AN ANALYSIS OF THE BROOK TYPE FIELD METER

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PREFACE

The behavior of the earth's electric field during severe weather has been the object of extensive research. Several methods and systems have been developed for detecting and recording the earth's electric field behavior during a lightning discharge. The system this experiment is concerned with is the Brook Type Field Meter presently in use at the Atmospherics Laboratory at Oklahoma State University.

It is not the purpose of this experiment to evaluate the electronic design of the system, but to analyse the subject field meter in such a way as to determine whether the data that it presents is a true representation of the earth's electric field behavior during a thunderstorm.

Research for this thesis was conducted at the Atmospherics Laboratory of the Oklahoma State University using available equipment with some original adaptations.

The writer would like to express his appreciation to Dr. Herbert L. Jones under whose direction this research was carried on at the Atmospherics Laboratory. I would also like to extend thanks to the program's project engineer, Mr. Ray Calkins, and to Mr. J. C. Hamilton for their time and technical assistance during the experiment.

Last, to my wife Nancy, thanks for her help in the preparation of the manuscript and for preparing the final copy for printing.

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CHAPTER I

INTRODUCTION

The electronic field meter under investigation in this thesis was built and installed at the Atmospherics Laboratory of Oklahoma State University during the summer of 1960. Since the design is that of M. Brook of New Mexico Institute of Mining and Technology, it is referred to at Oklahoma State University as the Brook Type Field Meter. The purpose of the Brook field meter is to record the behavior of the earth's electrostatic field in the vicinity of the earth's surface during thunderstorm and tornado activity. The types of field behavior that the instrument will record are yet to be determined. After a survey of the literature, it was concluded by the writer that no single instrument designed is capable of indicating both fast and slow field variations.

The use of an electronic system is in keeping with modern day practice where the development of indicating instruments using electron tubes has resulted in great improvements in the field of measurement. Keeping this in mind, it will be of interest to review later in this chapter some of the earlier methods that have been employed to measure changes of the earth's electrostatic field. As part of the final analysis of the Brook field meter, comparison will be made with some of these earlier systems.

It is appropriate at this point to discuss the earth's electric field to clarify what is meant by the subject field and its behavior.

In addition to this discussion of the earth's electric field, a description of one of its most influential elements, the thunderstorm, will be included.

The Earth's Electric Field

It was discovered in the latter part of the eighteenth century that the atmosphere possessed both a measurable electric field and an electric current flowing from the atmosphere toward the earth. Experiment has shown the normal or fine-weather electric field of the earth to be such that the atmosphere is positively charged with respect to the ground. Local variations of the electric field exist, especially in the vicinity of thunderstorms. In fact, the direction of the electric field is sometimes reversed near thunderstorms. However, as thunderstorms have been estimated to occupy less than one per cent of the earth's surface, the fine-weather field is by far the normal electric state of the atmosphere. Since its discovery this electric field has been the subject of much investigation. This field is due to the electric charge on the earth and manifests itself by the potential gradient it produces in the neighborhood of the earth. This potential gradient is considerable, even in clear weather and in the absence of any electrical storm. (Johnson, 1954).

Frequent irregular fluctuations of the potential gradient have been observed in addition to some rather regular diurnal and annular variations. The regular variations are greater near the middle latitudes and in the interior of the continents. The daily variations are greater in winter than in summer. The annual variations are comparatively small in the tropical regions and at points of great elevation such as mountain tops, but in the temperate zones the variation is often twice as much as the annual average value. There is little diurnal or annual variation in the potential gradient over the ocean. (Albright, 1939).

Here we shall not be concerned so much with the electrical state of the atmosphere during fine-weather, but rather with deviations from this normal state during the passage of precipitating clouds, in particular, thunderstorms. However, it was thought useful to mention some of the main features of the fine-weather electric field which represents a reference state, and relative to which the complex changes which occur in disturbed weather may be measured.

Since the discovery of the earth's electric field, many theories have been offered for the origin of the fine-weather electric field, but few have survived. Wilson[1] suggested the origin of the fine-weather electric field lay in thunderstorms and pointed out that, in consequence, its maximum value should occur when the regions of the earth most subject to thunderstorms attain their maximum activity. Whipple[2] investigated the matter in some detail and found a very close correspondence between the variation in thunderstorm activity over the whole globe during the Greenwich day and the variation of the potential gradient as measured in the Arctic and the Antarctic. Other experiments such as the Mt. Withington, New Mexico, experiment by Moore, Vannegut and Botka (1958)

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[1] C. T. R. Wilson, "The Maintenance of the Earth's Electric Charge," The Observatory (1922), discussed by B. J. Mason in The Physics of Clouds (Oxford, 1957), p. 366.

[2] F. J. W. Whipple, "On the Association of the Diurnal Variation of Electric Potential Gradient in Fine Weather With the Distribution of Thunderstorms Over the Globe," Quart. J. Roy. Met. Soc. (1929), discussed by B. J. Mason in The Physics of Clouds (Oxford, 1957), p. 366.

give support to the theory that it is possible for thunderstorms to maintain the earth's electric field. Most recent authorities agree that perhaps it is entirely possible for thunderstorms to maintain the earth's electric field, but most likely some of the ions are provided by other sources.

A thorough analysis of all the sources that are said to be partially responsible for the potential difference between the earth and atmosphere cannot be made in the space of this thesis. However, the thunderstorm is of sufficient importance to this paper to warrant a brief discussion. It was stated previously that the electric field varies locally in the vicinity of a thunderstorm, its direction sometimes reversed. It is this phenomenon that will be of most importance to this experiment.

The Thunderstorm

The thunderstorm, as its name suggests, is a storm that is accompanied by lightning and its resulting thunder. Lightning and thunder are attending characteristics of the typical thunderstorm, but they are in no way responsible for the development of the storm. In the well-developed storm, where lightning and thunder are very pronounced features, they are never more than incidental phenomena and never operate as originating or controlling factors.

The characteristic thunderstorm is a local storm of convective origin and short duration usually occuring on warm days when the relative humidity is high. One of the most important characteristics of the thunderstorm is its strong updraft of air. Although this vertical motion of the air is not so apparent as the lightning and thunder, it is this factor that is responsible for the development of the storm. (Humphreys, 1940).

The physical manifestations of lightning have been with us from the remotest times, but only comparatively recently have the phenomena become even partly understood. Franklin in his electrical experiments between 1740 and 1750 succeeded in identifying lightning as the static electricity of his time. Beyond this fact little was learned until within the past fifty years. The real incentives to obtain additional knowledge lay in the necessity for protecting against lightning's effects and to aid in severe storm forecasts such as possible tornadoes.

In spite of the great interest in the manner in which charges arise in thunderclouds, the question is still one of great controversy.

A number of theories have been advanced, but those of C. T. R. Wilson and G. C. Simpson or modifications of their theories received most consideration. Both theories postulate ascending currents of air and relative motion of rain drops of different sizes.

Wilson's[3] theory depends for its explanation upon the presence of large numbers of ions in the atmosphere. Many of these ions, both positive and negative, attach themselves to minute particles of dust and extremely small drops of water to form large ions as contrasted with unattached or small ions. Over land the number of small ions of each sign ranges from about 300 to 1,000 per cubic centimeter, and the large ions from 1,000 to 80,000 per cubic centimeter. The small ions do not play an important part in Wilson's theory. The mobility of an ion is

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[3] C. T. R. Wilson, "Some Thundercloud Problems," Journal Franklin Institute, (1929), discussed by C. F. Wagner and J. M. Clayton in "Lightning Phenomena," Electrical Transmission and Distribution Reference Book (Pittsburgh, Pa., 1950), pp. 542-543.

the steady velocity that can be attained under a voltage gradient of one volt per centimeter. The large ions have very low mobility ranging from 0.0003 to 0.0005 centimeter per second. Under a gradient of 10,000 volts per centimeter this would correspond to a velocity of only three centimeters per second.

Wilson's theory premises the existence of the normal electric field which occurs during fine-weather. In magnitude this field is of the order of one volt per centimeter at the surface of the earth and gradually decreases with altitude until at 30,000 feet it is only about 0.02 volt per centimeter. A relatively large drop of water in such a field will become polarized by induction, the upper side acquiring a negative charge and the lower side a positive charge as shown in Figure 1. The velocity of fall under the influence of gravity of such a charge will be large with respect to the velocity of the slowly moving ions.

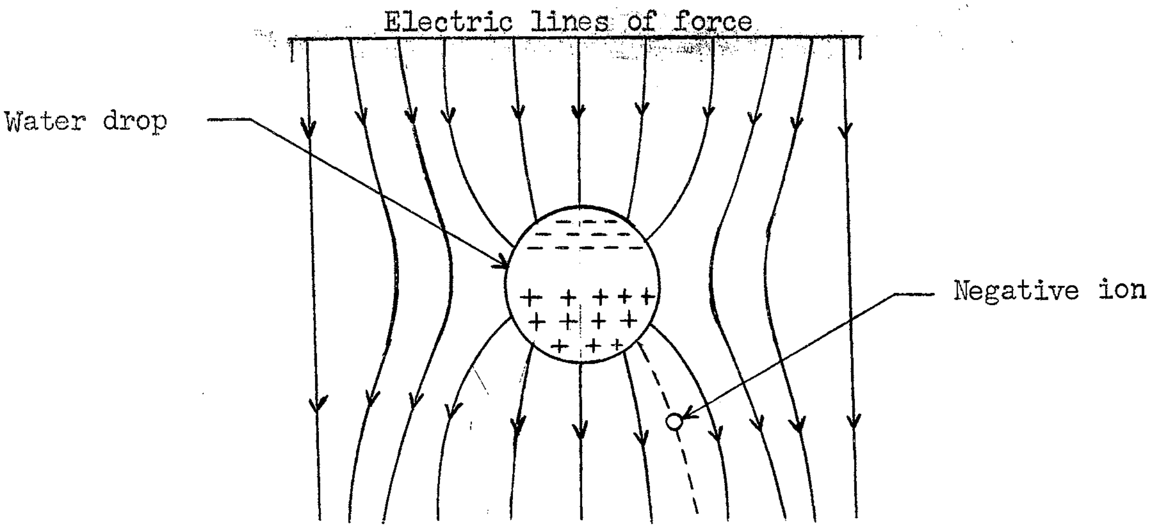

Figure 1. Capture of negative ions by large falling drops.

At the under surface of the drop a selective action with regard to the slowly moving ion occurs. The negative ions tend to be attracted and positive ions repelled. No such selection occurs at the upper surface. As a result of this action, the drop accumulates a net negative charge. With the loss of the negative ions the remaining ions are predominantly positive. The smaller drops descend with a lower velocity and thus their velocity becomes more nearly equal to that of the velocity of the large ions under the influence of the electric field. It becomes possible then for the small drops to pick up positive charge by impact with the positive ions.

Thus the original charges, which were distributed at random and produce an essentially neutral space charge, become separated. The large drops carry the negative charges to the lower portions of the cloud and the small drops retain the positive charge in the upper portion. According to Wilson's theory, the lower portion of the cloud is negatively charged and the upper portion positively charged.

The explanation by Simpson[4] is based on a fact of laboratory observation that when a large drop of water falls through an updraft of air so that the surface of the drop is blown off in fine spray, the small particles of spray are negatively charged, leaving a corresponding positive charge on the large drop. Simpson reasoned that this process of electrical separation must be at work on a large scale in every convective shower where heavy precipitation is falling through a strong convection current. The result would be an accumulation of negative

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[4] Sir George Simpson, "The Mechanism of a Thunderstorm," Proceedings Royal Society (London, 1927), discussed by C. F. Wagner and J. M. Clayton, "Lightning Phenomena," Electrical Transmission and Distribution Reference Book (Pittsburgh, Pa., 1950), p. 542.

electrical charge in the upper and outer portions of the cloud where the small particles of fine spray are carried by the rising and spreading convection current, while positive charge is accumulated in the central or lower portions of the cloud wherever the heaviest accumulation of large falling raindrops occurs.

It is seen that there is a direct contradiction between these two theories. It was this contradiction that led Simpson and Scrase[5] to investigate the charge distribution in a more direct manner. Free balloons equipped with clock-operated apparatus to measure electric gradient, atmospheric pressure, and relative humidity were released during storms. It was found that in general the main body of a thundercloud is negatively charged and the upper part positively charged. A concentration of positive charge appears to exist frequently in the base of the cloud. According to Simpson and Scrase, the cloud structure of the type shown in Figure 2 offers a satisfactory explanation of practically all the soundings obtained in their investigation.

As between the Simpson and Wilson theories, the induction theory of Wilson seems to offer an adequate explanation of negative charge in the lower regions of the cloud and the concentration of positive electricity higher up in the cloud. It does not explain the positive charge found at the base of the cloud.

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[5] Sir George Simpson and F. J. Scrase, "The Distribution of Electricity in Thunderclouds," Proceedings Royal Society (London, 1937), discussed by W. J. Humphreys in Physics of the Air (New York, 1940), pp. 317-318.

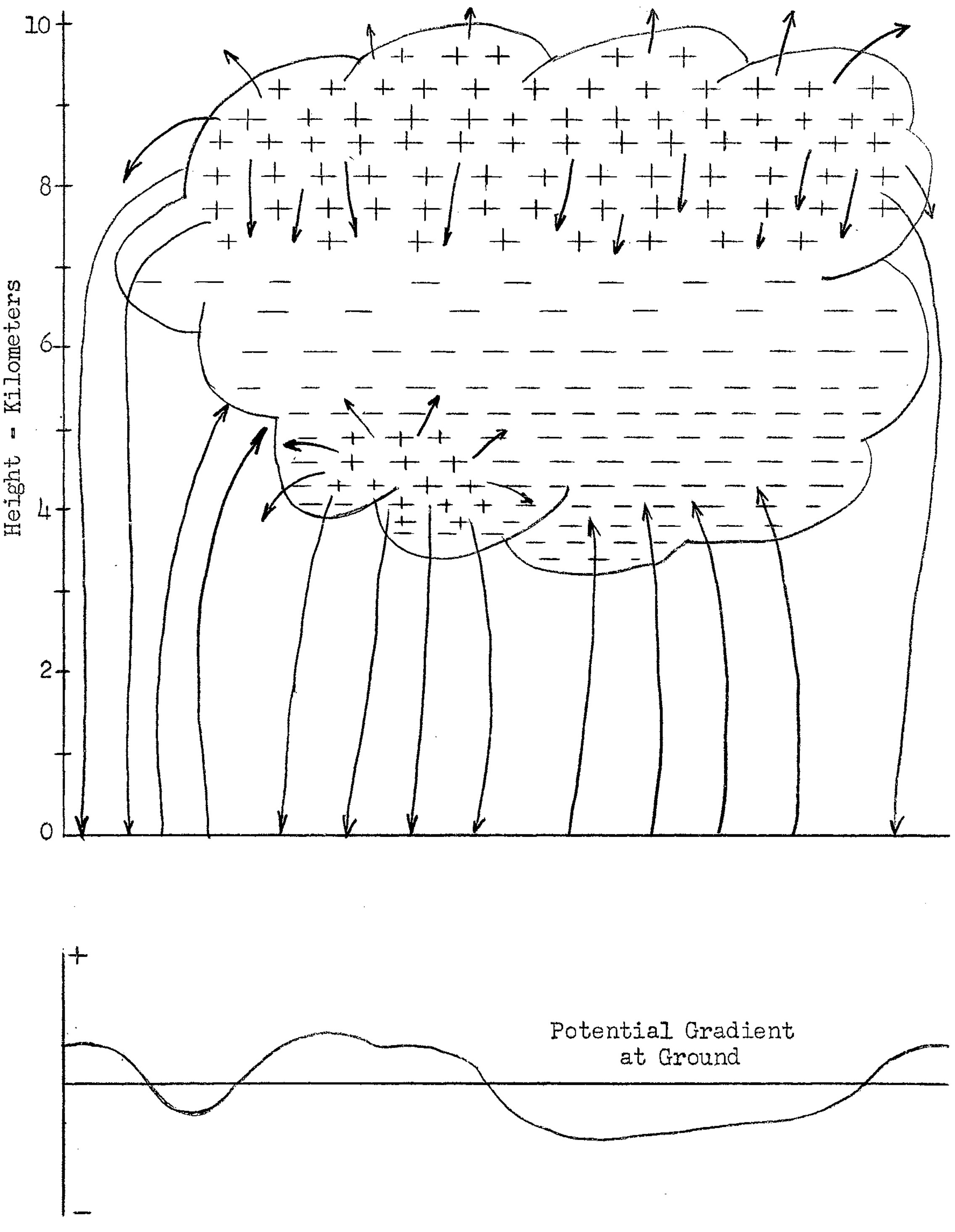

Figure 2. (After Simpson and Scrase.) Hypothetical case of a cloud with a positive charge in the upper part, a negative charge in the lower part and a small region of strong positive charge near the base.

Lightning

Lightning discharges may occur from cloud to cloud, between parts of the same cloud, or between the cloud and the earth. Before the discharge to earth, the electrical gradient within the cloud must be very much greater than at the earth where the gradient never exceeds about 100 volts per centimeter. Thus the discharge tends to be initiated at the cloud rather than at the ground. In a region occupied by water droplets of the size expected in clouds the critical breakdown voltage is 10,000 volts per centimeter. This value is 30,000 volts per centimeter in air without water droplets. (Humphreys, 1940). This phenomenon likewise tends to initiate the discharge from the cloud. In addition the lower pressure at the higher altitudes, even with the absence of water droplets, decreases the breakdown gradient.

Photographs of lightning strokes have revealed their typical characteristics. A lightning discharge which usually appears to the eye as a single flash is usually made up of a number of separate strokes that travel down the same path. Each separate stroke starts as a downward leader from the cloud with the leader of the first component stroke of a flash being preceded by a "pilot streamer". As the pilot streamer proceeds, it is accompanied by points of luminescence which travel in jumps, giving rise to the term "stepped leader". As the leader strikes the ground, an extremely bright return streamer propagates upward from the earth to the cloud, following the same path as the main channel of the downward leader. The charge distributed along the leaders thus is discharged progressively to the ground, giving rise to the very large currents associated with lightning discharges. The rate of propagation, about ten per cent of that of light, is determined by the rate at which the head of the lightning channel can become sufficiently conducting to accommodate these large currents. The charge that had been lowered from the cloud to the system of streamers by this means is further lowered to the ground. The former of these processes is relatively slow, requiring a time of the order of 10,000 microseconds, whereas the latter is relatively fast, requiring only about fifty to 100 microseconds. (Wagner, 1950). Since the same charge is involved in both stages, the difference in time explains the large difference in currents involved in the two stages.

