NASA TECHNICAL MEMORANDUM

NASA TM X- 53435

April 12, 1966

NASA TM X-53435

INVESTIGATION OF THE DEFLECTION OF AN ELECTRON BEAM AS A MEANS OF MEASURING ELECTRIC FIELD STRENGTH

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ABSTRACT

An electric field meter, which operates in the 1-V/m to 10-V/m range, has been constructed and tested. Measurement of the deflection of an electron beam by the field in question is the principle of operation. The beam deflection distance is directly proportional to the magnitude of the deflecting field.

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RESEARCH AND DEVELOPMENT OPERATIONS

ACKNOWLEDGMENTS

The advice of Mr. E. A. Grant of the Tuskegee Institute in designing of circuits, and the assistance of Mr. J. L. Johnson of the Research Projects Laboratory in preparing the beam detector is gratefully acknowledged.

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SUMMARY

An electric field meter, which operates in the 1-V/m to 10-V/m range, has been constructed and tested. Measurement of the deflection of an electron beam by the field in question is the principle of operation. The beam deflection distance is directly proportional to the magnitude of the applied field.

INTRODUCTION

The measurement of electric fields in interplanetary space, on the lunar surface, or in other similar environments is difficult because of the interaction of energetic photons, energetic-charged particles, or plasma with the metallic surfaces of the field meter. Problems with bearings and lubricants also diminish the usefulness of conventional field meters.

In an attempt to avoid some of these difficulties, a prototype electric field meter, based on the principle of the deflection of an electron beam by electric fields, was constructed and tested.

The apparatus (Fig. 1) is an instrument consisting of a beam source and a detector plate. The beam source is a conventional electron gun; the detector is a phenolic board coated with a film of carbon particles.

For test purposes, a uniform electrical field is applied by impressing a potential difference between the large parallel plates shown in the figure. The electron beam is deflected by the applied field, and the impact area on the detector is displaced accordingly. This displacement causes the beam current to divide in direct ratio with the displacement. The current flowing to each side of the detector plate is then amplified, and the resulting difference is an indication of the amount of beam deflection and applied field strength. Details of the phenolic detector board are shown in Figure 2. The board is coated with a film of "Carbon-X," a product of the G. C. Electronics Company of Rockford, Illinois. The carbon film serves as a resistor for the division of the beam current.

