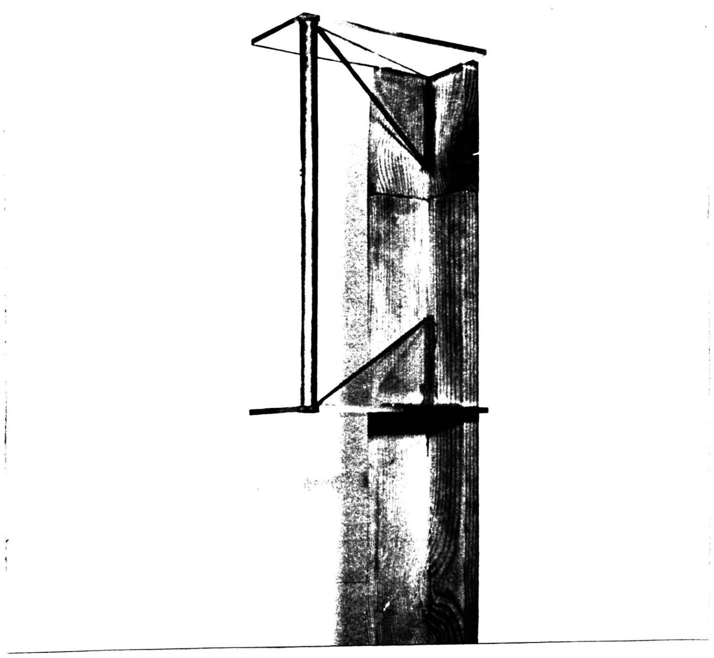


Fig. 11. The half wavelength parasitic antenna mounted so as to minimize discontinuity in its near fields

sturdy by using a large volume of wood, however, this wood is very dry so as to have a low dielectric constant and to prevent it from being lossy in character. The plates which were in actual contact with the antenna at its top and bottom are of polystyrene. The materials surrounding the antenna have been chosen so as to provide a minimum of discontinuity, and as a result the current distribution on the antenna should be changed very little from the form it would have in actual free space.

## GALVANOMETER CONSTRUCTION

In constructing the galvanometer, all design specifications and calculated data were adhered to except that pertaining to the coil and suspension. Number 38 enameled wire was the smallest available, and this permitted only the aforementioned 45 turns to be used on the coil. The smallest suspension material at hand was of 14K gold, 0.0038 cm in diameter, with a torsion constant 20 times that of the suspension called for in the design. As would be expected, the galvanometer sensitivity was decreased terrifically in comparison with that required, and the total galvanometer resistance reduced to 15.37 ohms, the coil having only 2.82 ohms of this total.

One design calculation was verified even with the galvanometer constructed in the above manner. It was found that 200 microamperes gave a deflection of 45 cm at 3 meters distance. Considering the different coil and suspension being used, solution of equation (36) for $B_g$ indicates that 5.07 Kilogausses would be required in the air gap to produce such deflection. This compares very favorably with the design value of 4.87 Kilogausses. Since the greatest possibility of error in design was the calculation of $B_g$, the calculated sensitivity of 39.3 $\mu$ volts for the galvanometer, using the design specifications, may now be considered quite correct.

## EXPERIMENTAL PROCEDURE

Even though the galvanometer sensitivity obtained was far from that desired, measurements of current distribution were made on the parasitic element with the driven antenna only 10 cm away in order to have a detectable galvanometer deflection. The constructed galvanometer was placed in the lower end of the vertical parasitic antenna. The current pickup slug was also placed inside the antenna and connected electrically to the galvanometer by a twisted pair so that it could be free to move through better than half the antenna length. Figure 12 shows a schematic view of the apparatus used.