Multiple strokes of lightning occur quite frequently during a thunderstorm. After the first stroke the potential of the charge center is lowered considerably, causing a high potential difference between this center and some other charge center within the cloud. The result is a progress of streamers into the cloud and further formation and attraction of streamers from the other charge center. Upon the meeting of two such approaching streamers, a relatively low-conducting path to the ground for the new charge center is formed. The resulting discharge traverses the same path blazed by the first stroke. The leader streamer of this stroke differs from that of the first stroke in that the step phenomenon is not present. Because of its characteristics this leader is known as a "dart" leader. Upon reaching the earth, a return streamer travels back to the cloud just as for the first stroke. (Wagner, 1950).

As the charge in the second charge center is dissipated by being carried to the ground, the above process might be repeated, resulting in another stroke.

Earlier Methods of Field Measurement

One of the first methods of determining potentials in the atmosphere was that employed by de Saussure, who used an electroscope equipped with a point, as shown in Figure 3.

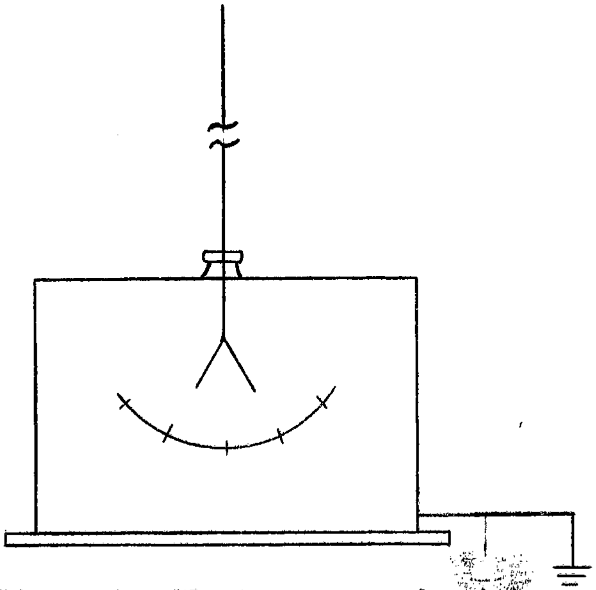

Figure 3. Electroscope and point. (Albright, 1939).

The base of the electroscope was grounded and the rod and point above served to bring the gold leaf to the same potential as the air surrounding the point. The divergence of the gold leaves is a function of the difference in the potential between the air surrounding the point and the earth. If the divergence of the leaves is calibrated in terms of volts, quantitative determinations can then be made.

Another form of apparatus, shown in Figure 4, employs a form of the Kelvin water dropper A. As the drops of water come out at the end of the tube and fall away, they are charged inductively by the surrounding air with small quantities of electricity that, on being removed from the dropper, bring it gradually to the same potential as the air at the height of the tube.

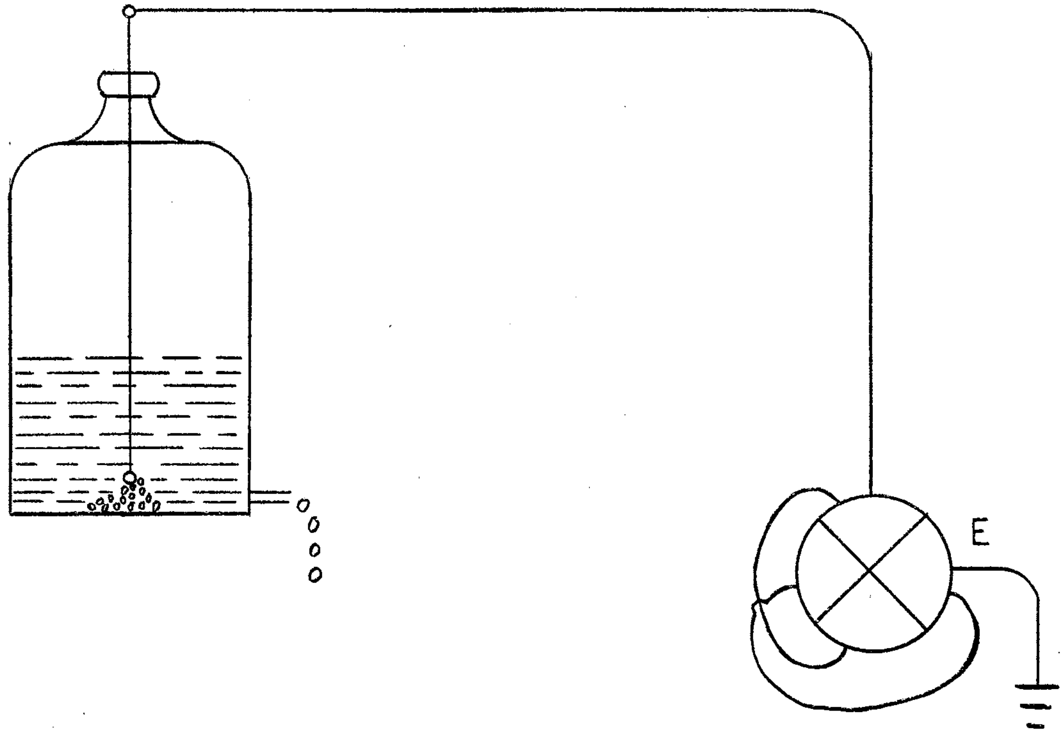

Figure 4. Kelvin's water dropper. (Albright, 1939).

In operation, the bottle acquires the potential of the air in about thirty seconds. The dropper is connected by a wire to one pair of the quadrants of an electrometer and the other pair is grounded; the needle of the electrometer E is charged to a definite potential, thus making a heterostatic arrangement.

Sometimes, instead of using the sharp points or a water dropper as a collector, radioactive material such as radium F (polonium) is placed on a small insulated tray A, Figure 5, and the tray connected to an electrometer in the same manner as above. The ionizing material brings the tray to the same potential as the air at the tray. A flame placed in the tray A would also bring the tray to the potential of the air; an oil lamp or lantern placed on the tray operates effectively.

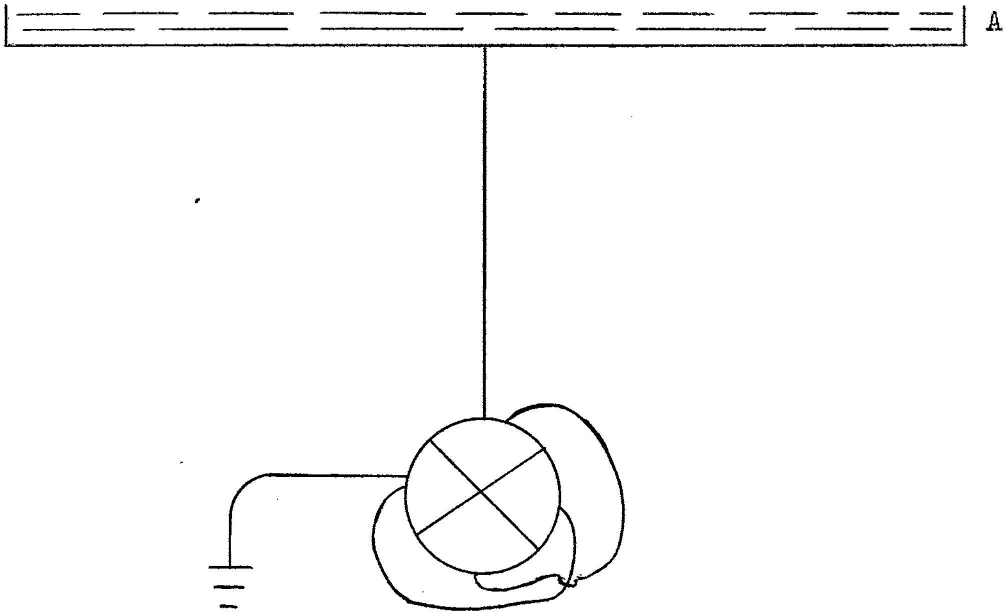

Figure 5. Radioactive collector. (Albright, 1939).

Much work has been done in the more recent years to develop highly accurate equipment for atmospheric field intensity measurement. Radiosonde equipment is used quite extensively for measuring potential gradient at various altitudes as well as inside clouds. The field mill is another device that is presently being used for measuring potential gradient. This method involves a capacitance which is alternately shielded and exposed to the gradient; the alternating flow of bound charge is measured.

CHAPTER II

THEORY OF FIELD BEHAVIOR

The subject of atmospheric electricity relates to the bulk electrical properties of the earth's gaseous envelope. The vertical extent of the study is conveniently confined between two natural equipotential surfaces, the earth and the ionosphere. The latter is a region of highly conductive gas existing at altitudes in excess of ninety kilometers. Experiment and theory show that it is possible for local concentrations of horizontal charge to build up in either the ionosphere or the earth without immediate dissipation. With these characteristics of the atmosphere, the earth and the lower boundry of the ionosphere can be considered as the two surfaces of a spherical capacitor. The space between the two surfaces is filled with a poorly conducting gas, the atmosphere. The above condition is seen to be analogous to a capacitor with a leaky dielectric. With the acceptance of the above theory, the concepts of charge, electrical force, current and resistance can be applied to the atmosphere and evaluated in terms of well-known units.

It has been estimated that the normal potential of the ionosphere is of the order of 360,000 volts positive with respect to the ground. The electric field is nonlinear and of the order of 100 volts per meter near the ground and about four volts per meter at ten to twelve kilometers. However, by proper assumptions the electric field can be linearized and the large-scale electrical aspects of the atmosphere discussed in terms of a simple equivalent electrical circuit having a capacitance shunted by a resistance. Measurements indicate that the electric current is relatively independent of height. (Johnson, 1954).

As stated earlier, the negatively charged earth and the positively charged ionosphere form a spherical capacitor with a layer of somewhat conductive air for a dielectric. The conductive of the air is small, but since the potential between the earth and the ionosphere is very large, the current through the air that forms the dielectric is considerable. This leakage current was estimated by Gish (1951) to be of the order of magnitude of 1800 amperes. This current is due to the downward flow of the positive ions and to the upward flow of the negative ions that are present in the air and in the existing electric field.

The magnitude of this current per square centimeter can be computed from the conductivity and potential gradient existing. Its magnitude is expressed by the relation

$$I = F(\lambda_+ + \lambda_-) \tag{2.1}$$

where F is the potential gradient, λ_+ is the conductivity due to the positive ions, and λ_- is the conductivity due to the negative ions. (Albright, 1939).

It can readily be seen from the preceding discussion that the flow of electricity through the atmosphere to the earth is sufficiently large to neutralize the charge on the earth capacitor in a short length of time if it were not replenished and maintained by some agency. As was stated in Chapter I, most recent authorities agree that the thunderstorm is the one large contributor to the maintenance of this charge.

It was stated previously in this chapter that the normal potential of the electric field at the earth is of the order of 100 volts per meter. This value is positive with respect to the earth when no thunderstorms are present. As the thunderstorm approaches, the value of the field decreases and may even go negative, the magnitude of the negative value increasing to a maximum at the point of closest approach of the storm. The electric field gradually recovers to its fine-weather value after the thunderstorm has passed on. Typical variations of this nature are shown in Figures 6 and 7. The traces in Figures 6 and 7 represent potential gradient at a fixed point on the ground as a function of distance from the thunderstorm centers. The cases of Figures 6 and 7 are typical with the upper portion of the cloud positively charged and the bottom of the cloud negatively charged. (Johnson, 1954).

The typical behavior of the electric field during thunderstorm activity can be explained in broad detail by considering the thundercloud as a giant electric dipole, with the center of a positive charge oriented vertically above a negative charge, Figure 8. (Mason, 1957). The positive charge represents the positively charged portion of the cloud and the negative charge represents the negatively charged portion of the cloud. The vertical distance from the earth to the lowest center of charge will be taken as Y_1 and the distance from the earth to the center of the upper charge as Y_2. The problem to be solved is to find the magnitude of the vertical component of the electric field measured at P from the two charge centers of magnitude Q_1 and Q_2 at a distance Y_1 and Y_2 respectively above the earth's equipotential surface. The distance along the equipotential surface from P to the projection of charge centers Q_1 and Q_2 on this surface will be called X. The diameters of the quivalent spheres containing charges Q_1 and Q_2 will be

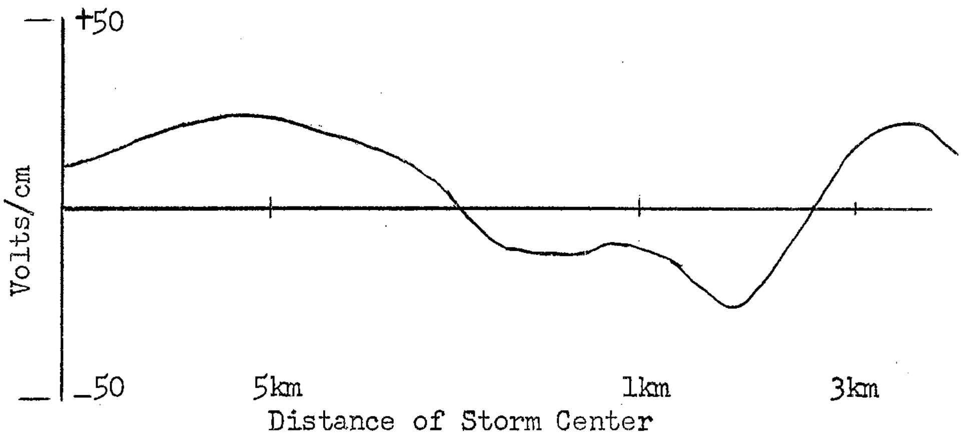

Figure 6. (After Simpson and Scrase.) Trace of a thunderstorm of small intensity.

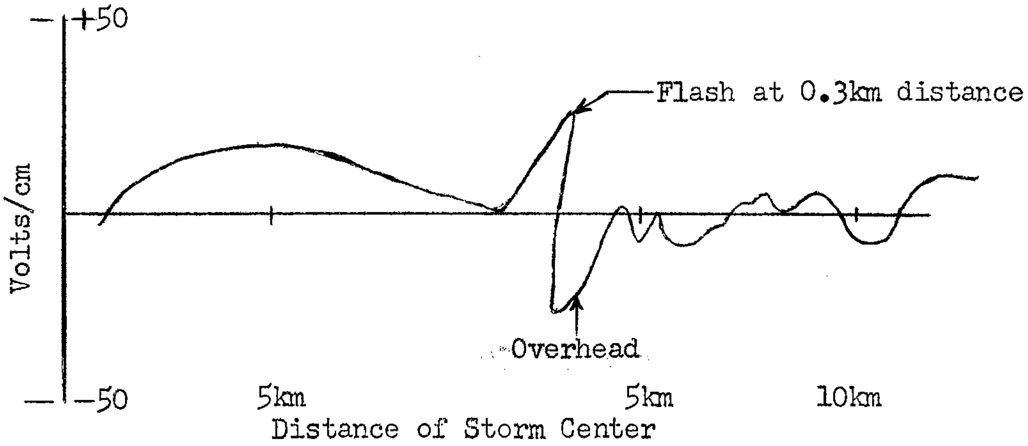

Figure 7. (After Simpson and Scrase.) Trace of a thunderstorm of violent intensity.

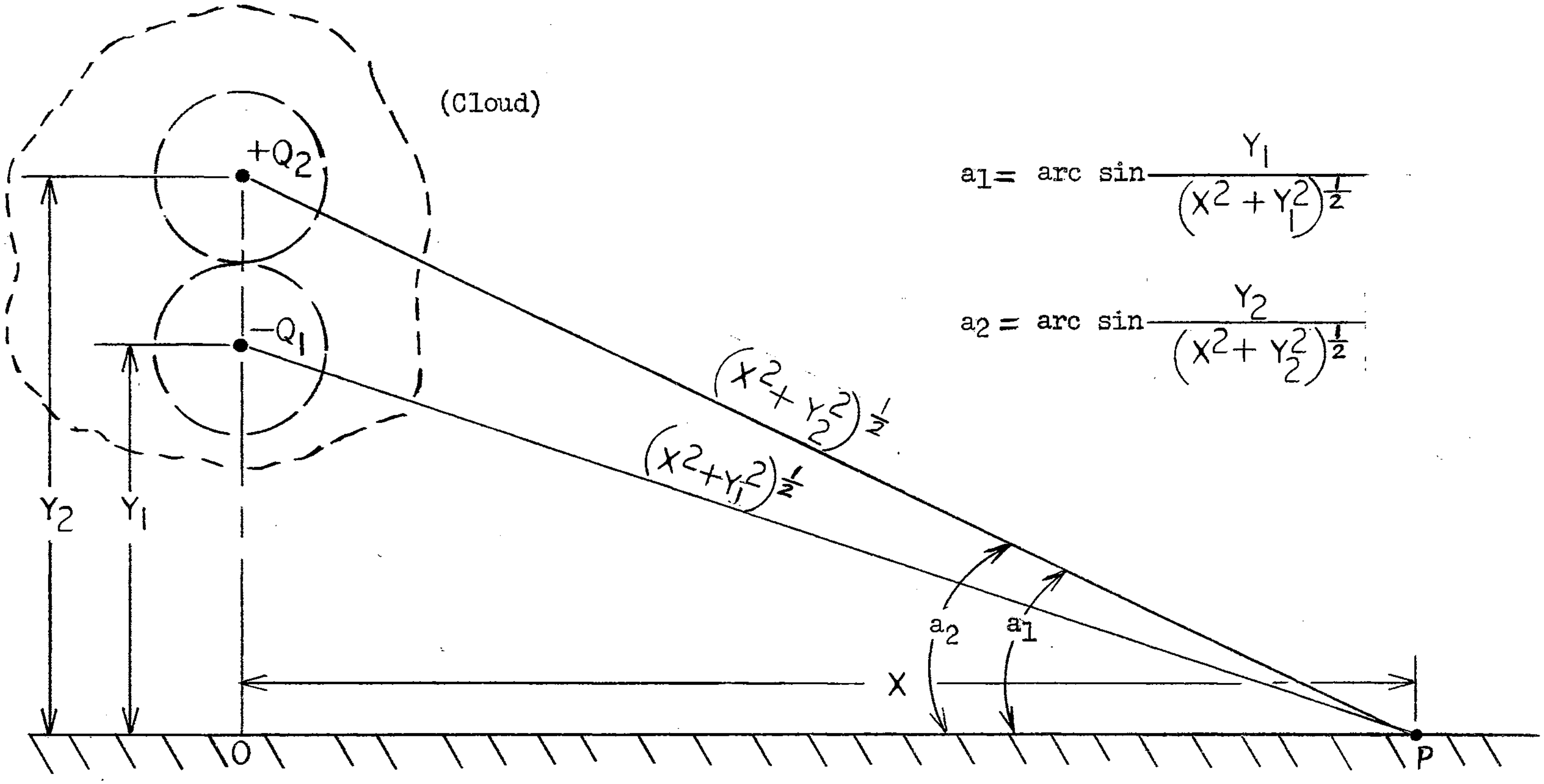

Figure 8. The geometry associated with the measurement of the vertical component of the electric field at point P from a dipolar cloud above point O.

of the order of the spacing between Q_1 and Q_2, i.e., $Y_2 - Y_1$.