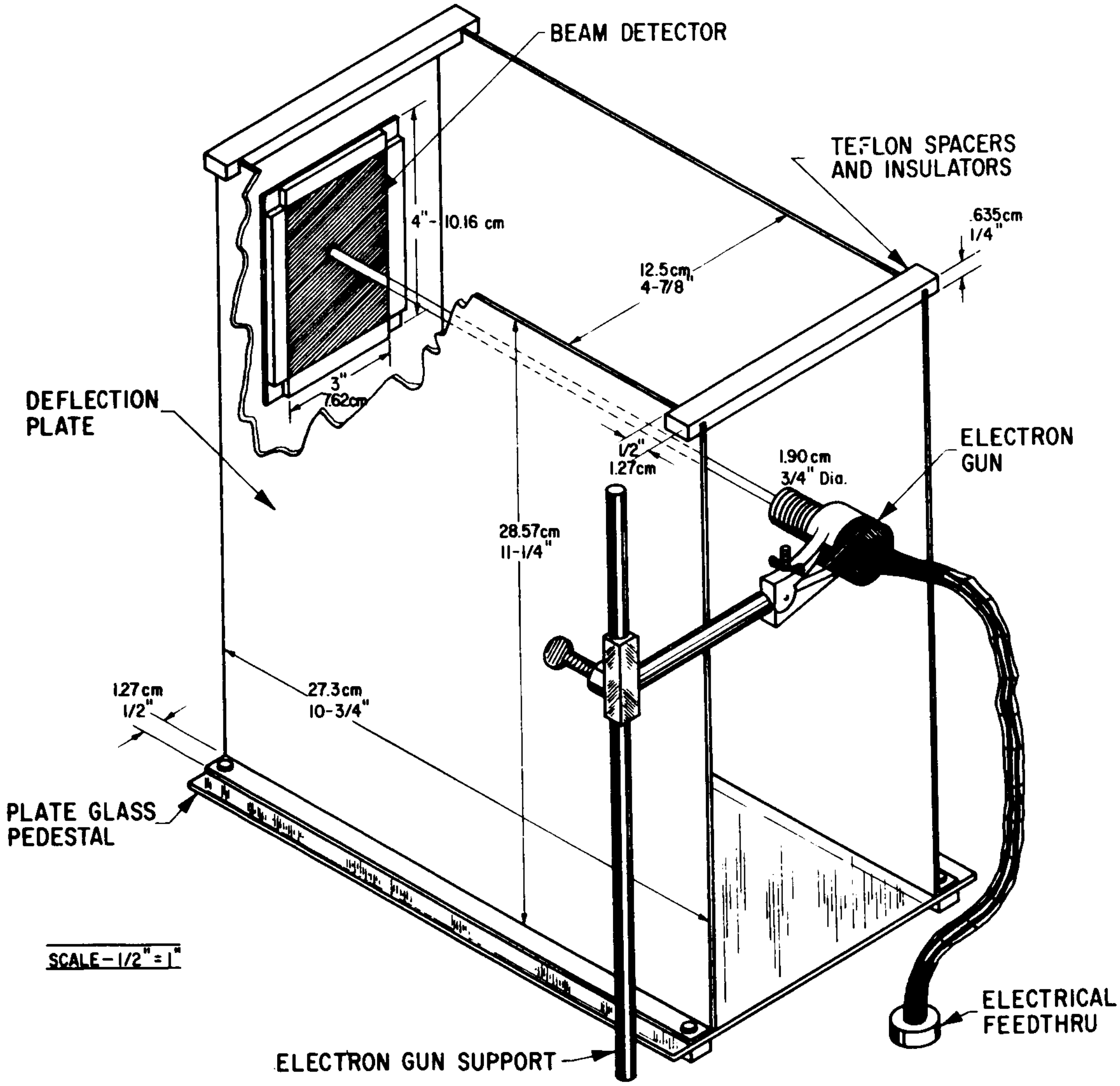

FIGURE 1. SCHEMATIC ARRANGEMENT OF EXPERIMENTAL COMPONENTS

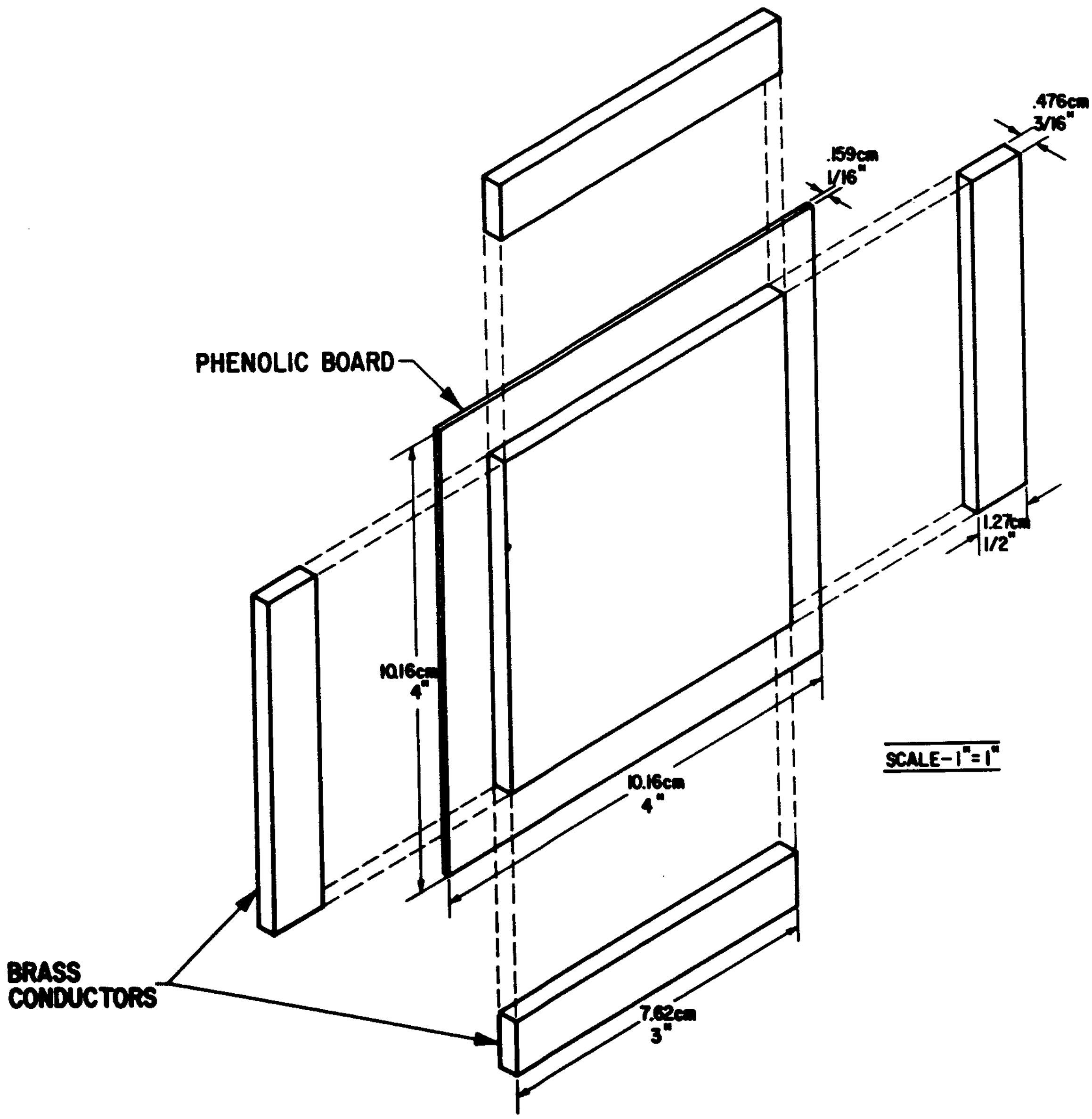

FIGURE 2. BEAM DETECTOR

The carbon film is carefully bonded to brass bars on four edges to assure uniform resistive properties.

The prototype electric field meter discussed here can measure electric fields in the 1-V/m to 10-V/m range, and the fields are directly proportional to the observed difference currents.

The electron beam is, of course, deflected by magnetic fields as well as by electric fields, and the instrument is potentially a magnetometer.

THEORY

An individual charged particle moving in a region containing electric and magnetic fields is accelerated by the fields. The equation of motion of the particle is obtained by equating the Lorentz force to the time rate of momentum change. Thus,

$$\bar{F} = q(\bar{E} + \bar{v} \times \bar{B}) = m \frac{d\,\bar{v}}{d\,t} , \tag{1}$$

where $\bar{F}$ is the force, m is the particle mass, q is the particle charge, $\bar{E}$ is electric field strength, $\bar{v}$ is particle velocity, and $\bar{B}$ is the magnetic field strength.

A reasonable set of assumptions about the quantities shown in the Lorentz equation for conditions where a field meter would be used are:

1. The electric and magnetic fields are uniform. This assumption is valid over the volume of space occupied by the field meter.

2. The electric and magnetic fields are constant, i.e., do not vary with time. This assumption is valid, for in the case of any one electron the time of flight of the electron from gun to target will be on the order of 10^{-8} seconds for a 300-eV electron beam over a distance of 0.185 meter, and the time variations in field strength from natural causes have periods from a few hundredths of a second to hours.

Under this set of assumptions the components of the Lorentz equation in a system of Cartesian coordinates are:

$$F_x = m\frac{d\,v_x}{dt} = q(E_x + v_y B_z - v_z B_y) \tag{2}$$

$$F_y = m\frac{d\,v_y}{dt} = q(E_y + v_z B_x - v_x B_z) \tag{3}$$

$$F_z = m\frac{d\,v_z}{dt} = q(E_z + v_x B_y - v_y B_x) \; . \tag{4}$$

These are the equations of motion of the charged particle.