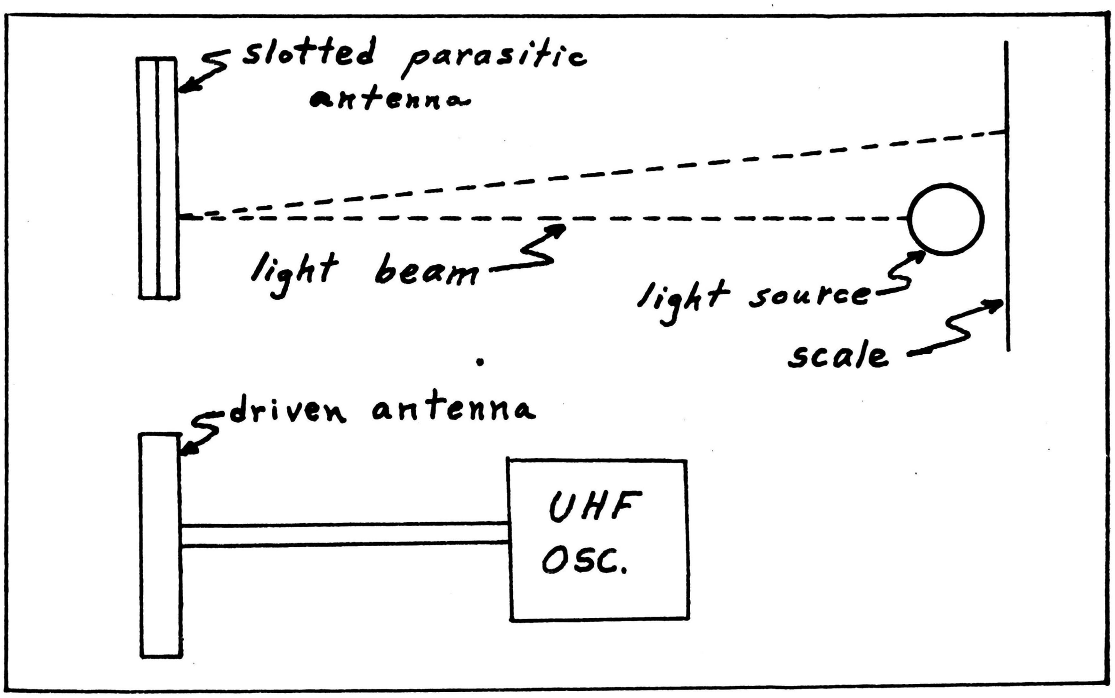



Fig. 12. Schematic layout of antenna current meaduring equipment.

A Leeds an Northrup Model 2100 combination 6 volt light source and opaque scale was placed 3 meters from the parasitic element to determine the galvanometer deflection. In order to obtain a maximum deflection, the galvanometer was positioned within the antenna so that at zero current the reflected light beam would just clear the edge of the antenna slot and then be deflected across the slot when the galvanometer is excited.

With low resistance in the constructed galvanometer, the filtering action of the $R_gC$ was so poor that a 100 ohm resistor could be added in series with the galvanometer without changing its sensitivity while a 120 ohm series resistor was found to increase the sensitivity by 20%. The 100 ohms in series would normally decrease the sensitivity to 1/7 the original value, but the ineffectiveness might be partially explained by the fact that filtering action without the series resistor was practically nil. The voltage delivered to the galvanometer, as a result, was that of a half wave rectifier, the d-c component of which is $1/\pi$ times its peak value. This explains about one-half of the 1/7 factor, and the other one-half is most likely caused by r-f currents on the galvanometer leads. The latter can not be readily investigated, however, since the exact effects of these currents are not known.

In taking current measurements on the antenna, the 120 ohm resistor was placed in series with the galvanometer, but even then the sensitivity was so small that the 10 cm separation of the antennas had to be used. Several experimental runs were made in measuring the current distribution along the upper end of the antenna. The results of each run were essentially the same and are presented in the first part of Table II. As given, these values require a correction since the relation between the voltage induced in the current loop and the galvanometer deflection is not known. Therefore, it is desirable to calibrate the galvanometer with some reliable standard.