The above problem is best solved by the method of electrical images as shown in Figure 9. It is seen from Figure 9 that the shape of the electric field will be unchanged when an equipotential is inserted along the plane of symmetry between the poles of an electric dipole. (Seely, 1958). The earth is such a plane of symmetry for a thunderstorm. In order to complete the electric field at point P, the complete dipole must be used, i.e., both the charge center and its image below the earth. Coulomb's law states that the electric field, a flux density concept, varies as the square of the distance from a point source. When the electric field is measured in free air it is given by

$$E_r = \frac{Q}{r^2} \; . \tag{2.2}$$

The vertical component of the electric field at P from each dipole is twice the value of the field from one pole because both the charge and its image contribute to the field. For any electrical charge center situated above the earth, the contribution to the earth's electric field is

$$\begin{aligned} E_Y &= 2\, E_r \sin a \\ &= \frac{2Q}{r^2} \sin a \; . \end{aligned} \tag{2.3}$$

Since $r^2 = X^2 + Y^2$ and $\sin a = Y/(X^2 + Y^2)^{\frac{1}{2}}$ the electric field of the earth from the lowest charge center is

$$E_1 = \frac{-2Q_1 Y_1}{(X^2 + Y_1^2)^{3/2}} \; . \tag{2.4}$$

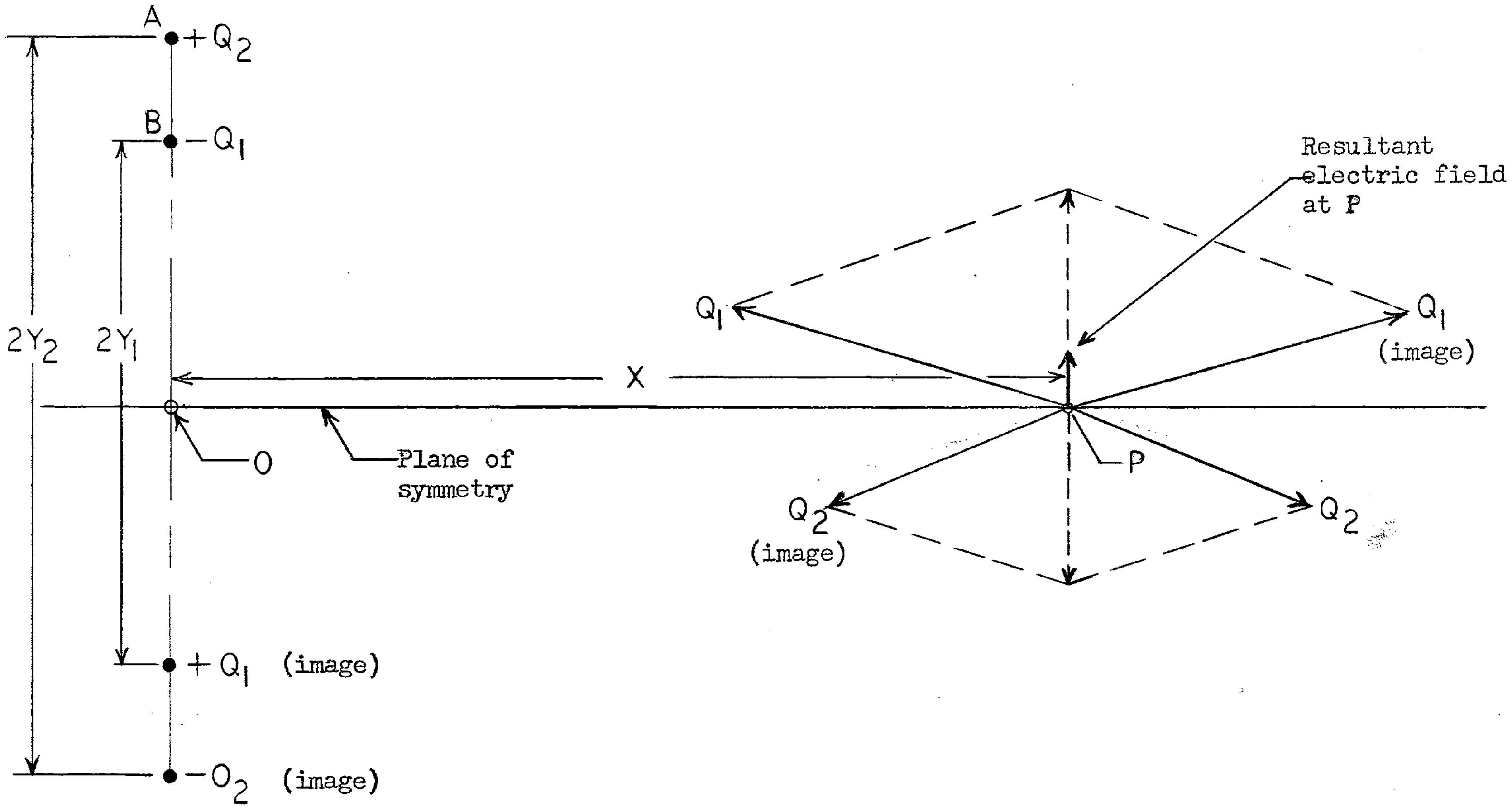

Figure 9. Vector representation of the electric fields at point P from charges Q_1 and Q_2 and the image charges of Q_1 and Q_2 located above and below the plane of symmetry.

and from the upper charge center the electric field is given as

$$E_2 = \frac{+2Q_2Y_2}{(X^2 + Y_2^2)^{3/2}} \ . \qquad (2.5)$$

The reason for opposite signs in the above equations for E_1 and E_2 is that Q_1 and Q_2 are equal in magnitude but opposite in charge. Q_1, the charge in the lower portion of the cloud, is negative in sign and Q_2, the charge in the upper portion of the cloud, is positive in sign. The total electric field of the earth is the sum of all the electric fields from the dipole. The earth's total electric field then becomes

$$E = E_1 + E_2 = \frac{2Q_2Y_2}{(X^2 + Y_2^2)^{3/2}} - \frac{2Q_1Y_1}{(X^2 + Y_1^2)^{3/2}} \ . \qquad (2.6)$$

Over the range of X in which this analysis is valid, there is no fine-weather field because the electrical state of the atmosphere is dominated by the thunderstorm which produces a very strong field. However, it is readily seen from the above equation that as X becomes very large the effect of the thunderstorm is no longer the dominant factor in producing the earth's electric field. With the thunderstorm at a great distance the limit approached for the earth's electric field is the fine-weather value.

If a cloud-to-ground lightning stroke lowers a charge δQ, originally at height Y_2 to the earth, the vertical field-change produced at point P is from equation 2.4

$$\delta E = \frac{2\delta Q Y_1}{(X^2 + Y_1^2)^{3/2}} \ . \qquad (2.7)$$

For a distant storm where $X \gg Y_2$ equation 2.7 reduces to

$$\delta E \simeq \frac{2\delta Q\, Y_1}{X^3} = \frac{\delta M}{X^3} \qquad (2.7)$$

where δM is the change in electric moment.

The field-change produced by an intercloud stroke when a charge δQ passes from point A to point B (Figure 9) is from equation 2.6

$$\delta E = 2\delta Q \left[\frac{Y_2}{(X^2 + Y_2^2)^{3/2}} - \frac{Y_1}{(X^2 + Y_1^2)^{3/2}} \right] . \qquad (2.8)$$

Again, if $X \gg Y_1$ and Y_2, equation 2.8 reduces to

$$\delta F = \frac{2\delta Q(Y_2 - Y_1)}{X^3} = \frac{\delta M}{X^3} \qquad (2.8a)$$

It is seen from equation 2.8 that for a particular value of X the field-change has zero value, and at this point it reverses sign. By studying the sign of the field-change as a function of distance, and in particular its reverse, Wilson[1] was able to determine the polarity of the thundercloud. He found that the field-change produced by a cloud-to-ground discharge was positive at all distances from the storm, i.e., it tended to augment the normal fine-weather positive field. The field-change due to an inter-cloud discharge was positive for near storms and negative for distant ones. This information pointed to the main positive charge of the cloud being situated above the negative charge center; the cloud was thus classified as having positive polarity.

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[1] C. T. R. Wilson, "Investigations on Lightning Discharges and on the Electric Field of Thunderstorms," Phil. Trans. Roy. Soc.A (1920), discussed by B. J. Mason in The Physics of Clouds (Oxford, 1957), p.373.

CHAPTER III

EQUIPMENT

This chapter will be devoted to a description of the Brook Type Field Meter and the test equipment used in the experiments presented in this thesis. It will also outline the test set-ups employed to gather needed data.

Field Meter

The Brook Type Field Meter consists of a field-sensing probe connected to a resistance-capacitance coupled vacuum tube amplifier. The signal level from the probe is controlled by means of an attenuator system made up of parallel resistance-capacitance networks. The amplifier also has gain control provided in one stage. The output from the amplifier is connected to the vertical-deflection system of a Tektronix Type 502 Oscilloscope. The horizontal sweep is not used in the oscilloscope and the amplifier output merely deflects the electron beam in an up or down direction.

A continuously advancing film record is made of the oscilloscope display using a Du Mont Oscillograph-record Camera. The recording is made at a speed of 600 inches per minute with timing marks placed on the film automatically at one second intervals. Thus the continuous advancing of the film furnishes the effective horizontal sweep. By careful measurement on the film, the time of a field variation can be determined.

The magnitude of the recorded field-change can be read directly with the aid of the graticule mounted over the face of the oscilloscope.

An oscilloscope is used to display the output from the electronic amplifier because the electron beam of the cathode-ray tube, having negligible inertia, can plot rapidly changing quantities that cannot be plotted with a mechanical indicating system. In addition, the indicating system of the oscilloscope requires a negligible amount of power for operation, which means that the source of the unknown signal is not loaded to an extent which would disturb its operating characteristics.

The Tektronix Type 502 Oscilloscope is a dual-beam, high-gain, narrow-band oscilloscope using a T60-type dual-gun cathode-ray tube. The instrument has identical vertical deflection amplifiers, one for the upper beam and one for the lower. Simultaneous horizontal deflection of both beams is provided by a single time-base generator and horizontal sweep amplifier circuit.

The Type 502 circuitry is arranged so that the instrument can be used in any of several configurations. It may be used as a conventional single-beam oscilloscope by applying an input signal to either of the vertical deflection amplifiers. It may be used to examine two wave forms simultaneously by applying input signals to both vertical amplifiers.[1]

The field sensing probe is essentially a flat-plate type antenna. It consists of a sheetmetal disk nine inches in diameter mounted at the

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[1] _Dual-Beam Oscilloscope Type 502 Instruction Manual_ (Portland, 1959), p. 4-1.

end of a one-half inch metal rod thirty-six and a half inches long. The base provided for antenna mounting is a cylindrical insulator made of teflon. The antenna is installed on top of the Atmospherics Laboratory above a two inch mesh wire screen that is laid in a horizontal plane on top of the laboratory to provide the required ground plane. The antenna is connected to the electronic amplifier through Type RG-11A/U coaxial cable. At the antenna end the center conductor of the coaxial cable is soldered to the metal rod with the shield or outer conductor connected to the wire screen.

A block diagram of the Brook Type Field Meter system is shown in Figure 10. A complete wiring diagram of the electronic amplifier is shown in Figure 11. The wiring diagram for the attenuator system is shown in Figure 12.

Frequency-response Test Equipment

The first series of tests was conducted to determine the frequency-response characteristics of the electronic amplifier. A block diagram of this test set-up is shown in Figure 13.

The signal source was a Hewlett-Packard Model 650A Test Oscillator. The Model 650A is a wide-range precision resistance-tuned oscillator covering from ten cycles per second to ten megacycles per second. It has a highly stable output signal level that is adjustable from thirty microvolts to three volts into 600 ohms. Frequency-response is essentially flat [±1db] throughout the complete extended range.[2]

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[2] *Operation and Servicing Manual for Model 650A Test Oscillator* (Palo Alto, Calif., 1956), p. 1.

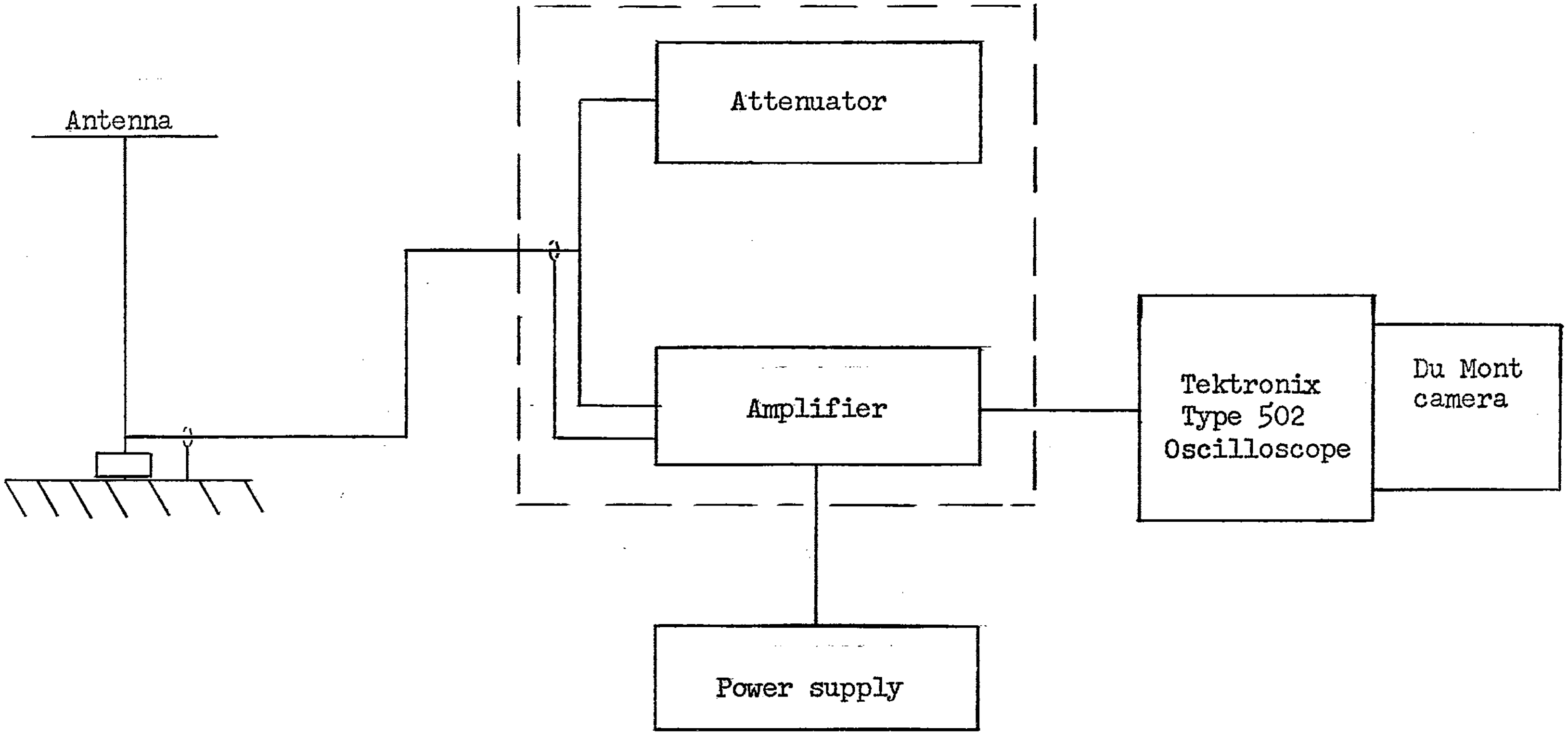
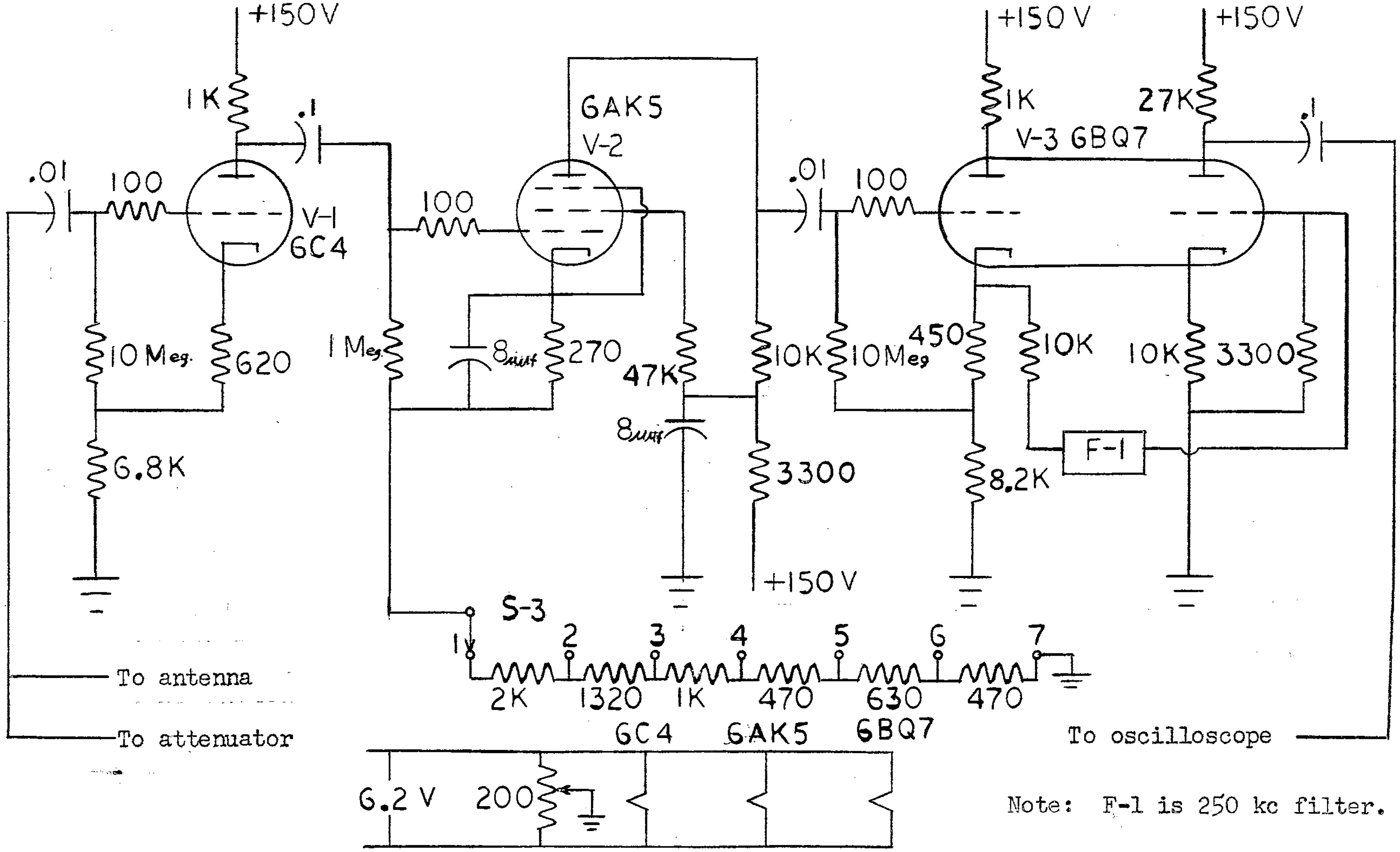


Figure 10. Block diagram of the Brook Type Field Meter installation.