Equations (2) through (4) are a set of linear differential equations of the form

$$\frac{d\,v_i}{dt} = \sum_{j=1}^{3} a_{ij}\, v_j + b_i(t) \; , \tag{5}$$

where the $b_i(t)$ are integrable functions of t, and the a_{ij} are constants. This set of equations may be written as

$$\frac{d\,V^T}{dt} = A\, V^T + C^T \; , \tag{6}$$

where V, A, and C are matrices of the form

$$A = (a_{ij}) \tag{7}$$

$$V = (v_1,\ v_2,\ v_3) \tag{8}$$

$$C = (C_1,\ C_2,\ C_3) \; . \tag{9}$$

For the equations under consideration, equations (2) through (4), the matrix A is

$$(a_{ij}) = \frac{q}{m}\begin{pmatrix} O & B_z & -B_y \\ -B_z & O & B_x \\ B_y & -B_x & O \end{pmatrix} \tag{10}$$

This system of equations is solved by the methods outlined in Reference 1, and shown in detail in Reference 2.

The solution functions for this set of linear equations are

$$X = X_o + \frac{\omega \bar{E} \cdot \bar{B} B_x}{2 B^3} t^2 + \frac{\bar{B} \cdot \bar{v}_o B_x + E_y B_z - E_z B_y}{B^2} t$$

$$+ \left[\frac{(B_y^2 + B_z^2) v_{ox} - B_x (B_y v_{oy} + B_z v_{oz}) - E_y B_z + E_z B_y}{\omega B^2} \right] \sin \omega t$$

$$- \left[\frac{B^2 (B_z v_{oy} - B_y v_{oz}) + E_x (B_y^2 + B_z^2) - B_x (E_z B_z + E_y B_y)}{\omega B^2} \right] (\cos \omega t - 1)$$

(11)

$$Y = Y_o + \frac{\omega \bar{E} \cdot \bar{B} B_y}{2 B^3} t^2 + \frac{\bar{B} \cdot \bar{v}_o B_y + E_z B_x - E_x B_z}{B^2} t$$

$$+ \left[\frac{-B_x B_y v_{ox} + (B_z^2 + B_x^2) v_{oy} - B_y B_z v_{oz} + E_x B_z - E_z B_x}{\omega B^2} \right] \sin \omega t$$

$$- \left[\frac{B^2 (B_x v_{oz} - B_z v_{ox}) + E_y (B_x^2 + B_z^2) - B_y (E_x B_x + E_z B_z)}{\omega B^3} \right] (\cos \omega t - 1)$$

(12)

$$Z = Z_o + \frac{\omega \bar{E} \cdot \bar{B} B_z}{2 B^3} t^2 + \frac{\bar{B} \cdot \bar{v}_o B_z + E_x B_y - E_y B_x}{B^2} t$$

$$+ \left[\frac{-B_x B_z v_{ox} - B_y B_z v_{oy} + (B_x^2 + B_y^2) v_{oz} - E_x B_y + E_y B_x}{\omega B^2} \right] \sin \omega t$$

$$- \left[\frac{B^2 (B_y v_{ox} - B_x v_{oy}) + E_z (B_x^2 + B_y^2) - E_x B_x B_z + E_y B_y B_z}{\omega B^3} \right] (\cos \omega t - 1),$$

(13)

where

$$B = (\bar{B} \cdot \bar{B})^{\frac{1}{2}}; \quad \omega = \frac{qB}{m}; \; v_x = v_{ox}; \; v_y = v_{oy};$$

$$v_z = v_{oz}; \; X = X_o; \; Y = Y_o; \; Z = Z_o \quad \text{at} \quad t = 0.$$

For electrons: $q = -e$, where $e = 1.60210 \times 10^{-19}$ coulomb, and $m = 9.1091 \times 10^{-31}$ kilogram. If the angle ωt is less than 10 degrees, the terms $\sin \omega t$ and $(\cos \omega t - 1)$ may be replaced by ωt and $-\frac{(\omega t)^2}{2}$; respectively, and will introduce errors of 0.5 and 0.27 percent in the $\sin \omega t$ and $\cos \omega t$ terms of the equations.

Assuming a path length of 0.185 meter and a beam of 300-eV electrons with no magnetic or electric fields present, the travel time of the electron from gun to target will be approximately 1.8×10^{-8} seconds. Using this approximation for the travel time when fields are present, a calculation of the magnetic field needed to rotate the beam through 10 degrees is $|B| \cong 0.5 \times 10^{-4}$ tesla, or approximately the earth's field strength.

Assuming as initial conditions that the electron is at the origin with its velocity directed along the z-axis at $t = 0$ (i.e., that $x_o = y_o = Z_o = 0$ $|v_o| = v_{oz}$, and $v_{ox} = v_{oy} = 0$ at $t = 0$) equations (11), (12), and (13) reduce to

$$X = \frac{\omega t^2}{2B^3}\left[-\bar{E} \cdot \bar{B}\, B_x + B^2 B_y v_{oz} + E_x(B_y^2 + B_z^2) + B_x(E_z B_z + E_y B_y)\right]$$

$$+ \left[\bar{B} \cdot \bar{v}_o B_x - B_x B_z v_{oz}\right] \frac{t}{B^2} \; . \tag{14}$$

$$Y = \frac{\omega t^2}{2B^3}\left[-\bar{E} \cdot \bar{B}\, B_y - B^2 B_x v_{oz} + E_x B_x B_y - E_y(B_x^2 + B_z^2) + E_z B_z B_y\right]$$

$$+ \left[\bar{B} \cdot \bar{v}_o B_y - B_x B_z v_{oz}\right] \frac{t}{B^2} \tag{15}$$

$$Z = \frac{\omega t^2}{2B^3}\left[-\bar{E}\cdot\bar{B}B_z - E_x B_x B_z - E_y B_y B_z + E_z(B_x^2 + B_y^2)\right]$$

$$+\left[\bar{B}\cdot\bar{v}_o B_z + (B_x^2 + B_y^2)v_{oz}\right]\frac{t}{B^2}$$

DESCRIPTION OF APPARATUS

The basic pieces of equipment used for the investigation were a vacuum system, an electron gun, an electron beam detector, and the associated electronic circuits needed to generate a beam of electrons and display the detector output in a meaningful manner. Each of these systems or pieces of equipment is described in the body of the report.

The vacuum system used consisted of a 45.7-cm (18-in.) diameter glass bell jar, a 15.2-cm (6-in.) oil diffusion pump, and a mechanical roughing pump. The system also contained a liquid nitrogen baffle, and when in use the vacuum system with experiment installed could maintain a vacuum in the 10^{-5}-N/m^2 (10^{-7}-torr) region. The system is commercially available from the Consolidated Vacuum Corporation, Model CV-18.