## GALVANOMETER CALIBRATION

If the current pickup loop is placed near the antenna center and the output of the driven antenna is changed, the voltage induced in the pickup loop will be at all times proportional to the voltage induced in another antenna in the immediate vicinity. A monitoring antenna can then be placed about one meter from the parasitic antenna, and the voltage induced in it can be measured with a VTVM. The relation between the galvanometer deflection and the monitoring antenna voltage may be determined by varying the output of the UHF oscillator driving the transmitting antenna. The latter variation can be obtained by changing the output coupling to the oscillator plate lines and by changing a coaxial stub at the oscillator output from open to short circuit. Since only the relative antenna current distribution is desired and the currents will be normalized, this provides a perfectly acceptable means for calibration. Figure 13 shows a schematic diagram of the calibration setup and, as may be seen, it differs from the current measuring

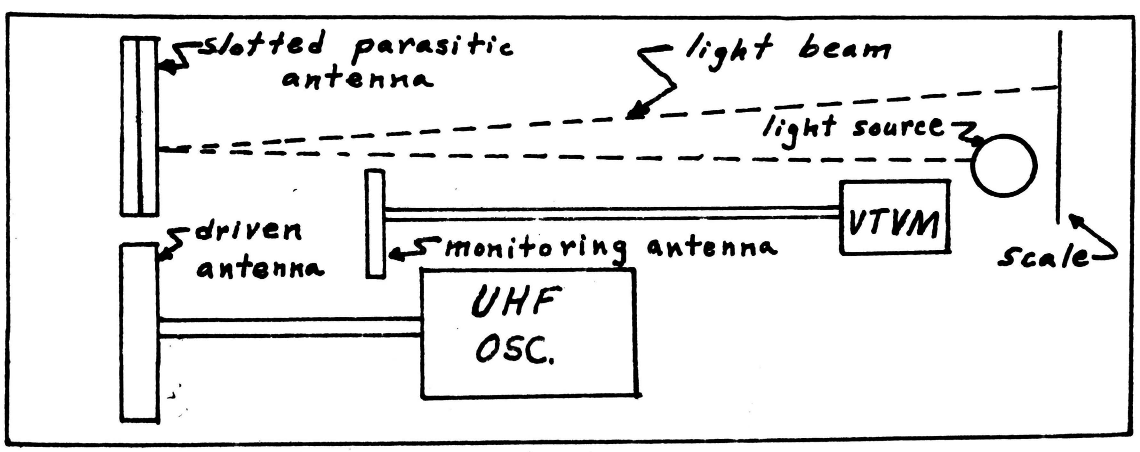



Fig. 13. Schematic diagram of galvanometer calibration equipment

setup only by addition of the monitoring antenna and VTVM. A pictoral view of the calibrating equipment, less the transmitting antenna, is shown in Figure 14.

Fig. 14. Pictoral view of calibration and current measuring equipment

The galvanometer was calibrated over the range from zero to the maximum galvanometer deflection obtained when making current distribution measurements. The calibration data is presented in Table I and is plotted as monitoring antenna voltage versus galvanometer deflection on Plate 3. The galvanometer deflection appears to be an exponential function of the loop voltage. Such could be expected because of the non-linear characteristics of a crystal when driven hard as in this case. The curve would probably have been more linear if the galvanometer had been constructed with as good a sensitivity as the design called for.

## TABLE I

## CALIBRATION OF THE SPECIAL GALVANOMETER WITH A VTVM STANDARD

x = galvanometer deflection (cm)

V = voltage induced in the monitoring antenna as measured by the VTVM (volts)

| x | V | x | V |
|---|---|---|---|
| 0.0 | 0.00 | 4.1 | 0.67 |
| 0.5 | 0.08 | 5.2 | 0.74 |
| 0.6 | 0.15 | 6.3 | 0.82 |
| 0.8 | 0.22 | 8.1 | 0.90 |
| 1.0 | 0.30 | 10.0 | 0.98 |
| 1.5 | 0.37 | 12.0 | 1.05 |
| 2.0 | 0.44 | 14.5 | 1.13 |
| 2.6 | 0.52 | 17.6 | 1.20 |
| 3.2 | 0.59 | | |