Note: F-1 is 250 kc filter.

Figure 11. Wiring diagram of the electronic amplifier in the Brook Type Field Meter.

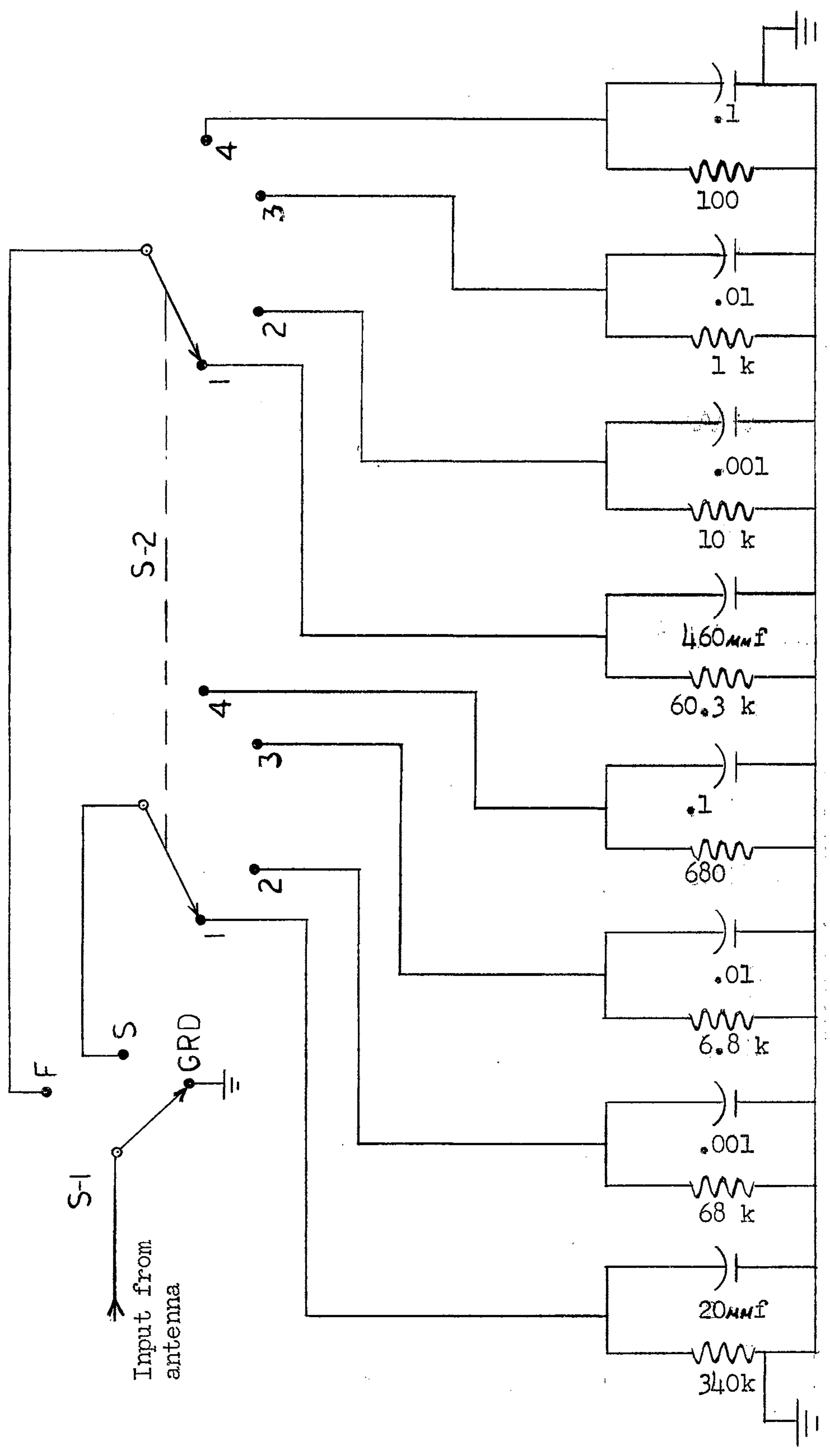


Figure 12. Wiring diagram of the Input Attenuator.

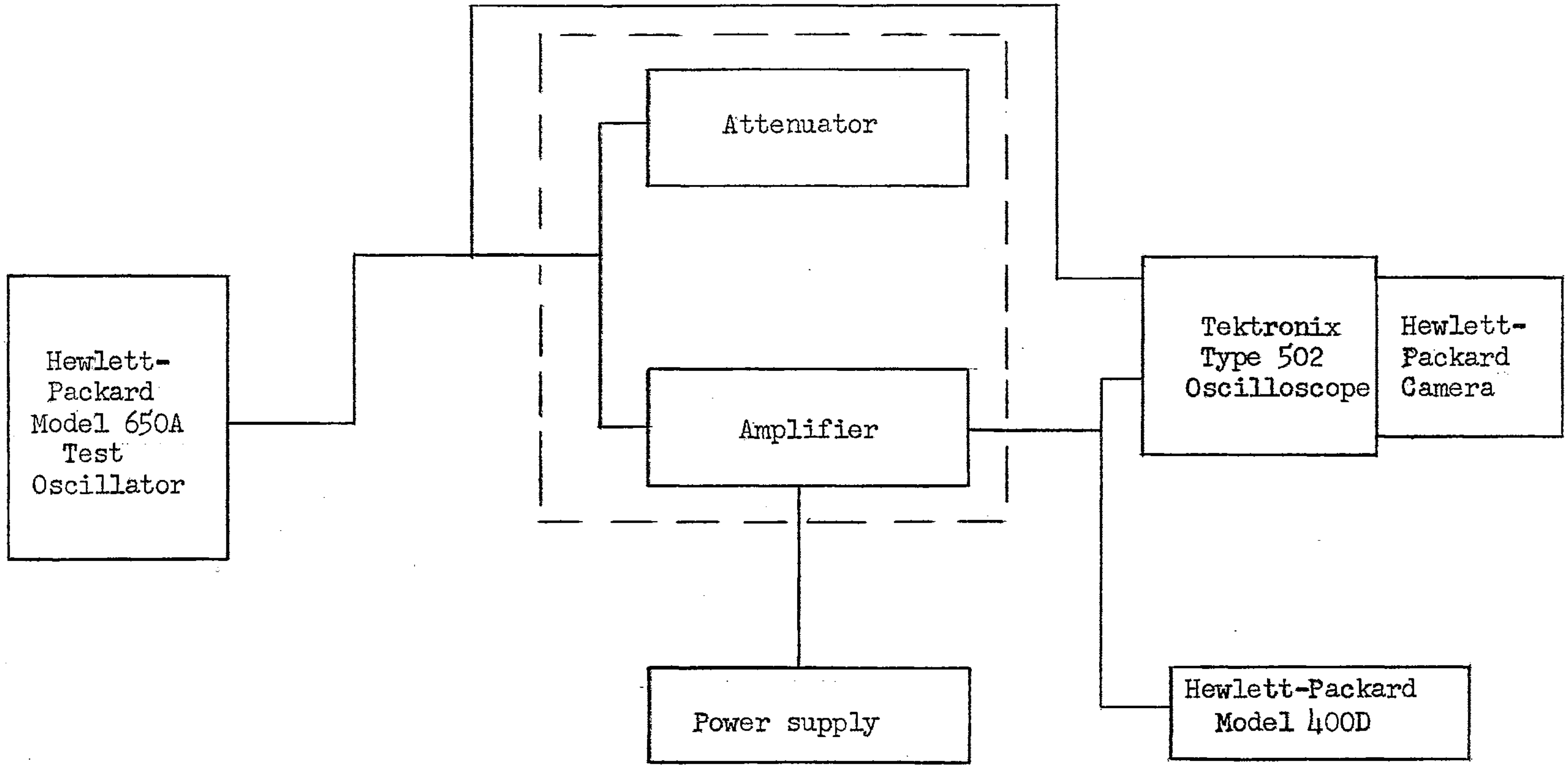


Figure 13. Block diagram of the test set-up for obtaining frequency-response characteristics.

The output voltage of the test oscillator was monitored constantly by use of the vacuum tube voltmeter provided in the oscillator package. The oscillator output was maintained at a constant level throughout the test.

A Hewlett-Packard Model 400D Vacuum Tube Voltmeter was used for indicating the amplifier output. This voltmeter operates over a frequency range of ten cycles to four megacycles and has an input impedance of ten megohms, effectively preventing disturbance to circuits under test. This voltmeter is capable of measuring gain, network response and output level with speed and accuracy.[3]

A Hewlett-Packard 196A Oscilloscope Camera attachment was mounted on the oscilloscope to photograph the trace of the input to the amplifier and its output trace.

Field-change Test Equipment

For this portion of the experiment a large wire screen was used to provide a uniform electric field around the field meter antenna. The multiple ply screen was fabricated of two-inch mesh poultry netting and supported by a wooden frame structure. The screen was ten feet square and was mounted on four legs that were one and one-fourth meters high. The subject screen was placed on top of the Atmospherics Laboratory directly over the antenna and its ground plane screen.

The electric field between the screens with a potential of V_s

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[3] *Operating and Servicing Manual for Model 400D/H Vacuum Tube Voltmeter* (Palo Alto, Calif., 1955), p. 1.

volts between the screens is

$$E = \frac{V_s}{d} \text{ volts/meter} \qquad (3.1)$$

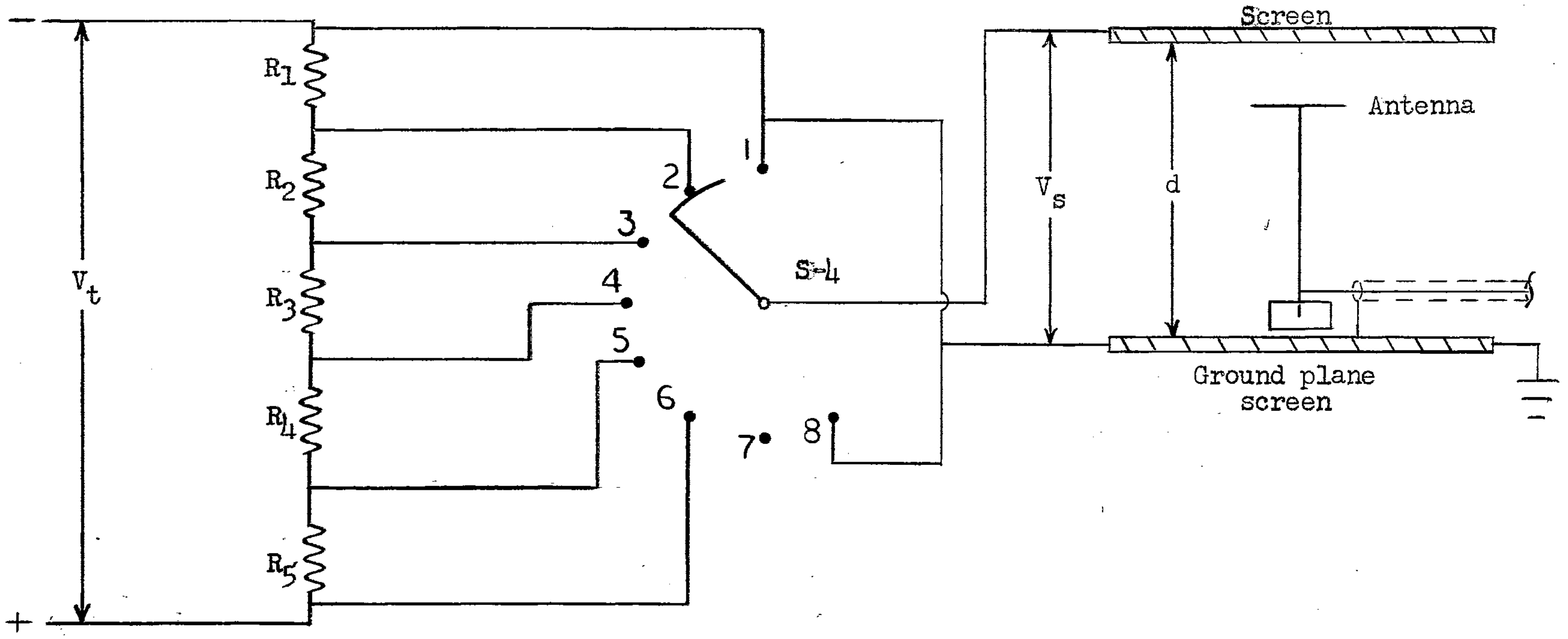
where d is the distance between the screens. Since d = 1.25 meters, equation 3.1 becomes

$$E = \frac{V_s}{1.25} \text{ volts/meter} . \qquad (3.2)$$

The system used for applying step voltages between the screens is shown by the schematic in Figure 14. For the field-change due to a voltage step, equation 3.2 becomes

$$\delta E = \frac{\delta V_s}{1.25} \text{ volts/meter} . \qquad (3.3)$$

For this portion of the experiment the output of the Brook Type Field Meter was displayed by the upper beam of the Tektronix oscilloscope with the field-change being displayed by the lower beam.



Notes: $R_1 = R_2 = R_3 = R_4 = R_5 = 12{,}900$ ohms.

Switch S-4 is equipped with shorting type wiper contact.

Figure 14. Circuit diagram used for obtaining field changes.

CHAPTER IV

DATA AND ANALYSIS

In this chapter the data obtained from tests run on the equipment described in Chapter III will be presented and analysed.

Frequency-response

For determining the frequency-response characteristics of the electronic amplifier portion of the Brook Type Field Meter, the test set-up was made in accordance with Figure 13.

The variation of amplification with frequency is expressed in decibels referred to on an arbitrary level which is taken as zero decibels. The significance of the frequency-response curves in this chapter can best be understood by considering what a decibel means. The decibel is a unit for expressing a power ratio and is given by the relation

$$\text{Decibels} = \text{db} = 10 \log_{10} P_2/P_1 \ . \qquad (4.1)$$

When the decibel is used to express relative amplification, it signifies power output as a function of frequency with respect to some arbitrary power. For the case under analysis in this thesis, the relative power standard chosen was the power output at 1,000 cycles per second. The power output at any other frequency is then proportional to $(E/E_{1000})^2$ where E is the voltage output at the frequency in question and E_{1000} is the output voltage at 1,000 cycles per second. Since the power output under these conditions is proportional to the square of the voltage, equation 4.1 can be rewritten for this particular case to give

$$\text{db} = 10 \log_{10} P_2/P_1 = 10 \log_{10}(E/E_{1000})^2 = 20 \log_{10}(E/E_{1000}). \quad (4.2)$$

This relation was read directly from the Hewlett-Packard 400D Vacuum Tube Voltmeter using the procedure described below.

For a starting point the ten volt, + 20 db scale was selected on the Hewlett-Packard 400D. The Hewlett-Packard 650A Test Oscillator frequency was set for 1,000 cycles per second and the output level adjusted to give a reading of 0 db on the 400D. The output of the 650A was noted to be 2.5 volts which was the input to the electronic amplifier. Holding the output level of the 650A constant at 2.5 volts and varying the frequency in steps from ten cycles to 400 kilocycles, a series of readings was taken to plot the frequency-response curves shown in Figures 15, 16, 17, and 18. The variation of the amplifier gain with frequency was read directly from the decibel scale on the 400D.

For the frequency-response curve in Figure 15, position S was chosen for switch S-1 [Figure 12], position 1 for switch S-2 [Figure 12], and position 1 for the V-2 bias switch S-3 [Figure 11]. Data was taken for plotting the frequency-response curve, then the procedure was repeated for S-2 in positions 2 and 3, respectively. It was noted that all three curves coincided. This is easily understood by noting from the schematics in Figures 12 and 13 that the attenuators are connected directly across the output terminals of the test oscillator; therefore, the input to the amplifier does not change with attenuator setting.