The electron gun used in the experiment was removed from a Mullard-type DH 3/91 cathode ray tube. The vertical and horizontal deflection plates were removed from the gun and it was then mounted in the bell jar on a 0.635-cm (0.250-in.) aluminum rod by means of a swivel clamp (Figs. 3 and 4).

The barium oxide cathode coating lost its emissive properties if repeatedly exposed to the atmosphere; but if the system was kept under vacuum the loss of emission was very slow. While the cathode did not retain its emissive properties indefinitely, the variation over a short period of time (maximum of one hour) was not sufficient to seriously affect the data.

The detector was made from a block of phenolic board (Fig. 2). The board was coated with a water suspension of colloidal carbon until a resistance of 200 000 ohms appeared between opposing electrodes. The colloidal carbon was obtained from a commercial product of G. C. Electronics called "Carbon-X," which is normally used to repair damaged carbon-type potentiometers.

The detector was then mounted in the bell jar a distance 18.5 centimeters from the last lens of the electron gun in the manner indicated in Figure 1. A glass shelf was used in the bell jar to support the detector.

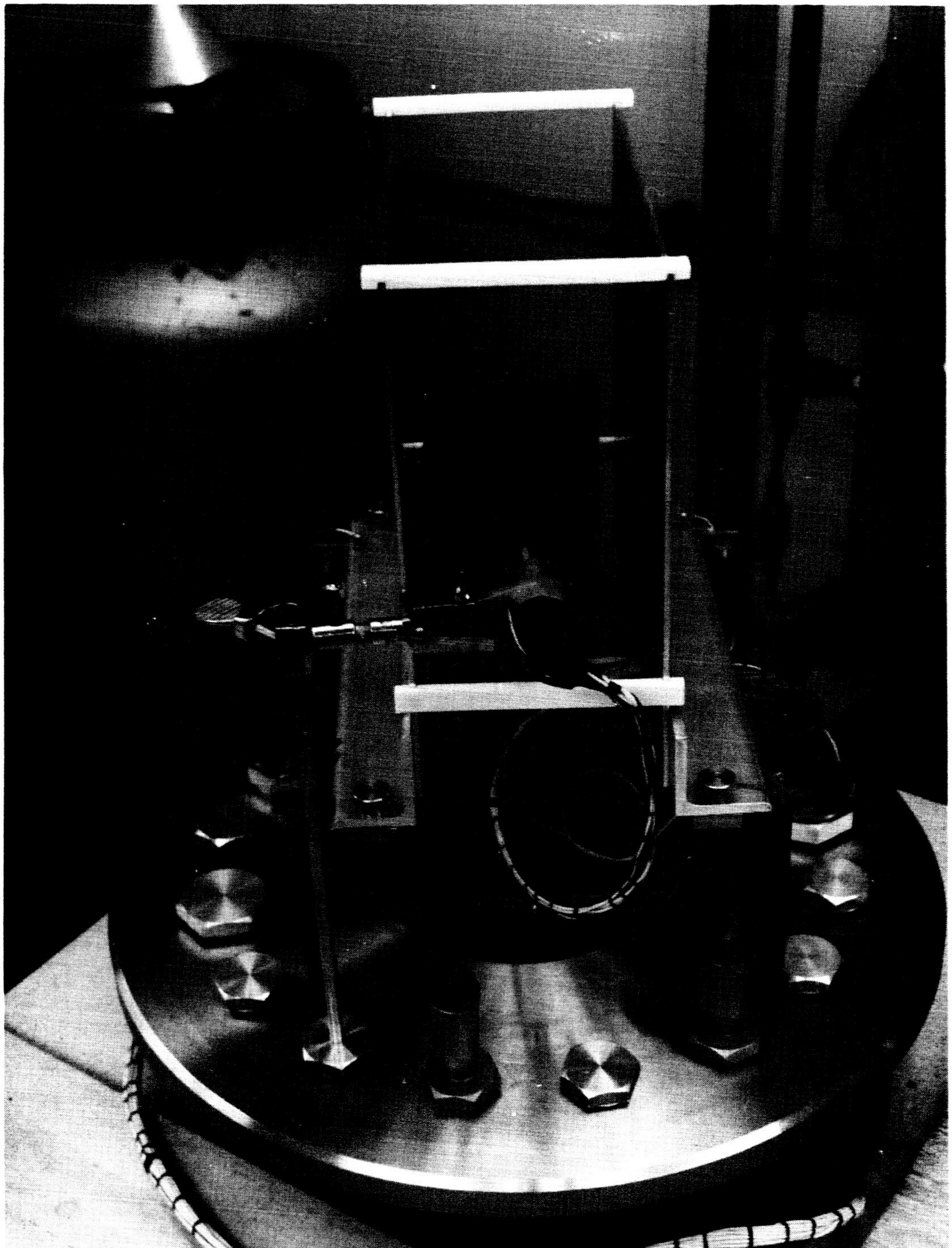

FIGURE 3. EXPERIMENTAL ARRANGEMENT IN VACUUM CHAMBER

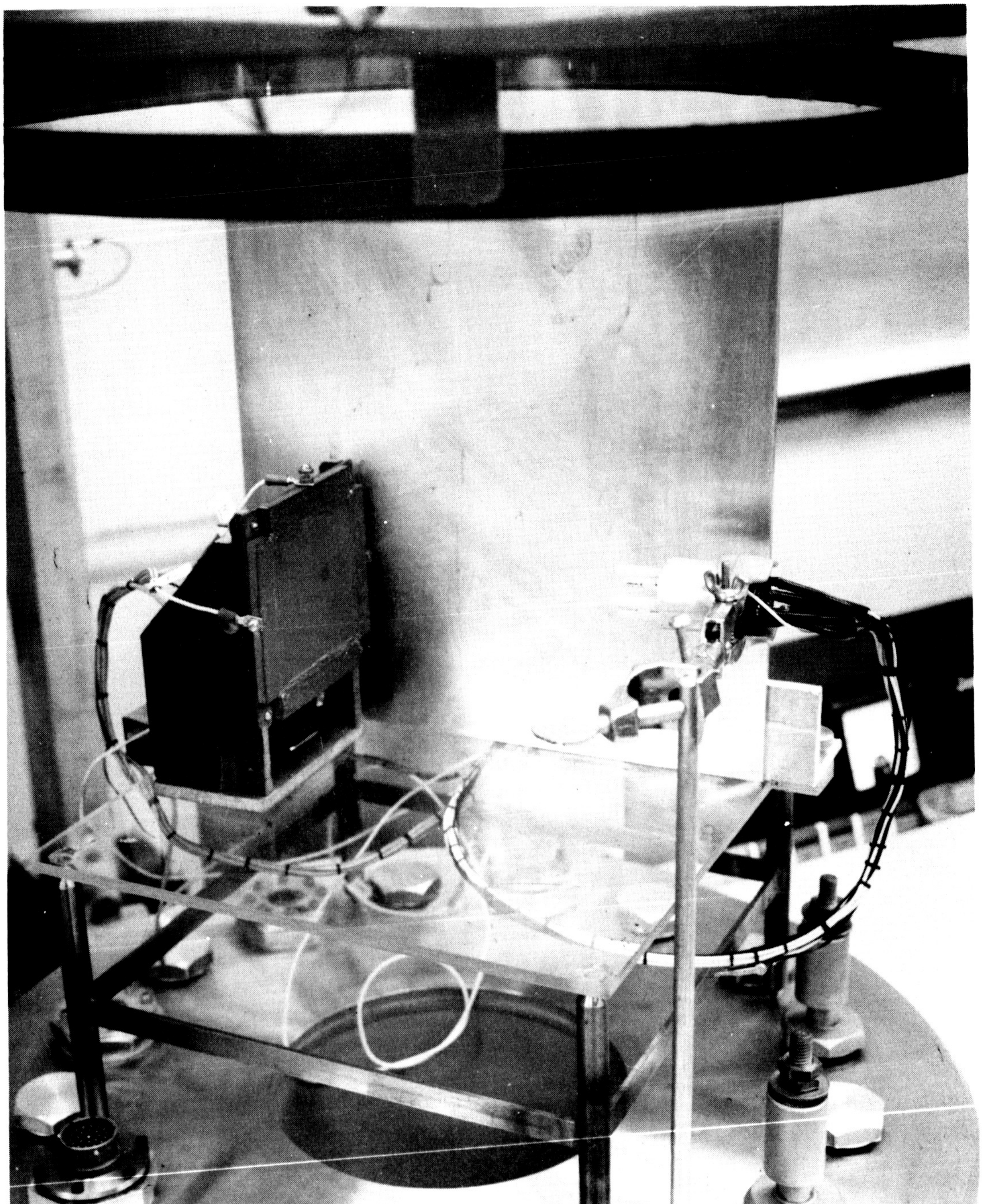

FIGURE 4. SIDE VIEW OF EXPERIMENTAL ARRANGEMENT WITH ONE DEFLECTOR PLATE REMOVED

Two parallel plates of aluminum were mounted on the glass shelf, as shown in Figure 1, to create a uniform electrical field in which to place the field meter. The plates were maintained parallel by four teflon spacers of 12.5-cm length (Fig. 1).