## TABLE II

## VARIATION OF CURRENT DISTRIBUTION ON A PARASITIC ANTENNA OF ONE-HALF WAVELENGTH AT 400 MC

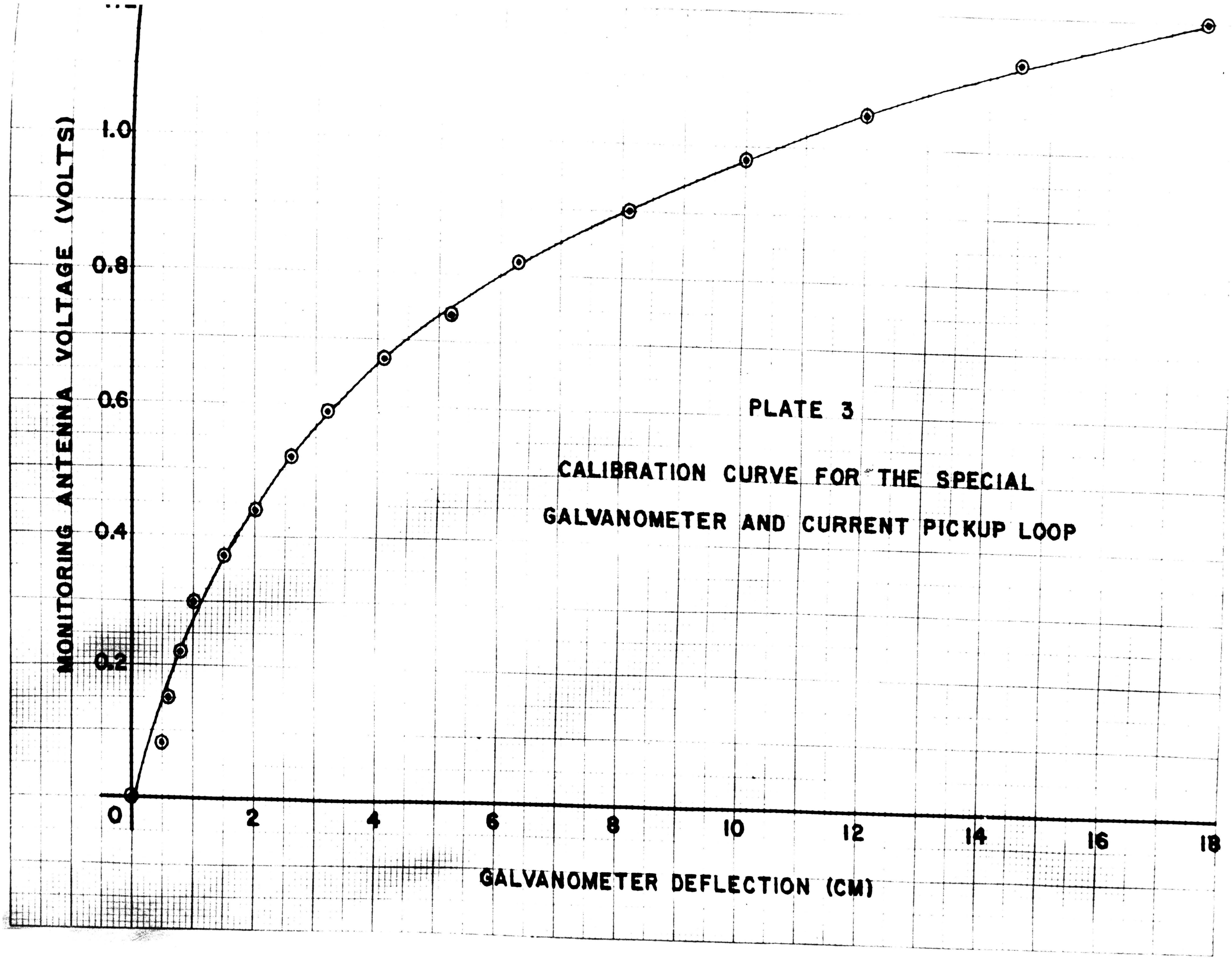
y = distance from upper end of antenna (cm)

x = galvanometer deflection (cm)

E = relative loop voltage corresponding to galvanometer deflection

P = per unit value of current distribution (E/1.2)