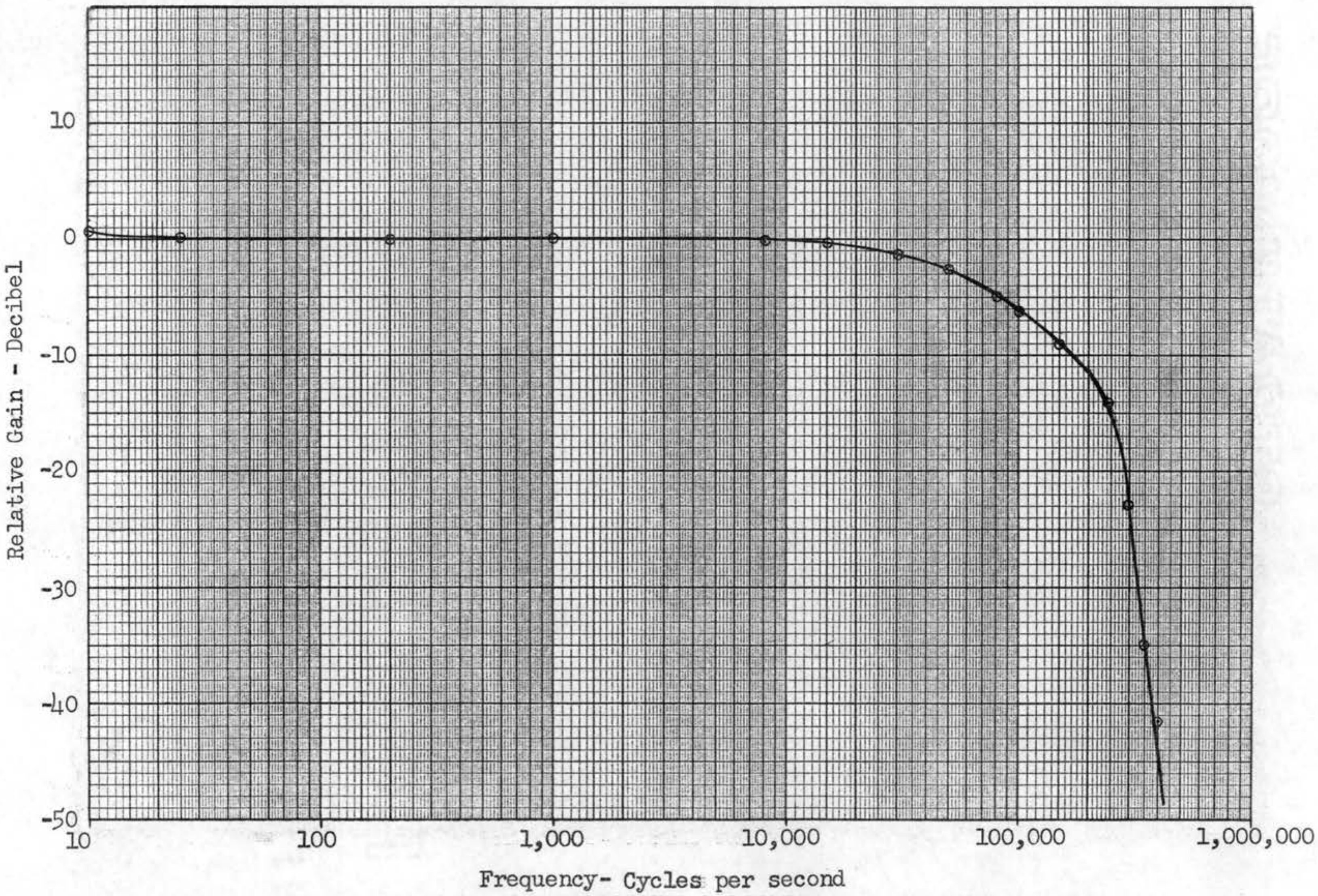


Figure 15. Frequency-response of the electronic amplifier [V-2 bias switch in position 1].

The procedure was repeated for switch S-1 in the F position, S-3 in position 1, and S-2 in positions 1, 2, and 3 respectively. The data obtained was identical to the data for the preceding switch settings. The frequency-response curve in Figure 15 is typical for all data.

An analysis of the curve of Figure 15 reveals that the frequency-response is essentially flat from ten cycles to approximately fifteen kilocycles before the curve starts to "roll-off". This is called the mid-band range of frequencies. It would have been of interest to plot the portion of the response curve below ten cycles, but no equipment was available to evaluate the performance in this range. It was noted in Figure 15 that the curve rises slightly at ten cycles.

To determine the effect of the V-2 bias adjust on amplifier gain, a series of readings was taken with switch S-3 in positions 1, 2, 3, 4, 5, 6, and 7 respectively. The results are the curves plotted in Figures 16 and 17. It is noted that the gain with switch S-3 in position 1 is taken as the reference level. It is of interest to observe that as the gain level increases, the response curves begin to "roll-off" as the frequency approaches ten cycles.

Filter F-1 was removed from the amplifier and replaced by a jumper wire. Data was taken for plotting curve A of Figure 18. The curve of Figure 15 is also plotted in this figure. It is noted that high frequency "roll-off" without Filter F-1 is the same as with the filter up to 200 kilocycles, but it is much more gradual from this point. This demonstrates that the range of the amplifier could be extended somewhat if necessary by removing the filter; however, the gain is down in this range until the results might be very poor.

It was stated previously in Chapter III that the input to the

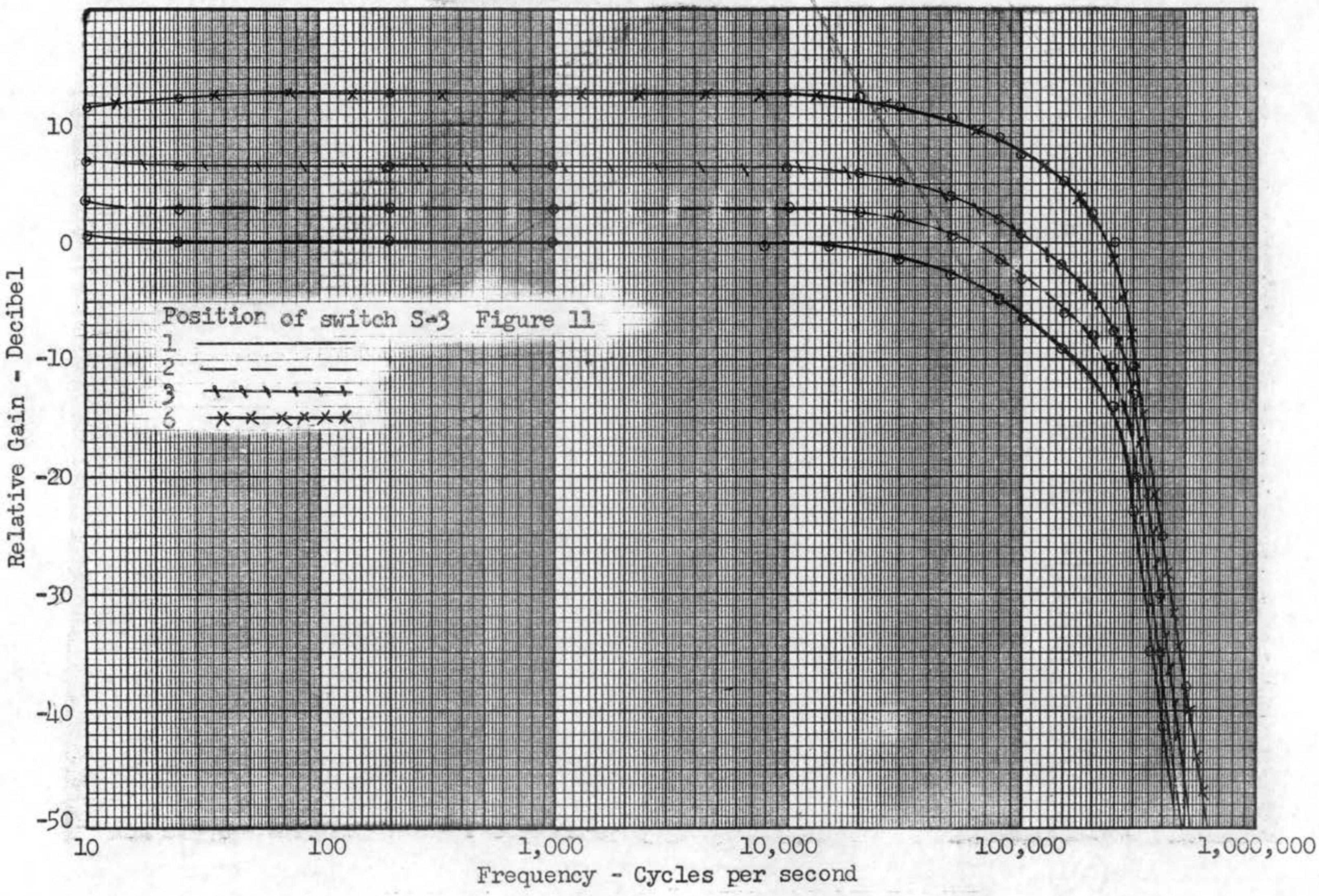


Figure 16. Effect of V-2 bias on amplifier gain

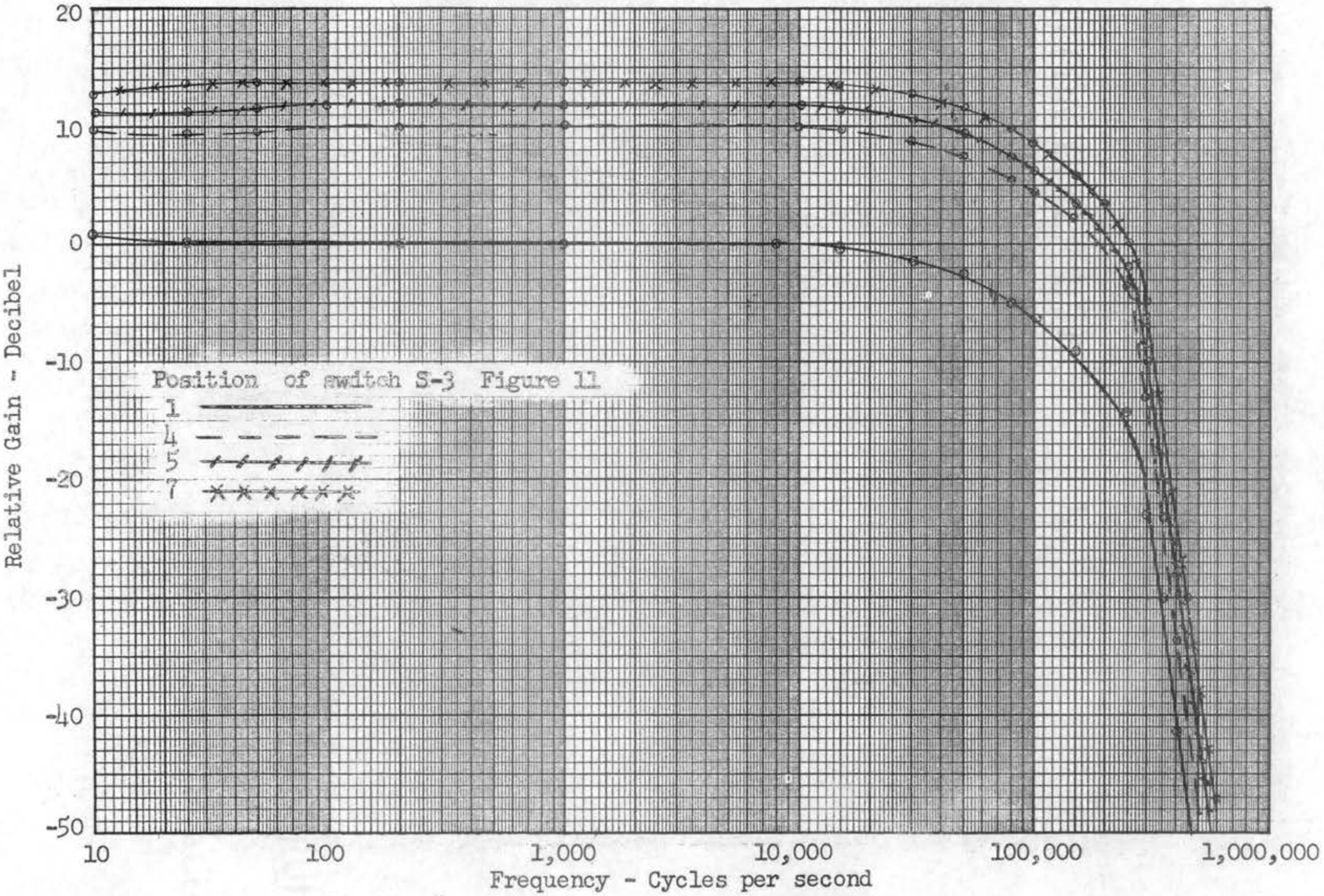


Figure 17. Effect of V-2 bias on amplifier gain.

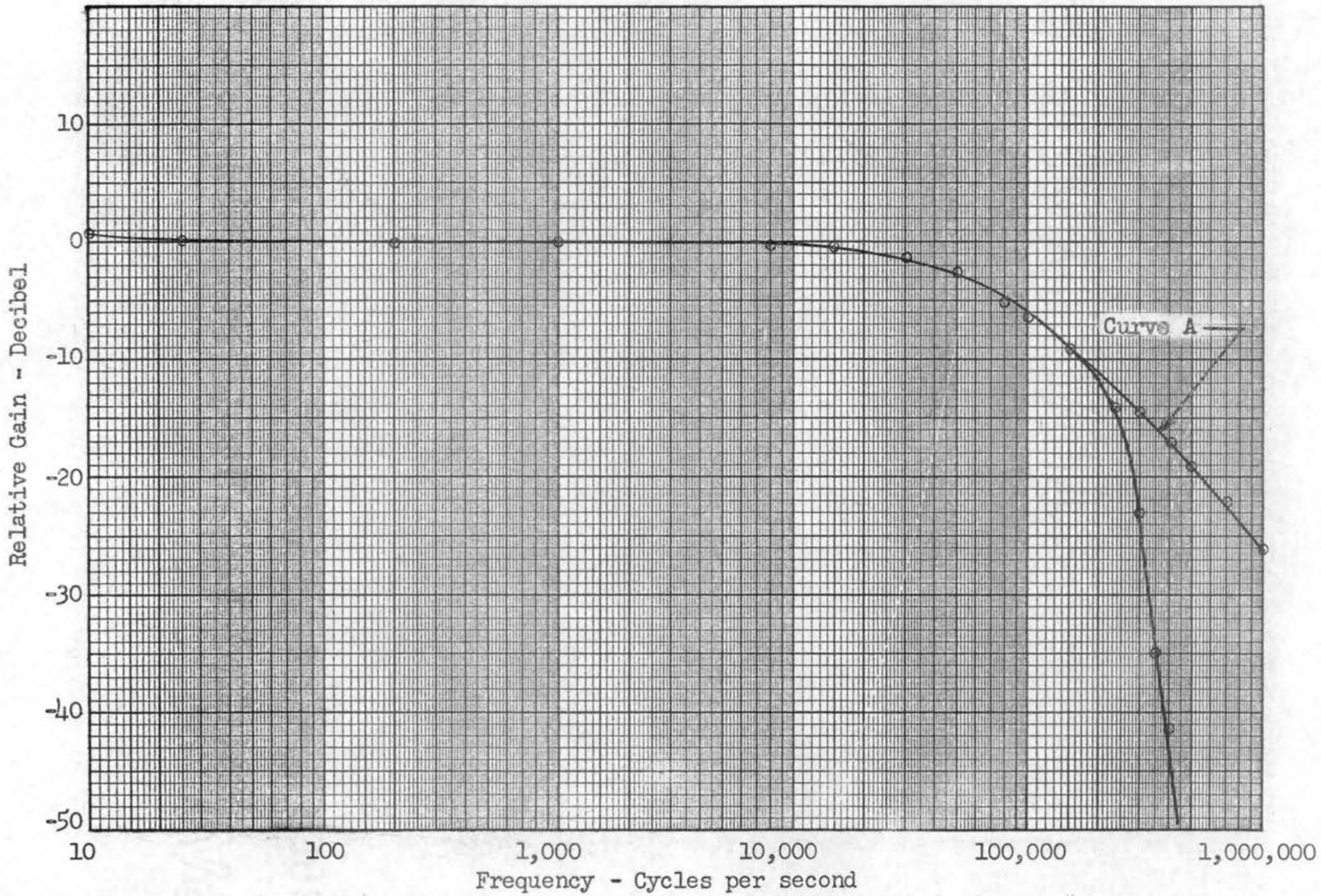


Figure 18. Frequency-response of the electronic amplifier without filter F-1 [Curve A]

amplifier was displayed by the upper beam of the oscilloscope and the output displayed by the lower beam. These traces were observed throughout the entire period of the test to note any unusual behavior of the amplifier. In general, the reproduction of the input signal by the amplifier was excellent throughout the mid-band frequency. Figure 19 demonstrates good reproduction of the input signal at 1,000 cycles per second with the V-2 bias switch S-3 in position 1. Figure 20 shows distortion beginning in the output due to the Filter F-1 at 250 kilocycles. Figure 21 shows considerable distortion in the output due to Filter F-1 at 300 kilocycles. However, 300 kilocycles is considerably beyond the efficient range of the filter and it was seen from the frequency-response curve that the gain is extremely low at this point. Figures 22 and 23 show clipping of the output at 1,000 cycles per second with the V-2 bias switch, S-3, in positions 6 and 7 respectively. In actual operation it would be reasonable to expect some clipping of the output if V-2 bias were increased to these levels. Figure 24 shows the clipping disappearing at eighty kilocycles. This is to be expected since this point is on the knee of the frequency-response curve.