The dc signal developed between the horizontal electrodes of the beam position detector was coupled to two operational amplifiers of a type "O" Tektronix oscilloscope plug-in unit. The outputs of each dc amplifier were then displayed on a Moseley Model 136 A recorder (Fig. 5).

The electron gun was operated by a circuit, as shown in Figure 6. Batteries were used to avoid ripple effects from dc power supplies.

DISCUSSION OF EXPERIMENT

It was at first contemplated that a beam of electrons focused to a spot no larger than 0.1 millimeter could be used to indicate electrical field strength by measuring the deflection of the spot when the field was present and when it was absent. If the deflection voltages necessary to return the spot to a "no field present" position could be measured, a suitable calibration technique could be used to indicate electrical field strengths.

The beam would impinge upon a metallic sheet with a hole of suitable size located at its center, and the "no field present" beam would be aligned with the hole. Detection would be accomplished by an electron multiplier. The beam current would be very minute to avoid space charge effects and should consist of monoenergetic electrons to avoid thermal spreading.

The magnetic field strength and direction were measured in the volume of space to be occupied by the electric field meter. This measurement was made with a Vickers, Inc., fluxgate magnetometer model, PM-1. The field varied with time, but a value of 0.46×10^{-4} tesla at an angle of 60 degrees from the horizontal was taken to be a representative value.

The time-of-flight estimate of a 300-eV electron in a field-free region of space over a distance of 0.185 meter was used as a first-order approximation.

Assuming that at $t = 0$, $v_o = v_{oz}$, $x_o = 0$, $y_o = 0$, $z_o = 0$, $v_{ox} = 0$, $v_{oy} = 0$, $B_x = 0$, $E_y = 0$, and $E_z = 0$, equations (11), (12), and (13) will be modified to