| y | x | E | P |
|---|---|---|---|
| 1 | 0.0 | 0.00 | 0.00 |
| 2 | 0.2 | 0.05 | 0.042 |
| 3 | 0.2 | 0.05 | 0.042 |
| 4 | 0.5 | 0.13 | 0.108 |
| 5 | 1.0 | 0.27 | 0.225 |
| 6 | 1.5 | 0.37 | 0.308 |
| 7 | 2.1 | 0.46 | 0.384 |
| 8 | 2.6 | 0.52 | 0.433 |
| 9 | 3.4 | 0.61 | 0.508 |
| 10 | 3.9 | 0.65 | 0.542 |
| 11 | 5.9 | 0.79 | 0.658 |
| 12 | 9.2 | 0.95 | 0.792 |
| 13 | 12.9 | 1.08 | 0.900 |
| 14 | 14.5 | 1.13 | 0.940 |
| 15 | 15.7 | 1.16 | 0.966 |
| 16 | 17.1 | 1.19 | 0.991 |
| 17 | 17.6 | 1.20 | 1.00 |
| 18 | 17.6 | 1.20 | 1.00 |
| 19 | 16.4 | 1.17 | 0.975 |


1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
MONITORING ANTENNA VOLTAGE (VOLTS)
GALVANOMETER DEFLECTION (CM)
PLATE 3
CALIBRATION CURVE FOR THE SPECIAL
GALVANOMETER AND CURRENT PICKUP LOOP