Field-change Data

For this part of the analysis, the Brook Type Field Meter was made ready for normal operation. The wire screen described in Chapter III was installed above the antenna to provide a uniform electric field. Step voltages were applied to the screen by means of the apparatus shown schematically in Figure 14. The output from the field meter was displayed by the upper beam and the field-changes were displayed by the lower beam of the Tektronix Type 502 Oscilloscope. Photographic

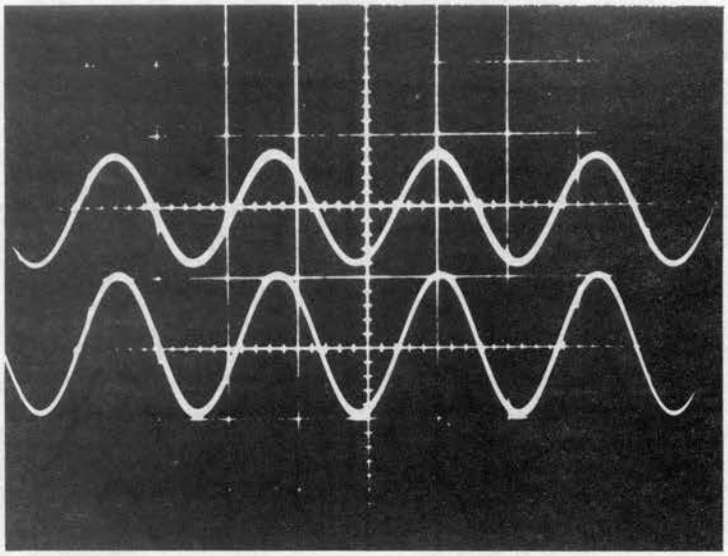


Figure 19. Good reproduction of the input signal shown by lower trace at 1000 cps. Input shown by upper trace.

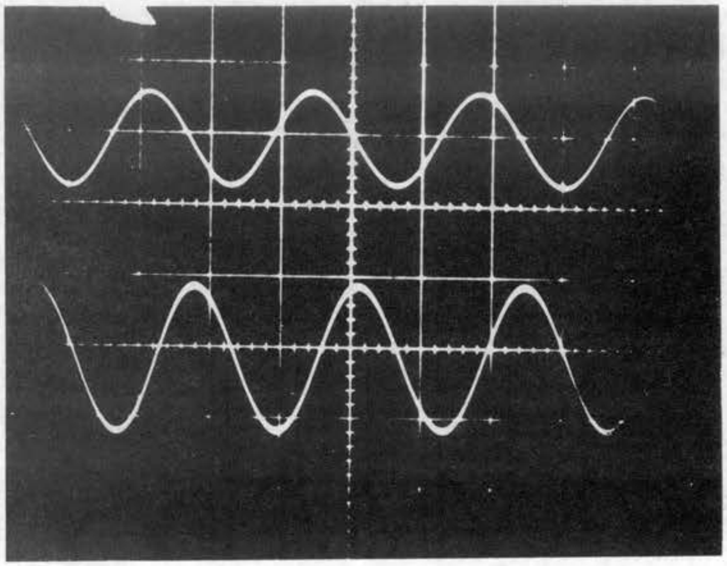


Figure 20. Lower trace shows distortion beginning in the output at 250 kc due to filter F-1. Input shown by upper trace.

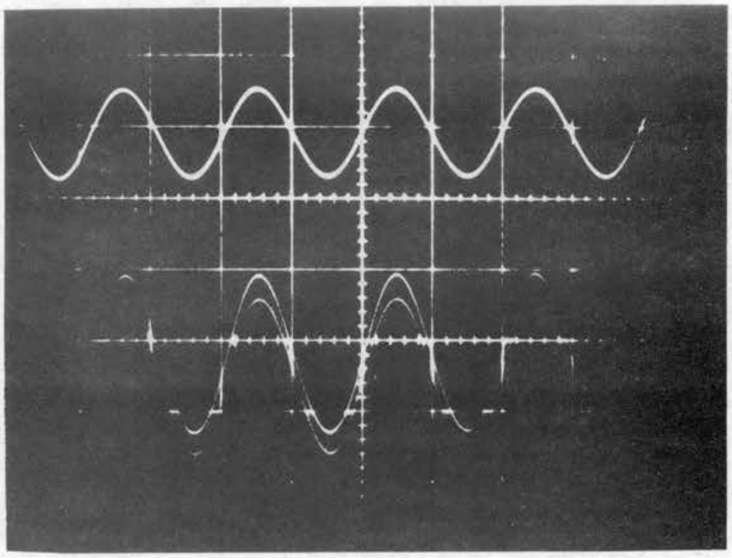


Figure 21. Considerable distortion of the output shown by the lower trace at 300 kc due to filter F-1. Input shown by upper trace.

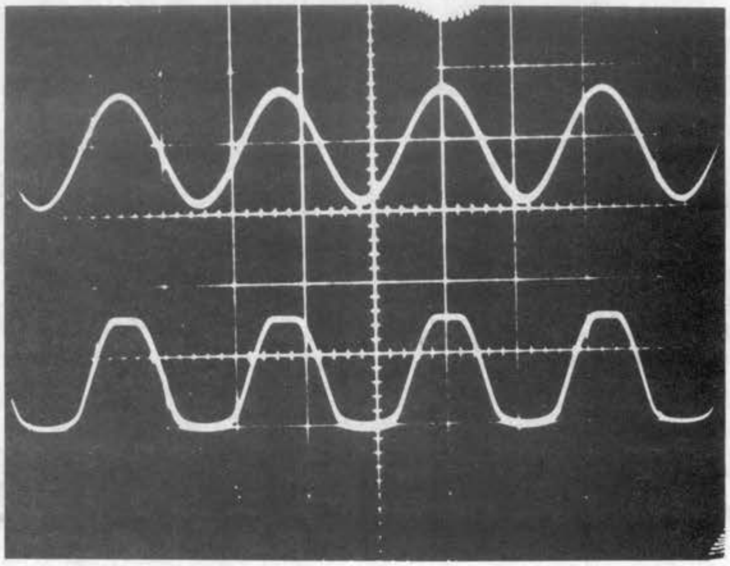


Figure 22. Clipping of the output shown by the lower trace at 1000 cps with V-2 bias switch S-3 in position 6. Input shown by upper trace.

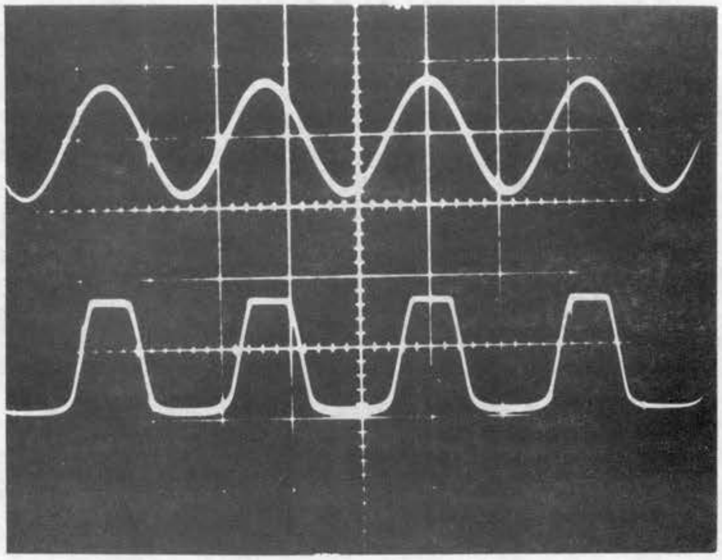


Figure 23. Clipping of the output shown by lower trace at 1000 cps with V-2 bias shown by upper trace.

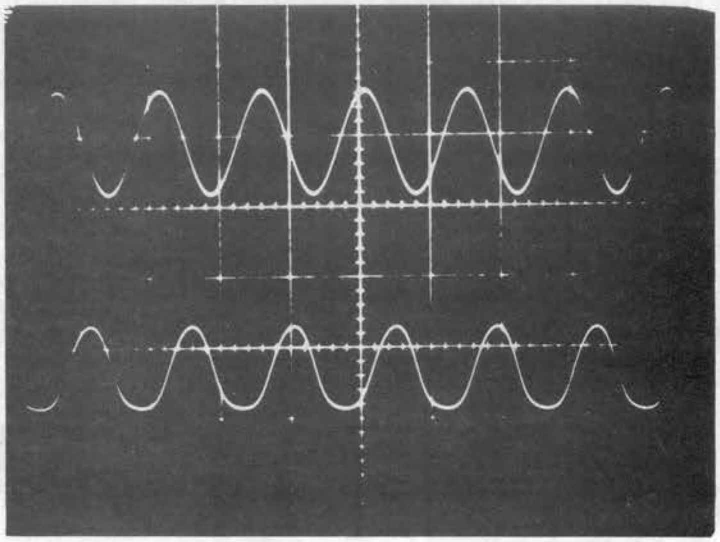


Figure 24. Clipping of the output disappearing at 80 kc shown by lower trace. Input shown by upper trace.

records were made on continuously advancing film by the Du Mont camera. The traces from the film are reproduced graphically in Figures 25 through 28. In each figure trace "A" is the output from the field meter and trace "B" is the field-change between the screens. The case for each figure will be discussed individually.

For the traces of Figure 25 the attenuator selector switch S-1 was in F position and switch S-2 was in No. 1 position. The V-2 bias switch S-3 was in No. 1 position. For each voltage step applied to the screen the field meter output is seen to be a vertical spike from Figure 25.

Attention is called to the intermediate step in the voltage trace in going from forty-eight to ninety-six volts per meter. This is readily explained by examining Figure 14. It is noted that switch S-4 is equipped with a shorting type wiper; i.e., when switching from position 2 to 3 these two contacts are shorted together. This action shorts across R_2 dropping the supply voltage V_t across the four remaining resistors. Therefore the voltage drop across each resistor momentarily increases by one-fifth its original value. The intermediate steps in going from ninety-six to 144 and 144 to 192 volts per meter are explained in a similar manner.

From Figure 25 it is seen that for a forty-eight volt per meter field-change the field meter output is 3.5 volts, giving a ratio of $48/3.5 = 13.7$. By examining other field-changes, we see the ratio to be the same. This indicates that the gain of the system is essentially constant for this range of field-changes.

An important fact to point out is that for a positive field-change the field meter output was a positive spike and for the negative

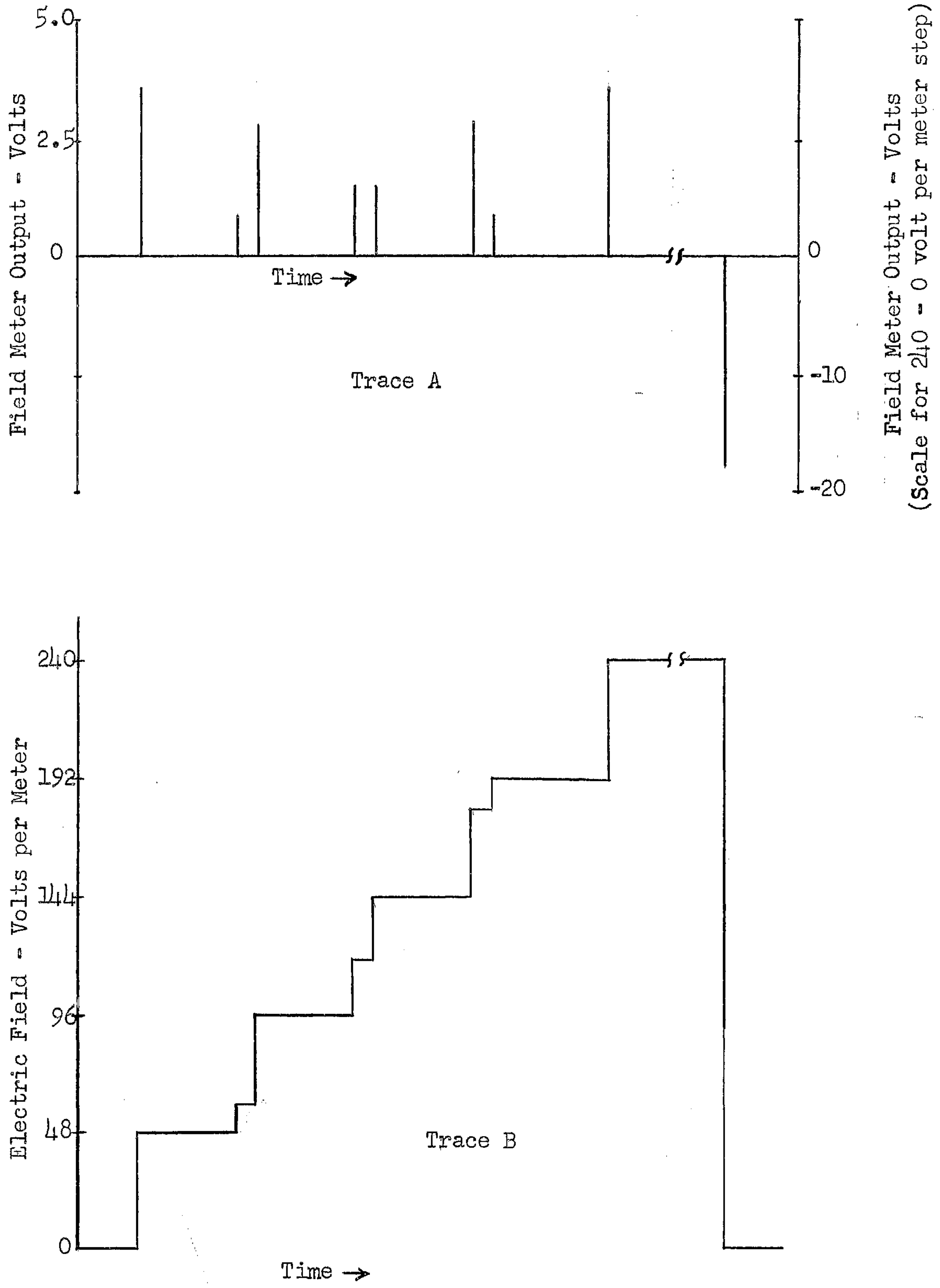


Figure 25. Traces of field-changes and field meter output /switch S-1 in F position, switch S-2 in No. 1 position, and switch S-3 in No. 1 position./

field-change, 240-0, the output was a negative spike. It is also noted that the field meter responds only to field-changes and not to steady state conditions.

Figure 26 shows the traces for the reverse steps of Figure 25. It is again noted that the ratio of field-change to field meter output is 13.7. Here, again, we see that for the positive field-change the field meter output was a positive spike and for negative field-changes negative spikes.

For the traces of Figures 27 and 28 the voltage steps were the same as for Figures 25 and 26 respectively, but the attenuator selector switch, Figure 12, was placed in the S position. Switches S-2 and S-3 were not changed. In this instance we get a field meter output of 6.1 volts for a forty-eight volt per meter field-change compared to 3.5 volts for the previous traces. This represents a gain of

$$20 \log_{10} 6.1/3.5 = 4.84 \text{ db} \qquad (4.3)$$

over the previous attenuator setting.

The traces of Figure 29 were made with a field of 120 volts per meter between the screens. The voltage was removed from the screens momentarily; then the two screens were shorted together. It is seen that the field meter responded to only a very small portion of the field-change as the charge on the screens began to decay. This indicated that the antenna system has a very small time constant since the frequency-response curve shows that the amplifier is capable of handling a larger portion of the field-change.

Figure 30 shows traces made with a 240 volts per meter field between the screens. The voltage was removed from the screens and

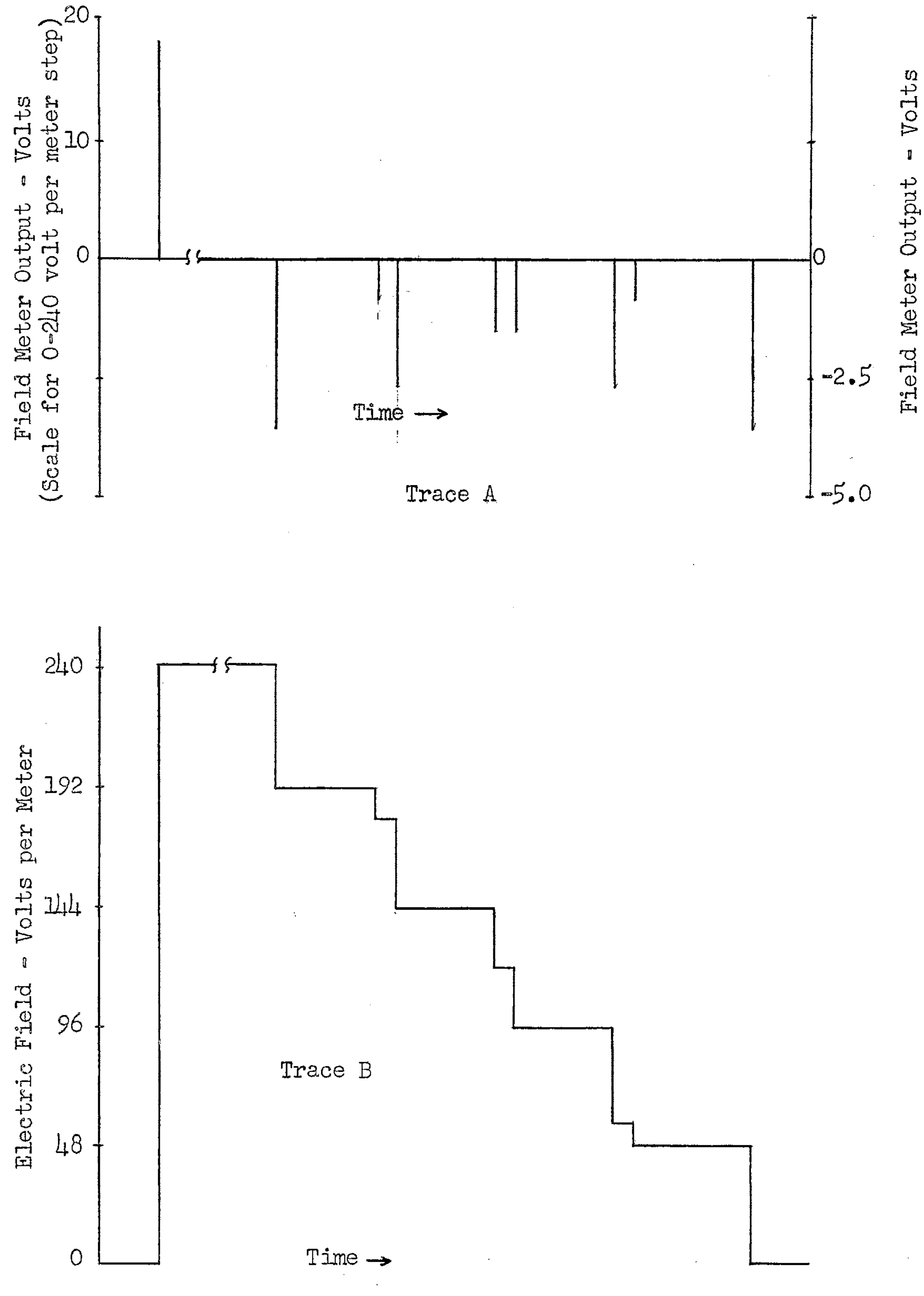


Figure 26. Traces of field-changes and field meter output /switch S-1 in F position, switch S-2 in No. 1 position, and switch S-3 in No. 1 position/.