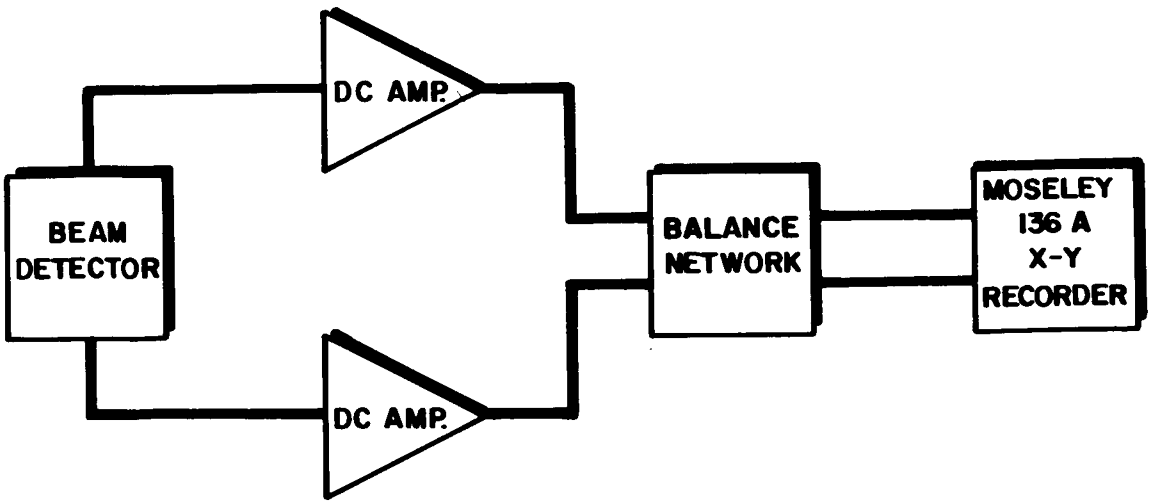

FIGURE 5. BLOCK DIAGRAM OF BEAM DETECTOR CIRCUIT

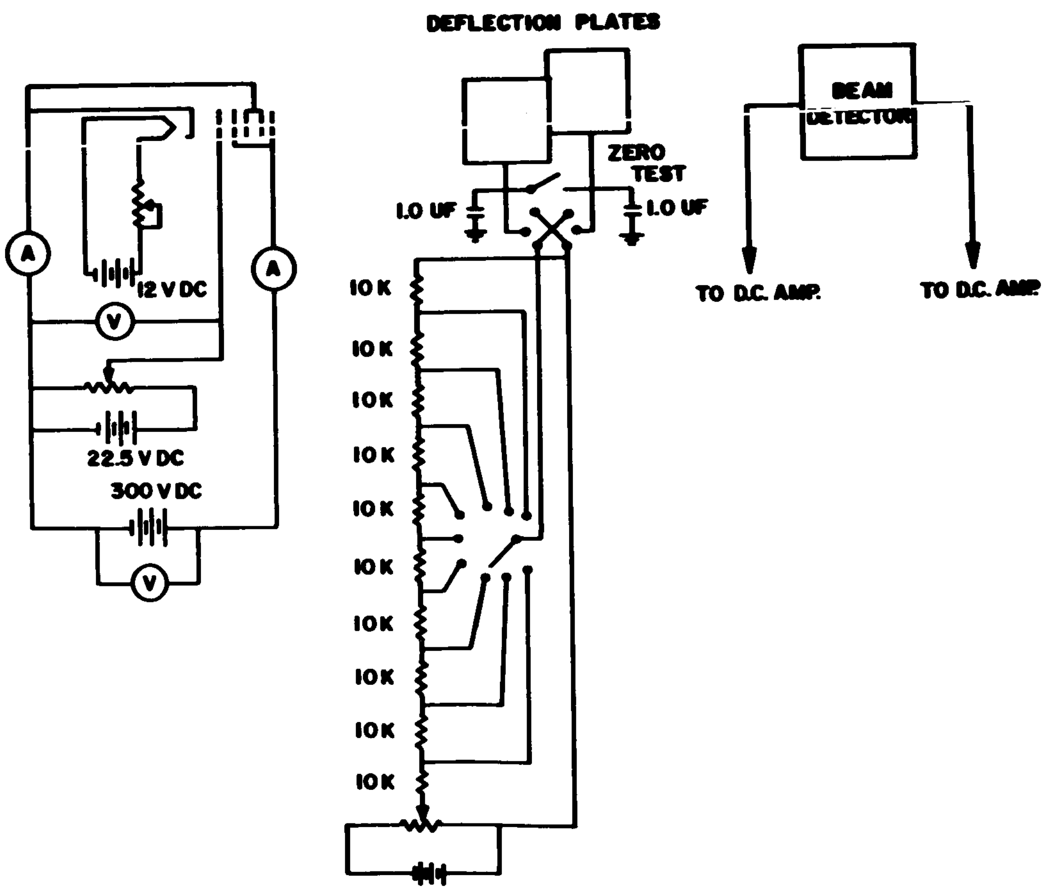

FIGURE 6. SCHEMATIC DIAGRAM OF ELECTRON GUN AND DEFLECTION CIRCUITS

$$X = (-B^2 B_y v_{oz} + E_x B_y^2 + E_x B_z^2) \frac{\cos \omega t - 1}{\omega B^3} .$$

$$Y = (\bar{B} \cdot \bar{v}_o B_y - E_x B_z) \frac{t}{B^2} + (-B_y B_z v_{oz} + B_z E_x) \frac{\sin \omega t}{\omega B^2}$$

$$Z = (\bar{B} \cdot \bar{v}_o B_z + E_x B_y) \frac{t}{B^2} + (B_y^2 v_{oz} - B_y E_x) \frac{\sin \omega t}{\omega B^2} .$$

If a magnetic field $|B| = 0.46 \times 10^{-4}$ tesla is assumed as the earth's field at an angle 60 degrees from the horizontal, then the electric field meter can be aligned so that $B_y = 0.4 \times 10^{-4}$ tesla, and $B_z = 0.231 \times 10^{-4}$ tesla.

If no fields are present, the time of flight of a 300-eV electron over a path length of 0.185 meter may be calculated as

$$t = \frac{S}{v} .$$

The velocity v is calculated as

$$v = \sqrt{\frac{2 K E}{m}} ,$$

where K E is the kinetic energy of the electron.

$$v \cong \sqrt{\frac{2 \times 300 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}} \cong 10.3 \times 10^6 \text{ meters/sec.}$$

$$t \cong \frac{0.185}{10.3 \times 10^6} \cong 1.8 \times 10^{-8} \text{ seconds}$$

The angular frequency of the electron is

$$\omega = \frac{e B}{m} \cong \frac{1.6 \times 10^{-19} \times 0.46 \times 10^{-4}}{9.1 \times 10^{-31}} \cong 8 \times 10^6 \text{ radian/sec}$$

and $\omega t = 8 \times 10^6 \times 1.8 \times 10^{-8} = 14.4 \times 10^{-2}$ radians or 8.25 degrees. Using the modified displacement equations and a change of electrical field strength of one volt per meter, the displacement changes in the X and Y directions will be

$\Delta X \cong 0.028$ millimeter

$\Delta Y = 0.0007$ millimeter.

These calculations indicate that the displacement caused by a transverse electrical field of one volt per meter would be very difficult to measure using the technique of returning the beam to the position occupied when no field is present.

A direct indicating device was used to avoid the difficulties that would be encountered in returning the beam to the zero position. This device consisted of a sheet of resistive material which varied linearly in resistance in all directions. This device was used as a beam detector.