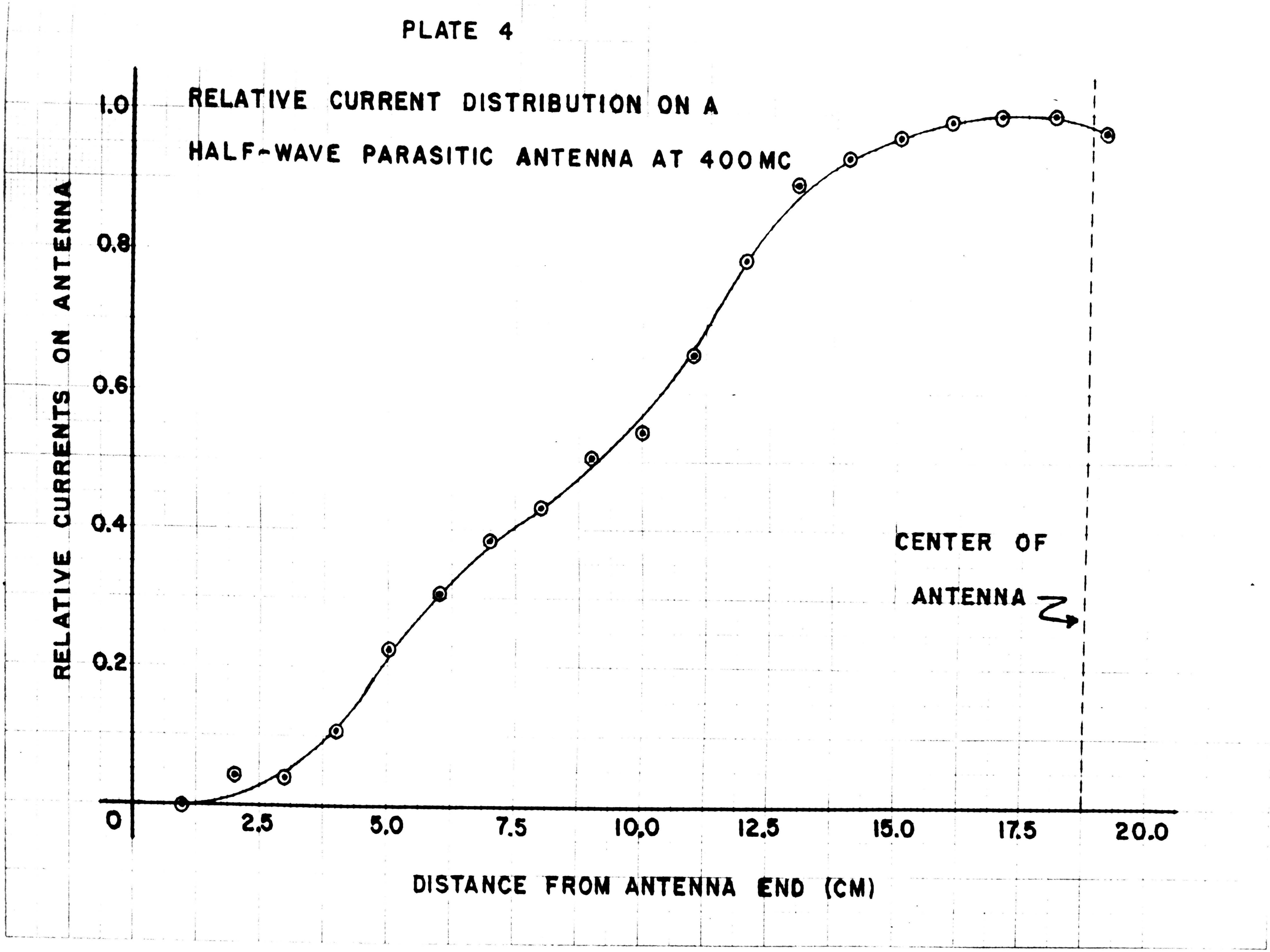


PLATE 4
RELATIVE CURRENT DISTRIBUTION ON A
HALF-WAVE PARASITIC ANTENNA AT 400 MC
RELATIVE CURRENTS ON ANTENNA
1.0
0.8
0.6
0.4
0.2
0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
DISTANCE FROM ANTENNA END (CM)
CENTER OF
ANTENNA

When the calibration curve was applied to the initial data of Table II, the normalized current distribution becomes as shown in Plate 4. Because of such close antenna coupling, the current distribution on the parasitic element would be expected to be a function of the current distribution on the driven element. The driven element was a half wave dipole fed by a coxaial cable, and from the nonsymetrical current distribution along the parasitic element, it may be deduced that the radiation pattern of the driven antenna was also nonsymetrical. However, there is nothing with which the results can be compared, and the degree of accuracy of the method has been neither proved nor disproved.

## RECOMMENDATIONS FOR FURTHER WORK

It is interesting to note that the Carboloy Company of General Electric has recently developed a platinum-cobalt permanent magnet alloy which has a maximum energy product nearly twice that of Alnico 5. However, the alloy which contains 23% cobalt and 77% platinum is presently not available commercially, but only on a laboratory scale. The large platinum content indicates, of course, that the material would be extremely high in cost.

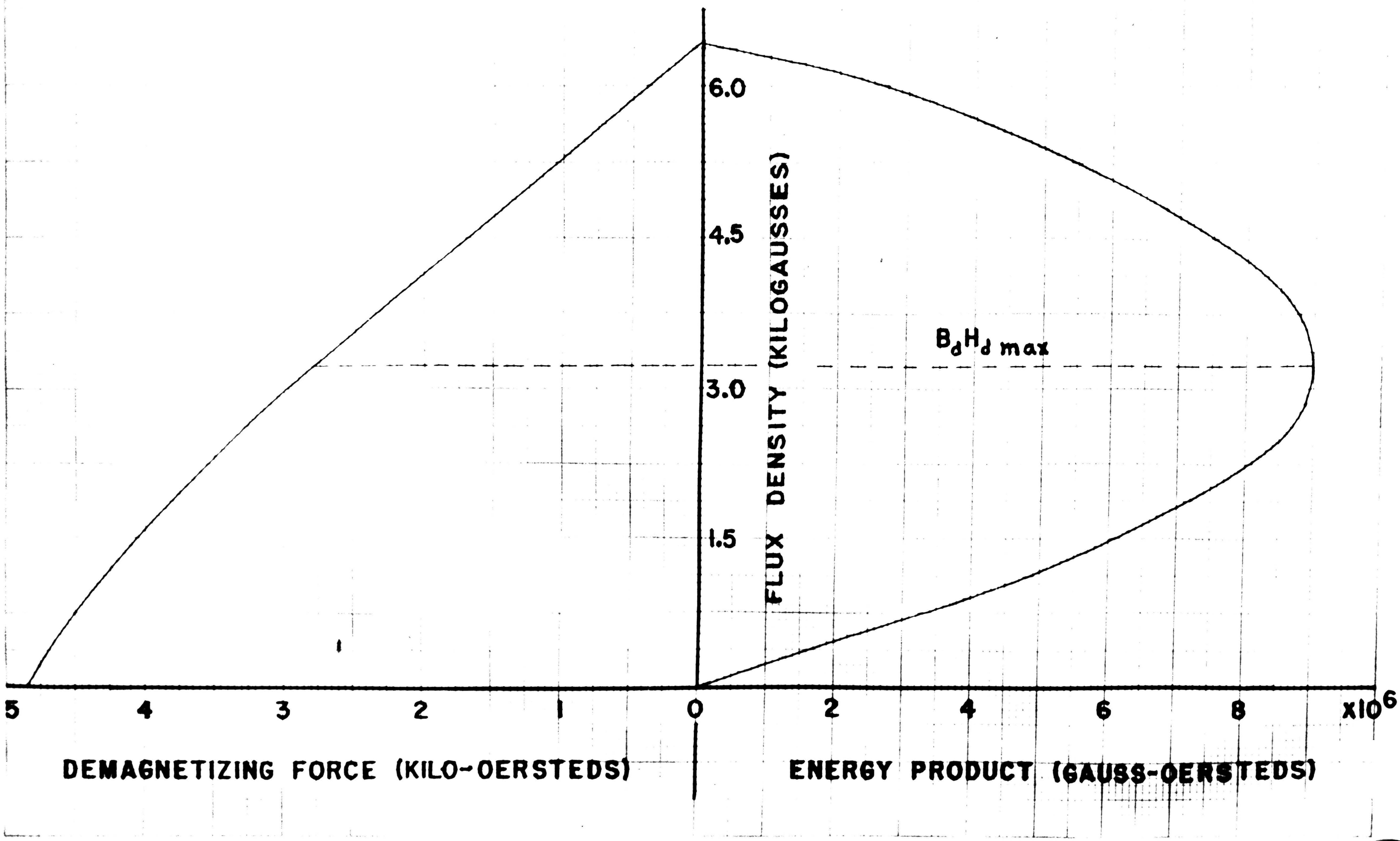
The coercive force of a permanent magnet is the quantity which determines the length to cross section ratio at which maximum energy product is available.[9] The de-