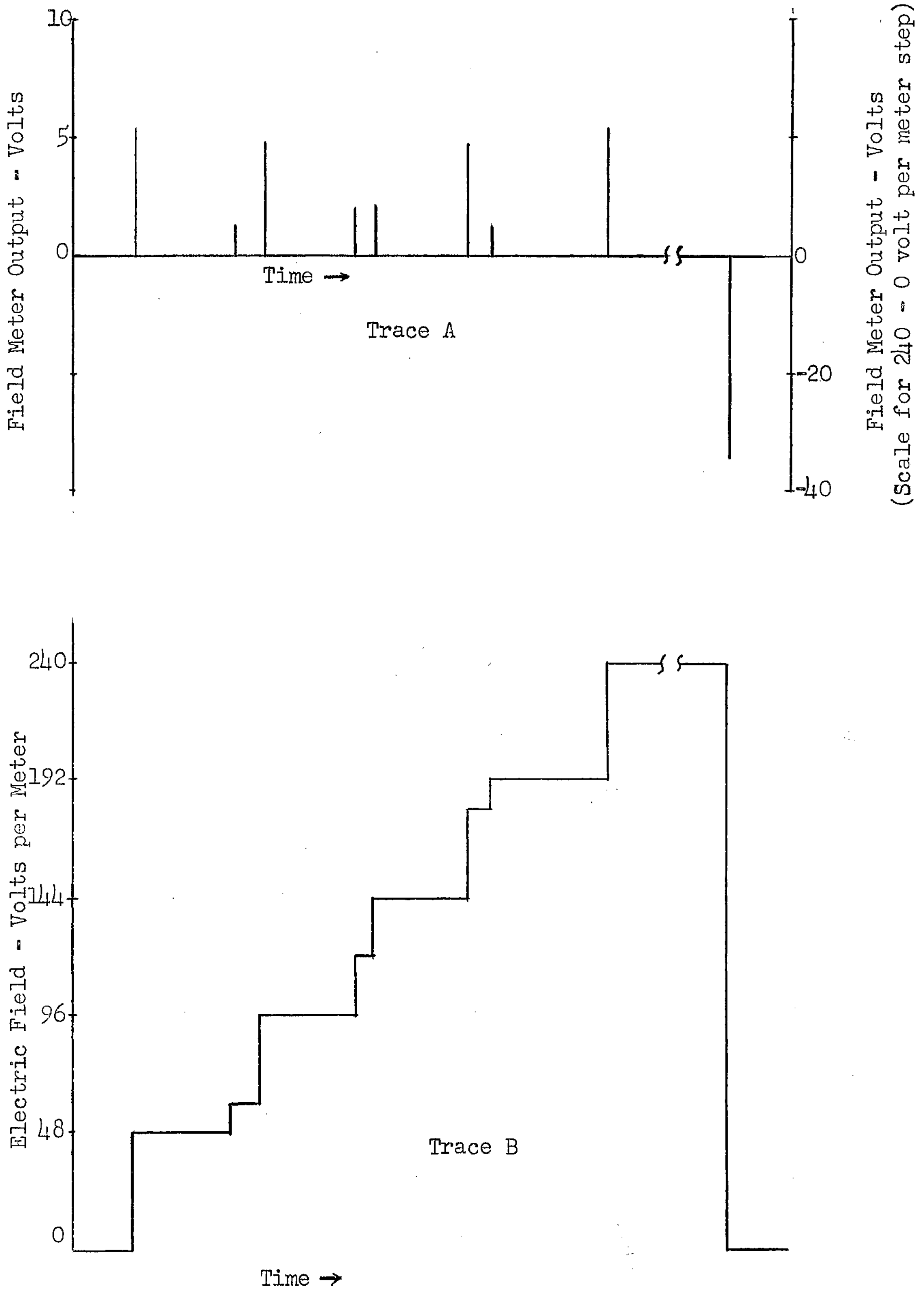
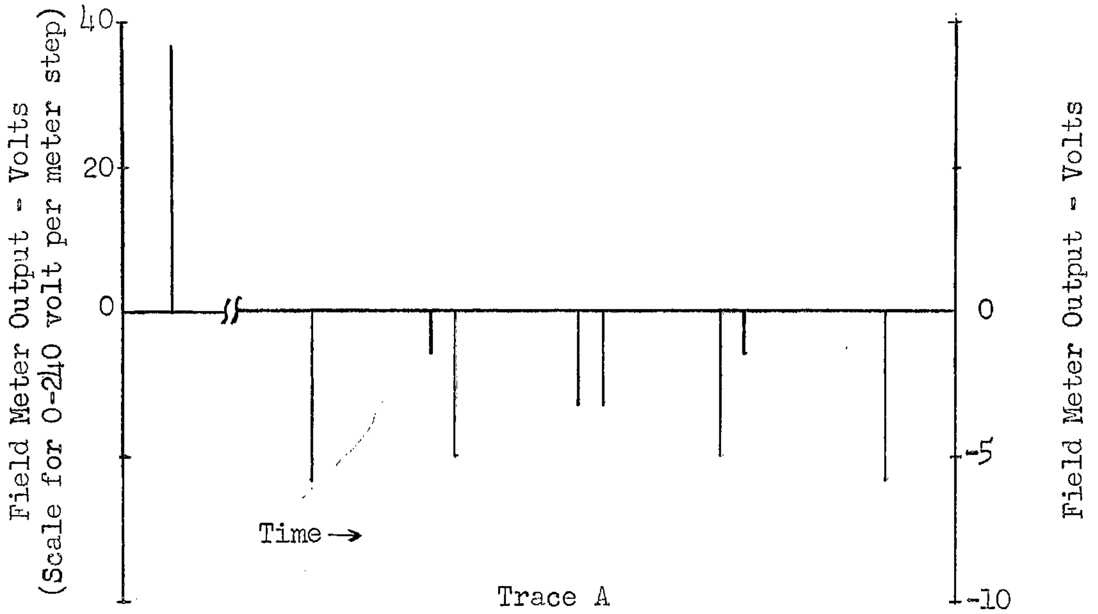


Figure 27. Traces of field-changes and field meter output [switch S-1 in S position, switch S-2 in No. 1 position, and switch S-3 in No. 1 position].



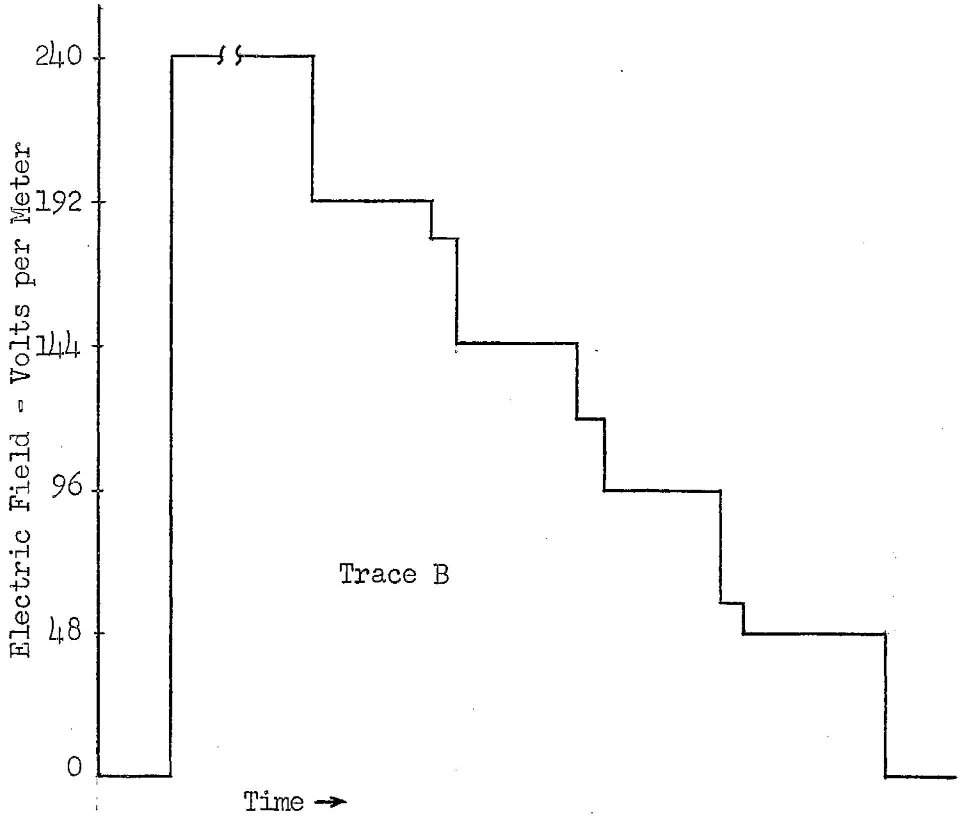


Figure 28. Traces of field-changes and field meter output /switch S-1 in S position, switch S-2 in No. 1 position, and switch S-3 in No. 1 position/.

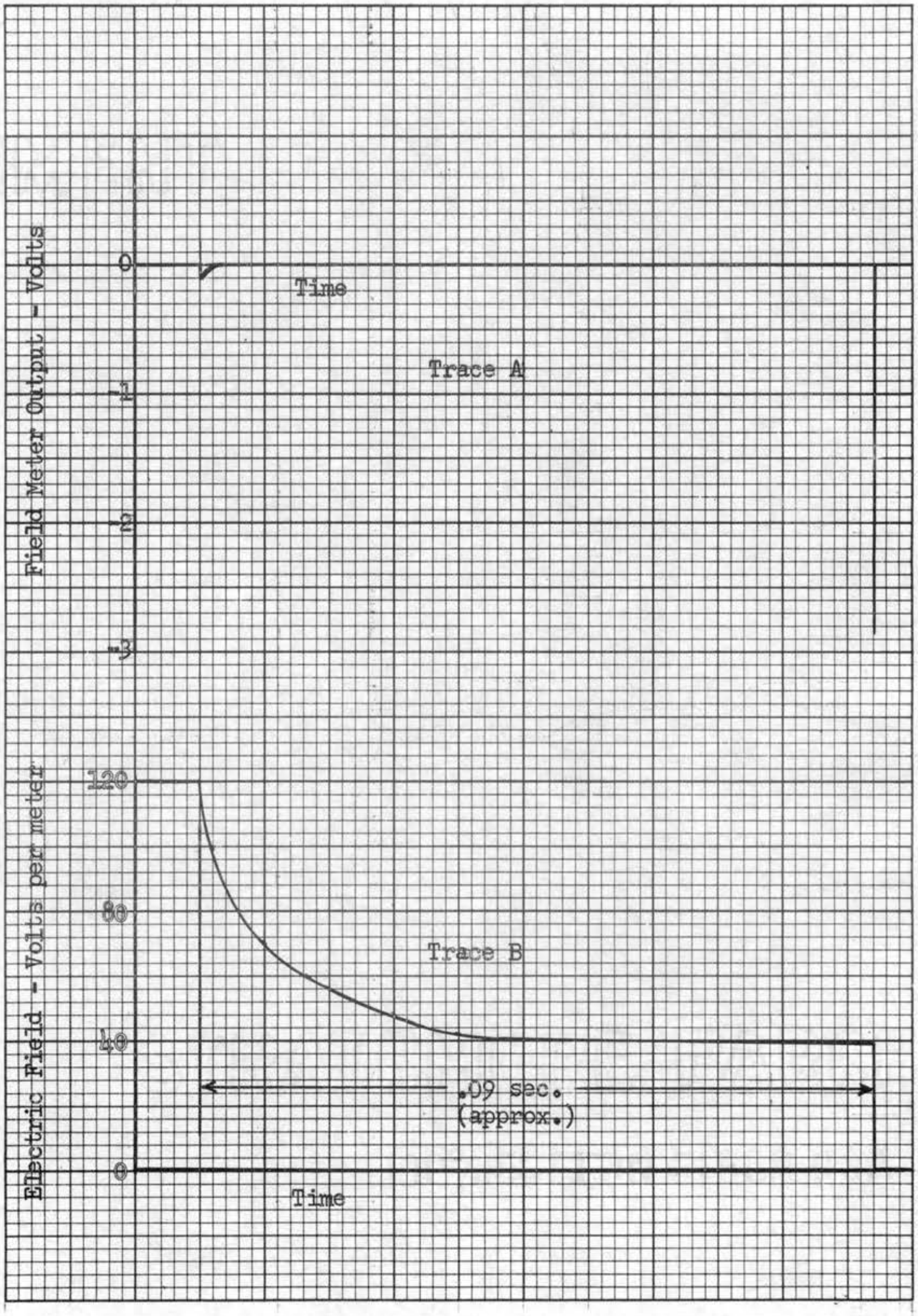


Figure 29. Traces of field-change and field meter output for open-circuit then short-circuit field decay.

the charge allowed to decay. Again the field meter responded to a very small portion of the field-change.

A plot of field-change versus field meter output is shown in Figure 31. The data for these curves were taken from Figures 25 through 28. In using the curves of Figure 31, one must remember that for positive field-changes the field meter output is positive and for negative field-changes the field meter output is negative.

Field-change Traces

Figures 32 through 34 show traces made from the output of the Brook Type Field Meter during a storm in the evening of October 13, 1960. Records are insufficient to correlate this data with that taken by the Q-3 Direction Finder in order to determine something of the nature of the lightning strokes. Thunderstorm activity has been insufficient during the course of this thesis to obtain data and keep accurate records.

However, by referring to the preceding data of this chapter, one is able to conclude considerably more about the field-changes shown in the traces of Figures 32 through 34 than was previously known. One important fact is that the positive spikes shown in the subject traces represent a field-change in the positive direction and the negative spikes a change in the negative direction. An analysis of the data obtained with the wire screen revealed that the Brook Type Field Meter responds only to fast varying fields. This means that in all probability the subject field meter will tell nothing of the electric field behavior in the intervals between successive separate strokes of a discharge. It seems reasonable to assume that considerable changing is

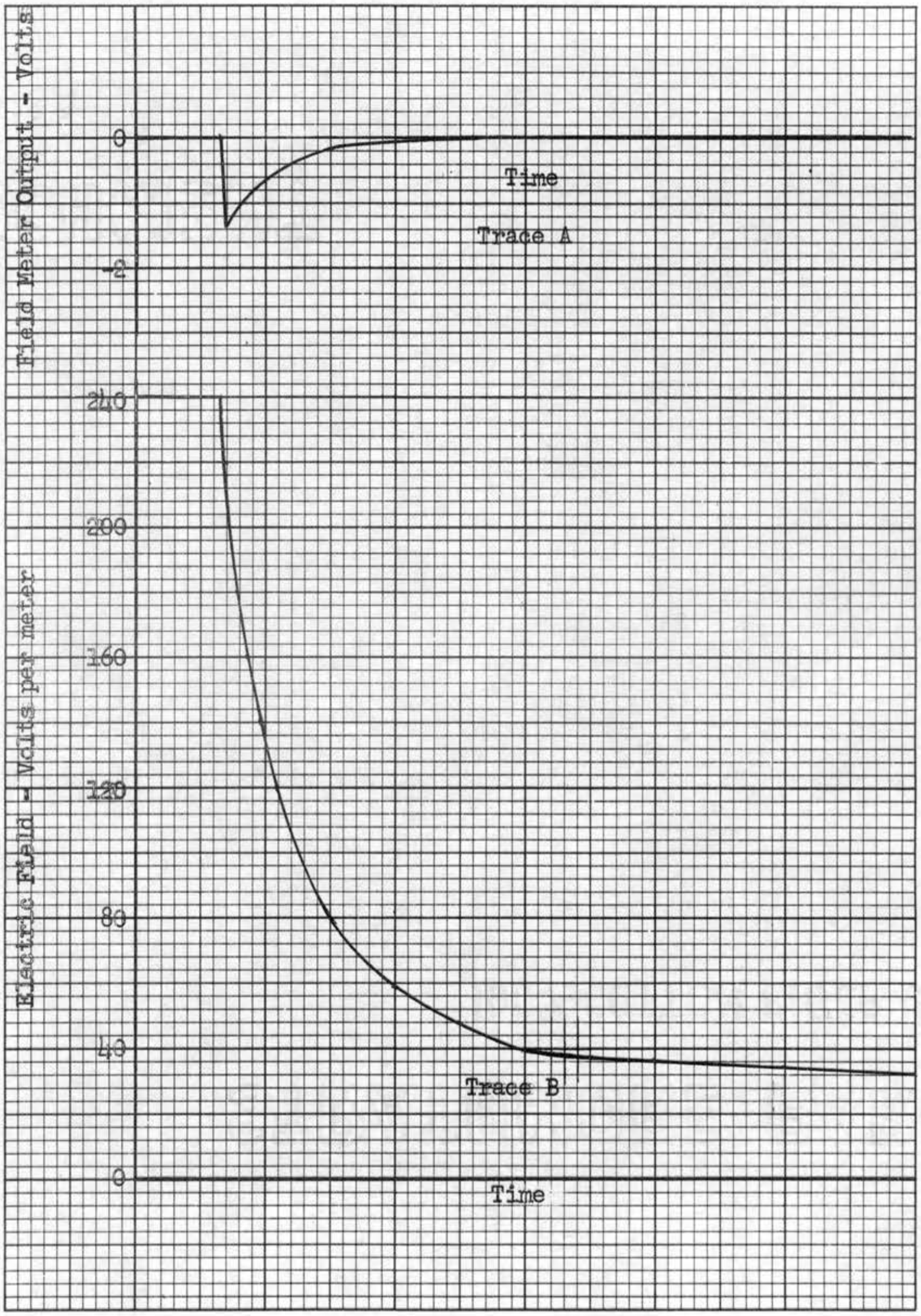


Figure 30. Traces of field-change and field meter output for open-circuit field decay.