The beam detector was constructed in the manner indicated in Figure 2. A piece of phenolic board was machined on each side to provide shelves to which four brass plates were attached with an epoxy glue. The brass plates were mounted so that the face of the phenolic board was flush with the surface of the brass.

A water suspension of colloidal carbon was then sprayed onto the face of the beam detector. The resistive surface was prepared by repeatedly spraying the beam detector surface until a resistance of 200 000 ohms was measured between opposing brass strips. A layer of optically active ZnS was then sprayed on the carbon surface until a slight cloudiness could be seen on the surface. The ZnS provided a means for visually examining the pattern produced by an electron beam incident upon the surface.

For this experiment only horizontal deflection of the beam was measured. Therefore, leads were attached to the beam detector as shown in Figure 5. These leads were attached at the opposite end to two dc operational amplifiers in a type "O" Tektronix plug-in amplifier. The amplifier outputs were then connected to a balancing voltage divider, and thence to a Moseley Model 136 A recorder.

A plate of brass shim stock was attached to the back surface of the beam detector and grounded. Four 0.05-μfarad capacitors, one to each brass strip, were attached to this plate to provide a shunt path for ac pickup.

The electron gun circuit was designed to allow the cathode of the electron gun to operate below ground potential. The last lens of the electron gun was at ground potential, and the beam detector was grounded through the dc amplifiers. Thus, an electron beam in an electrically field-free region was attained when no voltage was applied between the deflection plates.

It was found necessary to provide a path to ground for ac pickup on the deflection plates. The main component of the ac signal on the deflection plates was 60 hertz, and it was found that two matched 1.0-μfarad capacitors, one from each plate to ground, lowered this voltage to a negligible level.

Since the beam detector output was used in a dc mode the output from the dc amplifiers varied with the voltage changes of all the other elements of the experiment. The system was particularly sensitive to filament voltage changes caused by line variations. Since equipment was not available to eliminate the line voltage surges, batteries were used as power supply for the electron gun. Some drift due to polarization was still present, but after operating for a period of time of one hour or more a drift rate that was slow enough for the experiment to be performed could be established.

EXPERIMENTAL RESULTS

A set of data, shown in Figure 7, was obtained with the recorder in a time-driven mode of 10 seconds per inch, and by manually switching the deflecting voltage on and off. The length of time the switch was left in a given position was determined by watching the recorded data and switching when it was believed that an average pen position could be determined from the data. It was necessary to average for both the no-field-applied pen position and for the field-applied position.

The deflecting voltages were obtained from a 100 000-ohm voltage divider across a 3-V dry cell battery. The value of the deflecting voltage was measured with an RCA Senior Voltohmist vacuum tube voltmeter. It was necessary to change voltage scales on the voltmeter to measure the deflecting voltages. After measuring the value of the deflecting voltages, the voltmeter was removed before performing the experiment.

The input impedance of the voltmeter was 10 megaohms; therefore, the measured deflection voltage is within 0.4 percent of the true voltage, if the meter is error free. Because the meter cannot be read as closely as the error caused by placing the meter across the voltage divider, the measured voltages will be considered the true deflecting plate voltages.