(9) Ibid. pp. 7

magnetization and energy product curves for cobalt-platinum are shown on Plate 2, and it may be seen that the coercive

PLATE 2

TENTATIVE DEMAGNETIZATION AND ENERGY PRODUCT CURVES FOR A PERMANENT MAGNET ALLOY OF 23 % COBALT AND 77% PLATINUM



force is very large in comparison with Alnico 5. This allows the length to cross section ratio to be small; in fact, maximum energy product can be obtained with such ratio about 1/7 that at which Alnico 5 operates best.

With such good properties, this material would seem highly desirable for application to the galvanometer. However, in order to get maximum energy product with cobalt-platinum in the type of circuit already designed for Alnico 5, the magnets would need to be so short that the flux density available in the air gap would be less than that attainable with Alnico 5. In the same way, magnets placed with their axes of magnetization along the antenna diameter would have a length to cross section ratio so small that maximum energy product could not be achieved, and thereby again failing to produce a flux density equal to that available with Alnico 5. The cobalt platinum is subsequently eliminated from use in this particular galvanometer, but there is possibility of using it to great advantage for other antennas requiring a small galvanometer of somewhat different shape.

In some instances, it may be desirable to radiate less power from the transmitting antenna for antenna current measurements, or to locate the driven element at a greater distance from the parasitic element. If this is the case, the galvanometer sensitivity would have to be increased and could be done in two ways. The first of these is to increase the length of suspension since there is space available for doing so. The second method pertains to the magnets providing field excitation. By obtaining the magnets already magnetized, it is possible to lose some magnetization in the process of grinding them to conform to the design. Therefore, it is suggested that these magnets be obtained as unmagnetized stock, ground to the required dimensions by the individual, and returned to the manufacturer for proper magnetization.

The number 49 wire specified in the galvanometer design is very fine, having a diameter only 1/3 that of the average human hair. Winding the galvanometer coil with such wire would be very difficult without breaking the wire. As a result, it might be necessary to have the coil wound by an electrical meter company.

Because of the slot in the antenna, there will always be some degree of r-f fields in the antenna. This may cause r-f voltages to be induced in the galvanometer leads with resultant possibility of inaccuracy. This could be overcome by shielding these leads from the point where they leave the pickup slug to the terminals of the galvanometer.

If closer tolerances in the galvanometer air gap could be attained, the air gap could be shorter and the resultant galvanometer sensitivity would also be increased by this method. Even if the latter is not done, however, by using the previous design specifications and suggestions, the galvanometer should have enough sensitivity to obtain UHF antenna current distribution measurements which may be relied upon.