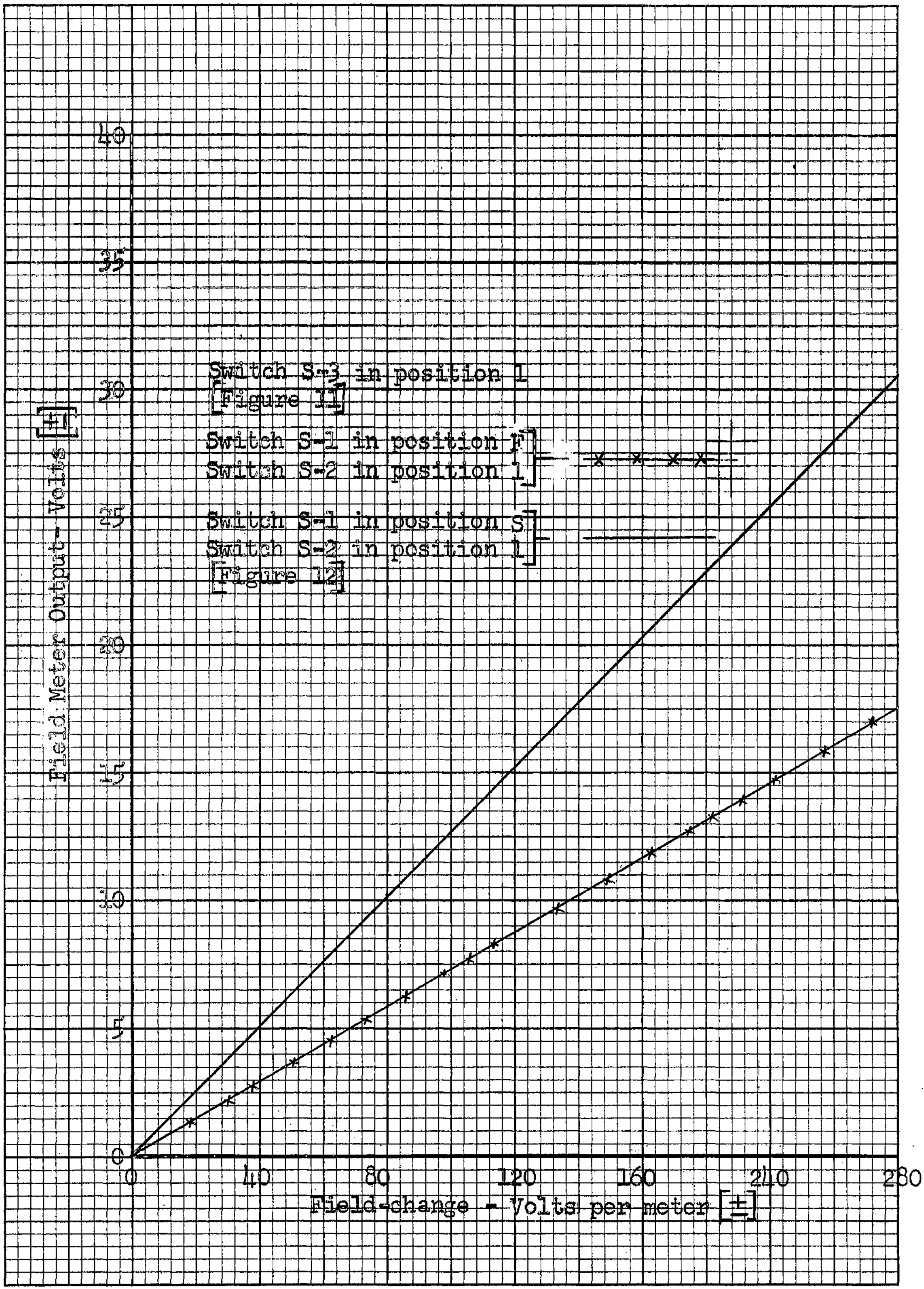


Figure 31. Field-change vs Field Meter output for two attenuator settings.

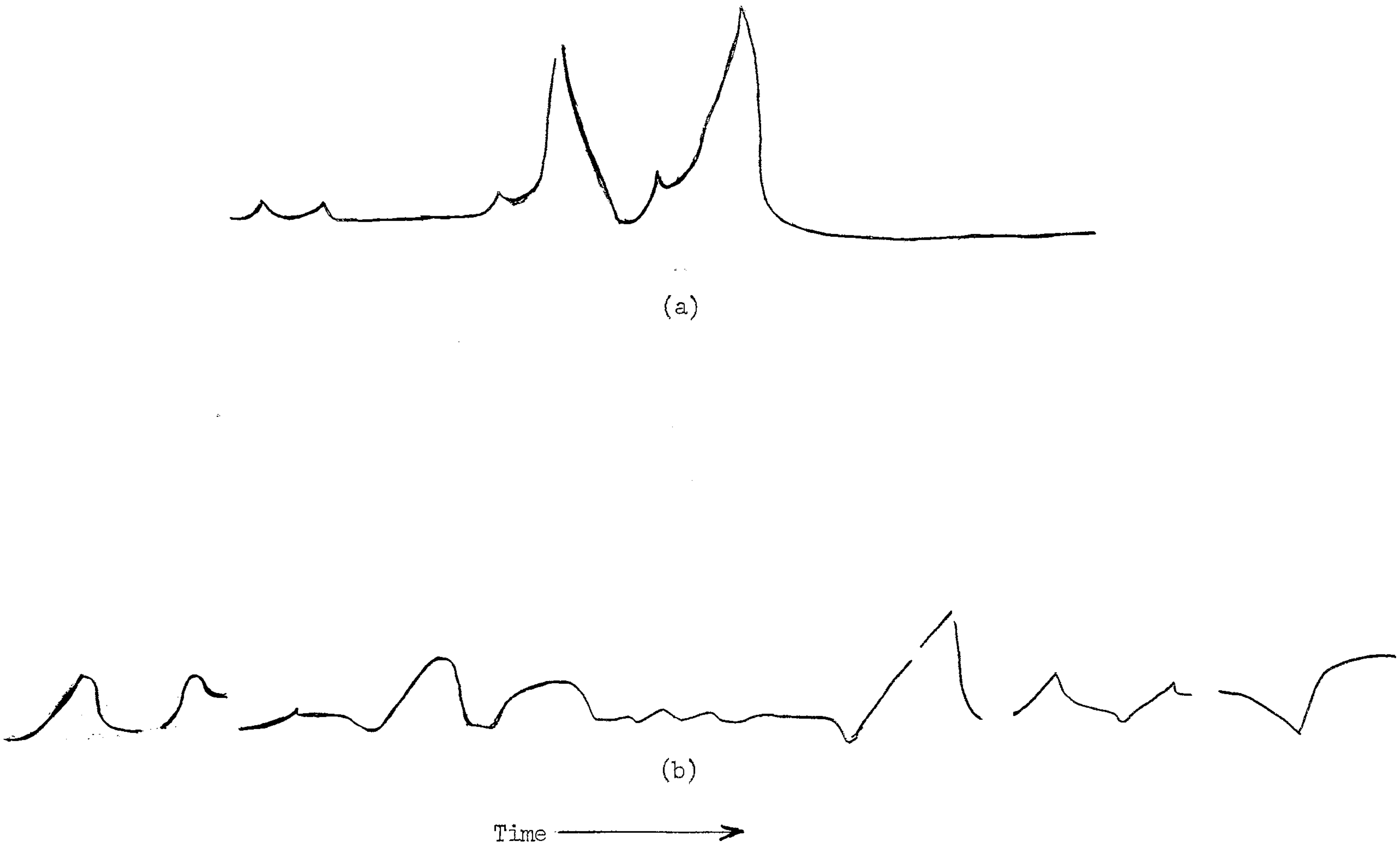


Figure 32. Traces made from the output of the Brook Type Field Meter, October 13, 1960.

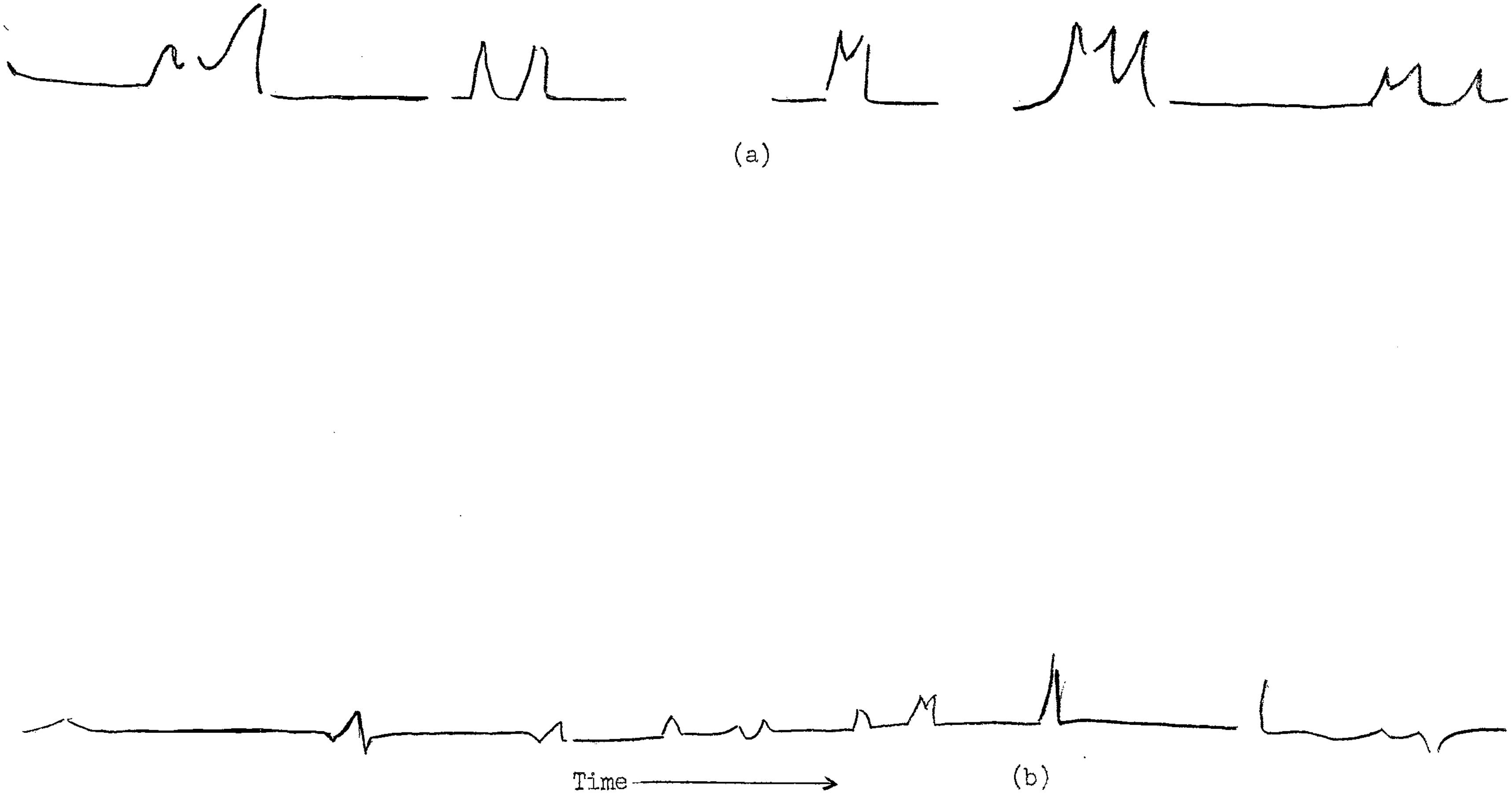


Figure 33. Traces made from the output of the Brook Type Field Meter, October 13, 1960.

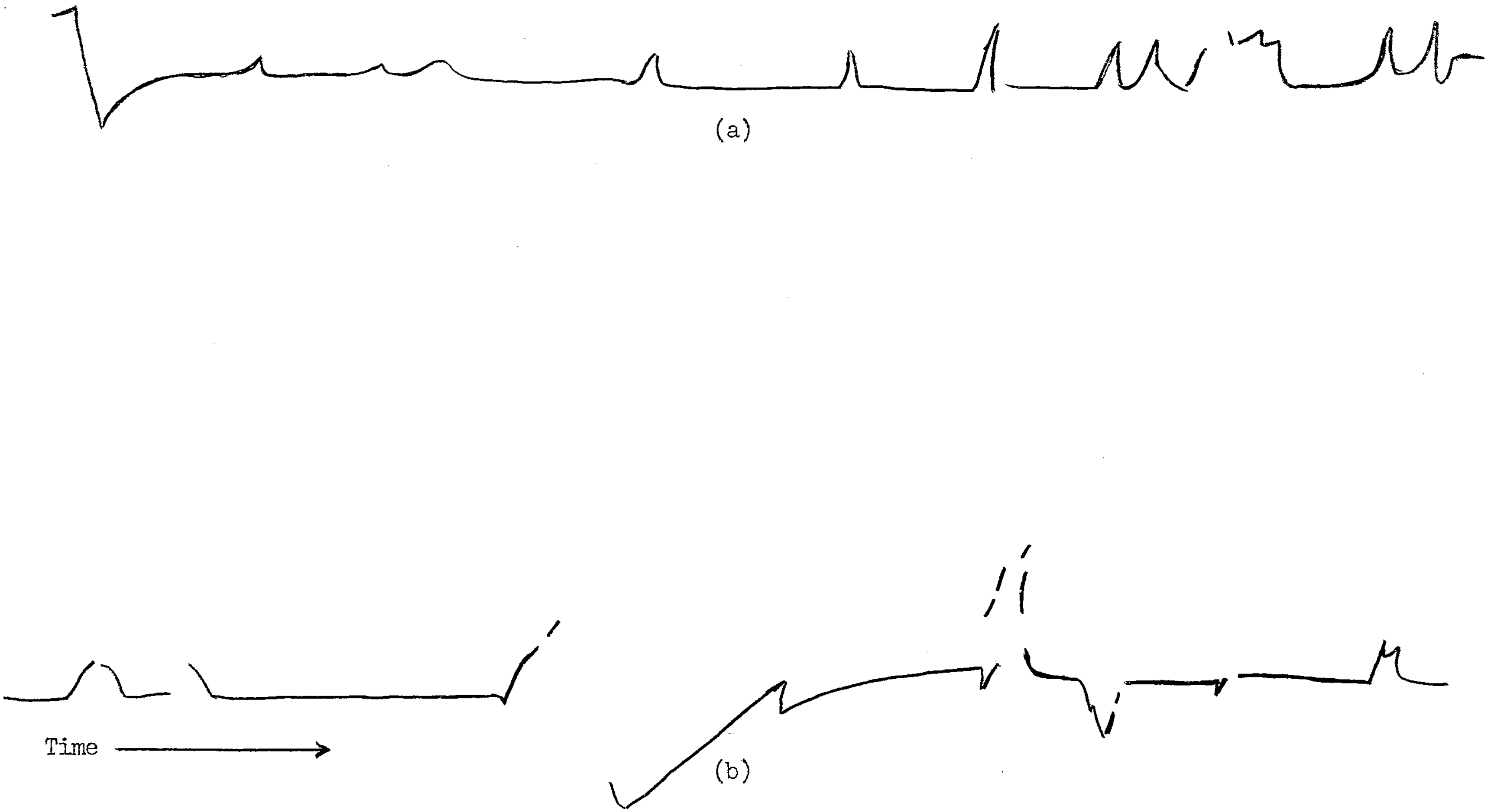


Figure 34. Traces made from the output of the Brook Type Field Meter, October 13, 1960.

taking place that is not recorded in the traces shown in Figures 32 through 34. This is in no way a disadvantage to the system. Much use can be made of an instrument that will detect and record the fast field-changes associated with cloud discharges. Instruments have been in use for a considerable length of time that will detect the slower changes. These, when used in conjunction with the Brook Type Field Meter, will serve to reveal much useful data about the electric field-changes during a lightning stroke.

It was stated earlier that nothing is available to aid in identifying the lightning strokes shown by the traces in Figures 32 through 34. However, by recalling the mechanism of a lightning discharge as presented in Chapter I and the dipole theory of Chapter II, some reasonable assumptions can be made. Referring to Figure 32a, one can see that the trace consists of two large spikes with a small spike in between. These are preceded by a series of smaller spikes. In all probability this trace represents a cloud-to-ground stroke since it was stated in Chapter II that such a stroke produced a positive change in the electrical moment. A reasonable assumption is that the small spikes represent the field-change associated with the step-wise movement of the stepped-leader and the larger spikes represent two return strokes. The small spike between the two larger spikes would represent the dart leader. This same line of reasoning can be applied to the traces of the other figures. It may be reasoned that the negative changes are caused by distant inter-cloud discharges since they cause a negative change in the electrical moment.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

It can readily be concluded from the frequency-response characteristic that the amplifier is quite capable of faithfully reproducing any input in the frequency range from below ten cycles per second to 250 kilocycles. Also it is seen from the curves of Figures 16-17 that the V-2 bias can be adjusted to give a considerable amount of gain. This will be important when measuring weak field-changes due to distant storms. It appears that the frequency range is sufficient to cover any field-changes due to lightning strokes. The important thing to note from the amplifier tests is that it will faithfully reproduce any field-change that is fed into it.

It was readily seen in Chapter IV that the Brook Type Field Meter responds only to fast field-changes. It was also seen from the frequency-response curve that the electronic amplifier was capable of operating at ten cycles per second or lower. This points to the fact that the data obtained is determined for the most part by the antenna and attenuator system until the high frequency limit of the amplifier is reached. This suggests that different antenna configurations could be developed to be used with the subject field meter depending on the type of data that is desired. It might be feasible to consider a second system utilizing a slower antenna system to cover an intermediate range between the present Brook Type Field Meter and the long wire field meter system presently installed at the Atmospherics Laboratory. It was seen in Figures 25 through 28 of Chapter IV that the field-changes generated by the wire screen appeared as vertical spikes on the film record. The thought comes to mind that this might not be true if the resolution were increased. This can be done by adding some value of horizontal sweep to the oscilloscope, at the same time maintaining the film speed of 600 inches per minute. This idea might be pursued in some future experiment.

It has been demonstrated that the Brook Type Field Meter will reveal much information about fast field-changes created by lightning discharges. It will be especially useful for recording the very fast components associated with each step-wise movement of a stepped leader.

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