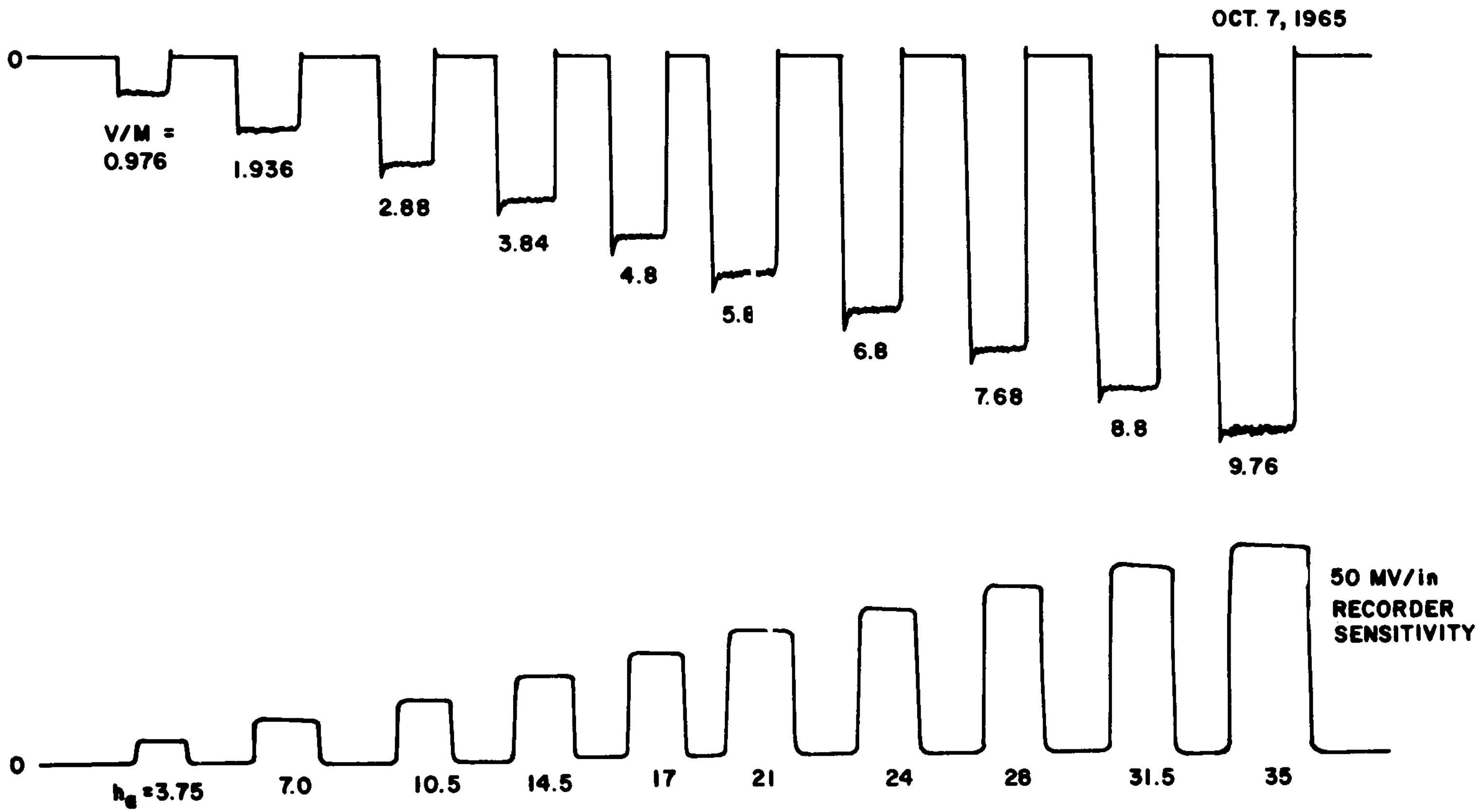

FIGURE 7. RECORDED DATA

To demonstrate linearity of the system, the data are displayed in Figure 8 as an output voltage on the abscissa and the strength of the deflecting field is shown on the ordinate. It will be noted that the data are displayed as two straight lines rather than one. The reason for this is that two different voltage ranges were used on the vacuum tube voltmeter to measure the deflecting voltage applied to the plates. The differences in meter calibration of the two ranges are assumed to be responsible for the curve displacement.

Further data will be obtained from improved versions of the experiment. The present data show that the technique used for beam deflection measurement is adequate for measuring field strengths of one volt per meter. Refinement of the experiment will establish the limits of sensitivity, and will indicate if the method will provide a satisfactory measurement of magnetic field. If so, an electrically shielded device might be used as a magnetometer which could compete with much more costly devices now in existence.

The contemplated improvements in the system include ac modulation of beam intensity, a tungsten emitter in the electron gun, and a magnetically shielded enclosure. Also, the effect of a sharply focused beam as compared to the very poorly focused beam used will be investigated

Although much development remains to be accomplished, an instrument could be built that would operate on the principle discussed in the report and that would measure electrical field strengths of one volt per meter.

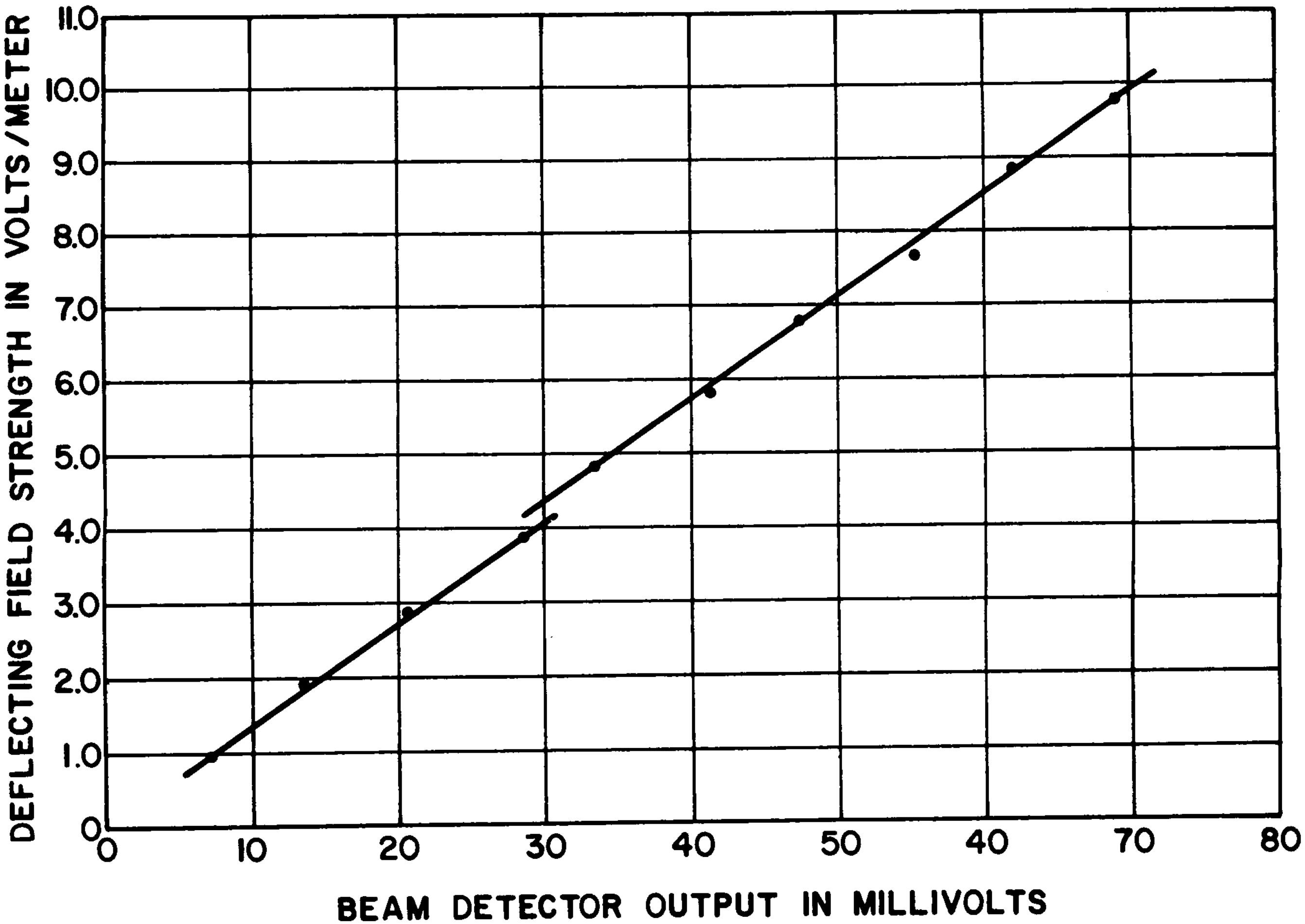

FIGURE 8. REDUCED DATA

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1. Murdoch, D. C.: Linear Algebra for Undergraduates. John Wiley and Sons, Inc., 1957, pp. 138-139.

2. Jones, R. C.: Solution and Application of the General Equation of Motion to the Electric Field Meter. MSFC Internal Note, R-RP-INJ-65-13, Sept. 20, 1965.

NASA TM X-53435 APPROVAL April 12, 1966

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This report has also been reviewed and approved for technical accuracy.

Gerhard B. Heller

for ERNST STUHLINGER
Director, Research Projects Laboratory