## CONCLUSIONS

By placing the detecting meter inside an antenna, it may be expected that some errors can be eliminated in measuring the current distribution on the antenna. It has been proven by calculation and with the aid of experimentation that a galvanometer, to be placed inside a cylindrical parasitic UHF antenna 1.41 cm in diameter and 37.5 cm long, can be constructed with a sensitivity sufficient for measuring the antenna current distribution when an exciting antenna radiating 10 watts is at a distance of 3 meters. The galvanometer as designed would provide a deflection of 1/3 radian with 33.3 microvolts applied at its terminals. In terms of current sensitivity, it would require 0.00025 ampere per mm deflection at a distance of one meter which is comparable to the sensitivity of good commercially made galvanometers.

The galvanometer actually constructed did not conform to the design requirements, and as a result its sensitivity was so low that the exciting antenna had to be placed only 10 cm from the antenna on which the current distribution was to be measured. The resulting measurements showed the current distribution to be unsymmetrical and nonsinusoidal. Since there is no data available with which to compare these results, there is nothing which would indicate them to be either correct or in error.

For current distribution measurements on other antennas, the galvanometer might require a different design. But in conclusion, it is logical to assume that the method outlined could provide current distribution measurements on UHF antennas which would be considerably more reliable than those obtained by previous methods. The only requirements for application of this method are that the antenna can be slotted for projection of the current loop and that it have a cavity within which the small galvanometer can be constructed.

## SUMMARY

The methods hitherto used to measure relative current distribution on UHF antennas have introduced errors by changing the current distribution on the antenna in the process of measurement. The principle difficulty has been the use of a current meter which is external to the antenna, thereby requiring some provision for wires leading from the antenna to the detector. That error can be eliminated by placing a small mirror galvanometer inside the antenna so that its deflection may be projected through a slot in the antenna by a beam of light. This paper concerns the design of such a galvanometer to be placed inside a hollow cylindrical parsitic antenna 37.5 cm lomg and 1.41 cm inside diameter. The galvanometer incorporates an Alnico 5 permanent magnet field of unique design. By making sure that the permanent magnets operate at an optimum energy product, by using very small wire in the coil and a sensitive suspension, a one-third radian deflection can be attained with 40 micovolts applied to the galvanometer.

The design specifications were not met in the actual construction of the galvanometer because of the inavailability of the proper suspension material and coil wire. Although the desired voltage sensitivity was not acheived in the galvanometer, one set of current distribution measurements was taken on the parasitic element with the exciting antenna only 10 cm away. There are no comparable results available with which the results of this thesis may be checked, but a background has been provided and suggestions are given to aid further

investigation into this manner of measuring antenna current distribution.

# APPENDIX

The following is a list of the equipment used in the experimental work of this thesis.

General Radio Co. vacuum tube voltmeter, Type 1800a Serial No. 1583

General Radio Co. wavemeter, Type 1140-A, Serial No. 896

Sensitive Research Co. microammeter, "University" model, Serial No. 11631

Leeds and Northrup light source and opaque scale Model No. 2100

Voltage regulated power supply, MSM EE Lab No. 19

Two dipole antennas of half wavelength at 400 mc

Surplus Radio Transmitter T-9/APQ-2, Serial No. 1471

The T-9/APQ-2 transmitter is a UHF push-pull oscillator from war surplus stock and has been revamped for use with a 60 cycle power source. The frequency of this oscillator is constant with variation of plate voltage and is also constant with time. The power output decreases slightly during the first hour of operation, but it becomes constant after that period.

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# VITA

The author, the son of Mr. and Mrs. F. H. Mullersman, was born March 27, 1930, at Flat River, Missouri. His early education was received in the grade school, junior high school, and senior high school of Flat River, Missouri. He completed one year of the pre-engineering curriculum at Flat River Junior College, transferred to the Missouri School of Mines and Metallurgy in September, 1948, and graduated from the latter institution in May, 1951, with a B. S. degree in Electrical Engineering. On June 4, 1951, he began graduate work at the Missouri School of Mines, and carried at the same time a graduate assistantship until January, 1952.